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ASSESSING THE ECOLOGICAL RAMIFICATIONS OF OFFSHORE SOLAR FARMS ON FISH POPULATIONS IN EUROPEAN MARINE ECONOMIES

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Abstract

The implementation of the European Union's National Renewable Energy Action Plans regulation in 2009 has facilitated the expansion of offshore solar power. This development presents potential implications for marine ecosystems and fish habitats. However, the degree of these effects is influenced by several factors, including project design, geographic location, and operational practices. It is essential to objectively assess the outcomes of these policies to inform both their ongoing implementation and future improvements. Rigorous evaluation ensures that policy decisions are based on evidence and can effectively address environmental and energy objectives. This study analyzes panel data from 27 European Union member states, covering the period from 1990 to 2023. A heterogeneous timing difference-in-difference model is employed to evaluate the impact of transformation policies on the expansion of offshore solar farms and their effects on marine ecosystems. The policies have significantly encouraged offshore solar power production in Western European Union member states. In contrast, similar effects were not observed in Central and Eastern European member states. The expansion of offshore solar farms has had a less significant effect on reducing ocean acidification in Western European countries compared to Central and Eastern European countries. The findings were validated through a placebo test, confirming the effectiveness of the policy measures.

Keywords: Offshore solar farms; fish population; ocean acidification; marine ecosystem; blue economy

1- Introduction

The National Renewable Energy Action Plans (NREAPs) of EU member states, aligned with the EU's renewable energy directives, have significantly influenced the development of offshore solar farms and their ecological implications for marine life, particularly fish populations. NREAPs, initially submitted under the 2009 Renewable Energy Directive (RED), outline national pathways to achieve EU renewable energy targets. The revised RED (2023) raises the EU's 2030 renewable energy target to 42.5% (aspiring for 45%). While NREAPs historically focused on onshore renewables and offshore wind, recent updates in countries like the Netherlands and Germany are increasingly integrating offshore solar. For example, the Netherlands launched a tender in 2023 to accelerate commercial-scale offshore solar projects, aiming to co-locate solar farms with wind farms to optimize sea space (SolarPower Europe, 2024).

The EU's Horizon Europe program and the Connecting Europe Facility provide funding for offshore renewable projects, including solar. For instance, the EU-SCORES project (2021–2025) is testing combined offshore solar and wind farms in Belgium and Portugal to assess environmental impacts and energy output. Additionally, the TEN-E Regulation (2023) prioritizes hybrid offshore grids to support multi-source energy farms, indirectly boosting offshore solar integration. The EU's Marine Spatial Planning Directive (2014) mandates coordinated planning for offshore activities, including renewables and fisheries. This helps minimize conflicts, such as by designating areas where offshore solar can coexist with fishing. For example (SolarPower Europe, 2024), (1) Offshore solar structures, like floating panels, can create artificial reefs, attracting fish and other marine organisms, such; pilot projects in the North Sea have observed increased biodiversity around solar arrays. (2) Exclusion zones around offshore solar farms may inadvertently protect fish spawning grounds, allowing populations to recover. This aligns with the EU's Common Fisheries Policy goals for sustainable stocks.

However, this does not come without negative effects and significant challenges as well (SolarPower Europe, 2024), for example, (1) Construction and operation of offshore solar farms can disrupt benthic ecosystems. A 2024 study in China found that offshore solar reduced water flow velocity by 0.03–0.07 m/s, leading to siltation and loss of intertidal habitats, which are critical for juvenile fish. Similarly, electromagnetic fields from underwater cables may interfere with fish navigation. (2) Pile-driving during construction and operational noise from maintenance activities can stress fish and marine mammals. For example, studies on offshore wind farms (which share similar construction methods) show temporary displacement of fish species like cod and herring. (3) Spatial overlap between offshore solar farms and fishing grounds, particularly in the North Sea, has raised concerns. Bottom trawling, which targets flatfish and crustaceans, is most affected, as solar infrastructure limits access to traditional fishing areas.

From another perspective, although NREAPs require developers to conduct evaluations under the Environmental Impact Assessment Directive (2014), evaluating effects on biodiversity, habitat loss, fisheries, and water quality in EU countries, however, till now not addressed three main problems: data gap, policy coordination, and scaling up sustainability. Therefore, this research questions as follows (SolarPower Europe, 2024): (1) To what extent does the NREAP policy implementation through offshore solar farms affect the fish population in the EU sea during the period between 1990 and 2023? (2) To what extent do different EU27 member states benefit or compromise in implementing NREAPs through offshore solar farms and their impact on fish populations? Accordingly, this research objective can be stated as follows: (1) To explore how offshore solar farm expansion from NREAP policy in the EU27 is affecting marine ecosystem and fish population for the period between 1990-2023, and to what extent this NREAP policy impacts blue growth. (2) To compare the experiences of different EU27 member states in implementing NREAP policy through offshore solar farms' marine ecosystem, and assess which models and policies are most effective. (3) To analyze the social, economic, and environmental dimensions of offshore solar farms with marine ecosystems, and understand how these dimensions interact to influence marine renewable energy and marine ecosystems during the same period.

By segregating the EU27 members into two groups based on economic structure and development, this research can identify the differences and characteristics of different economies within the EU. Group 1 is the European Union industrial countries (Western EU14) and consists of economically developed and diversified economies with high GDP per capita, advanced service-oriented structures, and strong innovation capacities. The EU14 members, such as Belgium, Germany, and the Netherlands, are notable for their NREAPs policy proactive approach to offshore solar farms and marine ecosystem conservation, while these nations have been developing 2009 regulatory frameworks, implementing support schemes, and hosting pilot projects (see Figure 1).

Group 2 is European Union emerging countries (Central and Eastern EU13), which includes economies in transition or with underdevelopment economies, which have lower GDP per capita, industrial structures in the process of transformation, and relatively lower innovation capacities. EU27 policies like the European NREAP, Green Deal, and the Common Fisheries Policy (CFP) strongly influence EU13's newer economies. These policies push for renewable energy adoption, creating a framework for the Marine Action Plan (MAP). Therefore, the increase of EU-wide policies regarding marine action plans has greatly increased the adoption of offshore solar farms in EU13 economies. For example, countries within the Central and Eastern European region are beginning to implement offshore solar farms and are creating legislation regarding marine ecosystem conservation.

The significance and novelty of this research using the difference-in-difference method lie in the following aspects: (1) An econometric technique for NREAP policy evaluation, comparing pre-post changes between a "treatment group" (affected by a policy) and a "control group" (unaffected) to isolate causal effects by controlling for confounding factors. (2) NREAP policy aims to promote offshore solar farms for carbon reduction, but potential ecological impacts require rigorous assessment. (3) Offshore solar farms' impacts on fish populations are confounded by climate, hydrology, and fishing activities. DIF's "double difference" (time trend + group contrast) isolates project-specific effects, avoiding misattribution in correlational analyses. (4) Existing studies focus on onshore solar or offshore wind impacts, while DIF application to offshore solar fish population research is scarce. The method breaks through limitations of single time-series or spatial analyses via dual contrasts (treatment vs. control areas; pre vs. post-project periods). (5) Fusing fishery monitoring data, offshore solar spatial data, and NREAP policy details, it constructs a "policy-project-ecology" trinity model, offering a new paradigm for interdisciplinary research.

The remainder of this study is organized into several key sections. The Literature Review examines recent research in the field, addressing both empirical and theoretical perspectives. The Data and Methodology section outlines the model specification and details the panel data estimators employed in the analysis. In the Empirical Results section, the outcomes of the panel data estimations are presented. Finally, the Discussion and Conclusion section offers an interpretation of the findings, discusses their implications, and provides concluding remarks.

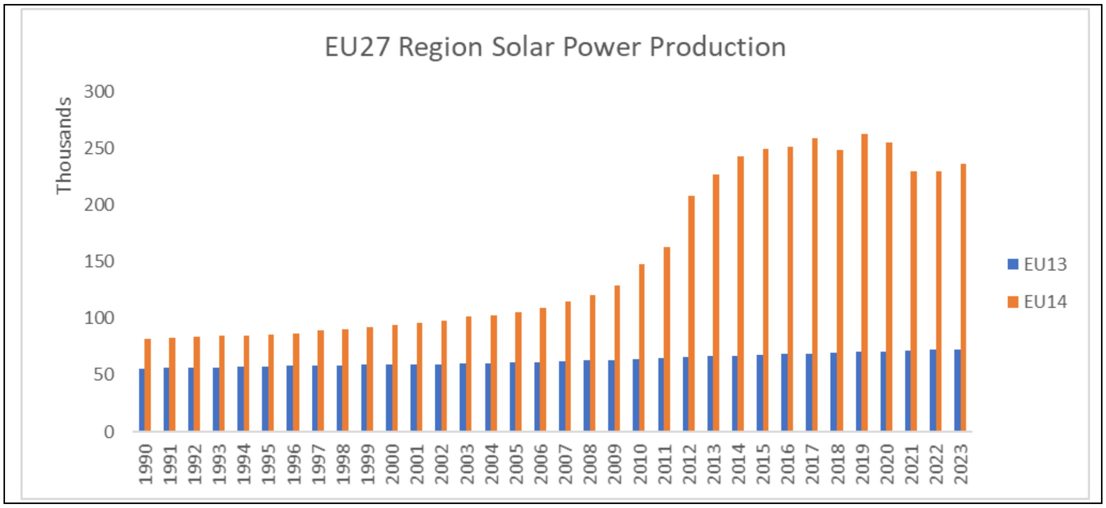

Figure 1 Offshore Solar power in the EU27 states (EU13 and EU14) during the period 1990-2023

2- Literature Review

The European Union has implemented a range of plans and measures to support the development of offshore solar farms and blue energy, with the overarching objectives of advancing renewable energy, facilitating energy transformation, and achieving carbon neutrality (Magkouris et al., 2023). The EU's Solar Strategy sets clear targets, aiming to increase installed solar photovoltaic capacity to over 320 GW by 2025 and nearly 600 GW by 2030. These targets provide a structured pathway for offshore solar power development, guiding resource allocation and the formulation of specific development plans (Salvador and Ribeiro, 2023).

Research in the North Sea region has highlighted a convergence in policy instruments for offshore renewable energy, attributed to both the liberalization of the sector and policy-learning effects (Rentier et al., 2023). Comparative studies in Denmark and Spain have emphasized the influence of public funding stability, federal structures, political interests, and policy discourse on the advancement of offshore renewable energy (Harguindéguy and Wokuri, 2024). Beyond the EU, several countries are actively pursuing offshore solar initiatives. In China, recent studies have proposed frameworks for detecting dust on photovoltaic panels in offshore floating solar power stations. These frameworks are designed to be compatible with existing image recognition models and incorporate specialized enhancement modules to improve recognition accuracy and operational efficiency (Wen and Lin, 2024; Cui et al., 2024). Similar research has been conducted in the Western Iberian Peninsula (Costoya et al., 2022) and India (Agarwala, 2021).

In Poland, the significance of offshore renewable energy within the national energy mix has been analyzed, with findings indicating varied public attitudes toward the construction of such projects. Factors influencing public perception include investment, environmental considerations, ecosystem impacts, and landscape changes (Chomać-Pierzecka, 2024). These observations are consistent with previous research, which underscores the cumulative effects of pragmatic policies and holistic marine spatial planning (Declerck et al., 2023; Salvador and Ribeiro, 2023).

Environmental assessments in the Dutch North Sea have examined the implications of offshore solar stations, noting that impacts on fish populations, water quality, birdlife, bio-deposition, and biofouling are dependent on the scale of the project (Vlaswinkel et al., 2023). In the Mediterranean Sea, studies have demonstrated that floating photovoltaic (PV) systems contribute to the removal of carbon dioxide from the ocean, thereby mitigating ocean acidification and supporting marine biology (Keller Jr et al., 2022). However, ocean-based negative emission technologies remain in the early stages of development due to high costs and technical challenges (Hofmann et al., 2025; Xu et al., 2024; Ning et al., 2023).

The deployment of floating photovoltaic systems in both freshwater and marine environments is expected to increase significantly in the coming decade, driven by the need for rapid decarbonization and the desire to avoid competition for land near population centers. Environmental impacts associated with floating PV systems include shading, alterations to hydrodynamics and water-atmosphere exchange, energy emissions, effects on benthic communities, and impacts on mobile species (Rahman et al., 2022; Holmane, 2024; Benjamins et al.). In Brazil, integrated offshore wind-solar farms along the coastline have demonstrated the potential to generate up to 300% more energy than traditional hydropower (De Souza Nascimento et al., 2022).

From an economic standpoint, offshore solar power offers the EU an opportunity to reduce reliance on fossil fuels and increase the share of renewables in the energy mix. Studies in Spain have highlighted the importance of considering spatial constraints when assessing the economic viability of floating offshore solar farms, with such projects showing the greatest potential in the Levantine-Balearic region (Filgueira-Vizoso et al., 2025; Vaca-Cabrero et al., 2025). Across Europe, the development of offshore multi-use platforms faces challenges such as high investment costs, regulatory complexity, and the need for stakeholder coordination. Nevertheless, opportunities exist in technological innovation, policy incentives, and synergies between marine sectors and the blue economy (Zaiter et al., 2025; González-Cancelas et al., 2025).

Offshore solar farms are driving technological advancements in floating structures, anchoring systems, cable technology, integrated design, and intelligent operation and maintenance. These innovations are intended to improve energy efficiency while minimizing environmental impacts. The European Commission's "EU Strategy on Offshore Renewable Energy," released in 2020, outlines measures to support the sector's sustainable development and sets a target of at least 1 GW of ocean energy installed capacity by 2030, which includes offshore solar power (Dahlström et al., 2025).

Research has also demonstrated a positive relationship between external knowledge linkages and innovation within offshore renewable energy firms, particularly during the early stages of the technological life cycle (Barrett et al., 2024; Barrett and Crowley, 2025). Additionally, patenting trends indicate a surge in global filings between 2006 and 2012, followed by a period of stagnation and a subsequent resurgence after 2017 (Pasimeni et al., 2024).

H1: The treated policies of facilitating the development of offshore solar farms are likely to heighten potential risk to the marine ecosystem.

H2: The controlled policies of facilitating the development of offshore solar farms are likely to heighten potential risks to the marine ecosystem.

The EU and some member states have introduced Marine policies and Marine action plans related to offshore solar power, such as France, Belgium, and the Netherlands. However, there is a lack of in-depth research using the Diff-In-Diff approach to explore the impact of these policies on marine ecosystems. The current literature did not precisely measure how these policies affect the expansion of offshore solar farms on marine ecosystems in the EU27 region. Without this evaluation, it is difficult to provide an empirical basis for marine energy policy optimization. Moreover, there is no research applying the DID method to compare EU27 members that have adopted specific offshore photovoltaic technologies with those that have not. Without such research, it is impossible to determine the actual effects of these technologies in practice. This restricts the further promotion and improvement of these technologies in the field of the offshore solar power market in the EU. Lastly, offshore solar power technology development and the marine ecosystem involve the interests of multiple parties, including energy developers, landowners, and farmers. Although it is theoretically possible to create new value, the actual value-distribution mechanism remains unclear. Existing studies have not used the DID method to analyze the changes in the benefits of each party under different economic models and policies at the EU member level.

3- Method and data

3.1. Data collection

To identify the factors influencing the competitiveness of offshore solar farms across the EU27 countries, this study employed the difference-in-differences (DID) analytical approach. The analysis covered data spanning from 1990 to 2023. The treatment period, during which specific policy interventions were implemented, was defined as 2010 to 2023 for the countries considered as treated. For the empirical analysis, data were collected from EU24 countries over the period from 1990 to 2023. The selection of the DID methodology was based on its suitability for evaluating policy impacts by comparing changes over time between treated and control groups. The variable definitions in the study are as follows. Intercept: A dummy variable indicating whether a country was treated (=1) during the implementation of the National Renewable Energy Action Plan (NREAP) in 2010, or served as a control (=0). OSF (Offshore Solar Farms): Represents the surface area of thermal collectors, measured in thousands of square meters. GOV (Government Effectiveness): Reflects perceptions of the quality of public services, the independence and quality of the civil service, the effectiveness of policy formulation and implementation, and the credibility of government commitments. This is measured as a percentile rank among all countries, ranging from 0 (lowest) to 100 (highest). GDP (Gross Domestic Product): Calculated as the sum of gross value added by all resident producers in the economy, plus any product taxes and minus any subsidies not included in the value of the products. INN (Innovation Ecosystem): Measured by the number of trademark applications filed with national or regional intellectual property offices. FPP (Fish Population): Indicates total fisheries production, including the volume of aquatic species caught for commercial, industrial, recreational, and subsistence purposes. It also encompasses harvests from mariculture, aquaculture, and other forms of fish farming. OCN (Ocean Acidification): Typically measured using the pH scale, which quantifies the acidity or alkalinity of a solution. In this study, carbon dioxide emissions ($CO2$) were used as a proxy for ocean acidification, as increased $CO2$ absorption leads to lower pH values and higher acidity. All data for these variables were sourced from the World Development Indicators and Eurostat. Further details are provided in Table 1.

Table 1. Variable explanation list

Variable	Symbol	Source	Variable	Unit of Measurement
Dummy Variable	Intercept	WBD	Independent	Treated = 1, Controlled = 0
Offshore Solar Farms	OSF	Eurostat	Dependent	Thousand Square Meters
Government Effectiveness	GOV	Eurostat	Independent	Percentile rank terms
Innovation ecosystem	INN	WBD	Independent	Patent applications, residents
Fish Population	FPP	WBD	Independent	Metric Tons
Ocean Acidification	OCN	Eurostat	Independent	A metric ton of CO_2
Economic Growth	GDP	Eurostat	Independent	Current US dollars

3.2. Theoretical background

Externality Theory (Managing Environmental Spillovers) is an economic analysis of offshore solar farms (OSF) and marine ecosystems that involves integrating multiple theoretical frameworks to balance energy production, ecological preservation, and socioeconomic benefits. Negative Externalities (Ecological Costs), which include: (1) Habitat Disruption, construction of OSF (e.g., underwater foundations, cabling) may disturb seafloor ecosystems, affecting benthic organisms, coral reefs, or marine mammals. (2) Noise and Light Pollution, installation activities, or operational lighting could interfere with marine life behavior (e.g., migration and breeding patterns). Positive Externalities (Environmental Benefits) include: (1) Carbon Emission Reduction, OSFs displace fossil fuel-based energy, reducing greenhouse gas emissions and mitigating climate change impacts on oceans (e.g., acidification, warming). (2) Marine Conservation Co-Benefits, OSF structures may inadvertently create artificial reefs, supporting fish populations (e.g., if designed with eco-friendly materials).

The Difference-in-Differences (DID) method is a valuable tool for assessing how various factors within the externalities model influence the output of offshore solar farms. This approach enables researchers to evaluate whether the externalities model enhances production efficiency and supports marine ecosystem conservation, in comparison to the independent operation of offshore solar power projects under the NAREAP framework. The DID technique, as employed by Upton and Snyder (2017), Abadie (2018), and Xu (2017), is widely recognized for its effectiveness in policy evaluation studies. In this context, the method is applied using either cross-sectional or panel data, covering both EU14 and EU13 countries over two distinct periods: 1990–2010 and 2011–2023. The primary reason for selecting the DID method is its ability to provide unbiased estimates of the impact of offshore solar farms within the EU27 region. This ensures that the results are both reliable and robust. (1) Let y(i, t) represent the outcome of interest for country i at time t. (2) Observations are made for countries before (t = 0) and after (t = 1) the implementation of the treatment. (3) Countries exposed to the treatment during the relevant period are assigned D(i, t) = 1. (4) Countries not exposed to the treatment are assigned D(i, t) = 0. These serve as the control group. (5) In this study, the EU14 countries constitute the treated group, while the remaining countries serve as controls. According to Abadie (2018), countries can only be considered as treated or untreated based on their exposure status during the specified periods. The DID estimator is typically calculated using a linear parametric model, following the procedures outlined by Card (1985) and Abadie (2018). For this analysis, it is assumed that the outcome variable is generated according to a variance process, as specified in the theoretical model.

$$Yi,t = \mu i,t = \delta(t) + \alpha \cdot Di,t + \eta(i) + vi,t \quad (1)$$

In Equation (1), several key terms are defined as follows: $\delta(t)$: This term denotes a component that is specific to each point in time. α: This parameter measures the effect of the treatment. $\eta(i)$: This represents a component unique to each country. $v(i, t)$: This variable captures country-specific shocks. These shocks have a mean of zero within each period and are directly correlated over time. $y(i, t)$ and $D(i, t)$: These are the observable variables in the model.

$$P(Di,t = 1|-\mu i,t)=P(Di,1) =1 \quad (2)$$

For t = 0, 1, by performing the addition and multiplication operations on the conditional expectation $E[\eta(i) \mid D(i,1)]$ as presented in Equation (1), the expression is transformed as follows:

$$Yi,t = \delta(t) + \alpha Di,t + E[\eta(i)| Di,1] + \varepsilon i,t \quad (3)$$

From Eq. (3); $(i,t)=\eta(i)- E[\eta(i)]| D(i,1)]+v(i, t)$. It should be noted that $\delta (t)=\delta (0) + (\delta(1)-\delta (o)t$,

And; $E[\eta(i)]| D(i,1)]=E[\eta(i)]| D(i,1)=0]+E[\eta(i)] \mid D(i, 1) =1]- E[\eta(i)] \mid D(i,1)=0]D(i,1)$.

Let $\mu= E[\eta(i)]| D(i,1)=0] +\delta(0)$, $\tau= E[\eta(i)]| D(i, 1) = 1]- E[\eta(i)]| D(i,1)=0]$, and $\delta=(\delta(1) - \delta (o)$.

Equation (4) is derived below:

$$Yi,t = \mu + \tau Di,1 + \delta t + \delta Di,t + \varepsilon i,t \quad (4)$$

The constraints applied to Equation (2), specifically setting t = 0, 1, indicate that the expectation $E[1, D(i,1), t, D(i, t)]$ holds under the condition that the error term $\varepsilon(i, t) = 0$. This framework establishes the basis for further analysis. The variables presented in Equation (4), along with the parameter δ, can be estimated using the ordinary least squares (OLS) method. This approach provides a straightforward means of obtaining parameter estimates within the specified model. Furthermore, the structure of the equation allows for the identification of treated countries based on their level of dependence. This is determined by the condition D(i,1) = 1 and the inclusion of the country-specific variable $\eta(i)$. Equation (4) may also be simplified further, as outlined below.

$$Yit = \delta + \delta_i \times TREAT_i + \delta_{it} \times POST_t + \beta^{2\times 2}{}_t TREAT_i \times POST_t + U_{it} \quad (5)$$

In this analysis, Yit denotes the outcomes associated with several factors, including offshore solar farms (OSF), the intercept, government variables (GOV), gross domestic product (GDP), innovation (INN), ocean-related factors (OCN), and financial policy parameters (FPP). The term δiTREATi identifies countries that have received the treatment at a specific point i. Meanwhile, δitPOSTt refers to countries that have been exposed to the treatment after its implementation. The interaction term, represented as β2×2tTREATi×POSTt + Uit, captures the combined effect of the treatment dummy for a particular group of countries and the post-treatment dummy for those countries within the regression model. This section incorporates both EU13 and EU14 member states that have experienced the treatment, both before and after its introduction. The objective is to identify the key determinants influencing offshore solar farm development. Uit represents the country-specific, serially uncorrelated transitional component, reflecting changes in renewable energy investments and the state of marine ecosystems within individual countries. The methodology applied here is known as the difference-in-differences (DID) approach. Based on the condition outlined in Equation (2), the resulting model is presented in Equation (6) below;

$$\delta = \{E[Yi,1|Di,1=1]-E[Yi,1|Di,1=0]\} - \{E[Yi,0|Di,1=1]-E[Yi,0|Di,1=0]\} \quad (6)$$

Model formulation is essential when analyzing cross-sectional data pairs, specifically (Y(i,t), D(i,1)) for time periods t = 0, 1. In this context, the study utilizes panel data to capture differences before and after a particular event across various countries. The observed outcome is represented by the values Y(i,1) and Y(i,0), reflecting measurements at two distinct time points. The parameter δ is then estimated using the ordinary least squares (OLS) method, which is a standard approach for such analyses.

$$\delta = E[Yi,1-Yi,0|Di,1=1] - E[Yi,1|Yi,0,Di,1=0] \quad (7)$$

Based on the deduction from Equation (2), when considering t = 0, 1, the difference v(i,1) - v(i,0) represents an average that does not depend on D(i,1). As a result, in the absence of any treatment applied to the countries, the mean outcomes would exhibit the same variations as those observed in the treated countries. Abadie (2018) notes that this modeling approach can be restrictive, particularly when the treated and untreated groups possess different, unbalanced exploratory variables that are associated with the dynamics of the outcomes. This limitation may affect the validity of the results if such differences are not properly addressed. Drawing an analogy to the foundational work of Ashenfelter (1978), it is important to account for these variations among the countries under study and to address the heterogeneity present across them. To manage these concerns, Ashenfelter and Card (1985) proposed a model specifically designed to accommodate such differences:

$$Di,1 = \begin{cases} 1, \text{if } yi,1 - k + ui < Y \\ 0, \text{otherwise} \end{cases} \quad (8)$$

In this context, K represents a positive integer, Y is a constant, and u(i) denotes a random variable. The scenario described considers the behavior of countries with relatively low offshore solar farm output factors. Following the treatment period, countries exhibiting lower offshore solar farm output are expected to implement and strengthen policies aimed at expanding their offshore solar energy sector. This response is primarily driven by the requirements of the Paris Accord and the influence of marine environmental advocacy groups. The Difference-in-Differences (DID) approach is applicable under the condition specified as (i, 1−k). This condition must be satisfied for the analysis to yield valid results. The effect on the group subjected to the intervention is outlined below:

$$f(\theta,Di1)= \begin{cases} -\mathrm{Yi1}, \mathrm{Di1} = 1 \\ |\ \mathrm{Yi0}\ |, \mathrm{Di1} = 0 \end{cases} - [E(\mathrm{Yi0} \mid \mathrm{Xi}, \mathrm{Di1} = 1) - E(\mathrm{Yi0} \mid \mathrm{Xi}, \mathrm{Di1} = 0)] \quad (9)$$

The equation X(i) = (i, 1-k) defines a vector, X(i), which represents the observable characteristics of each country. As outlined both in this article and in Abadie (2018), these characteristics are established at time t = 0. Equation (9) addresses the sequence in which matching is performed during the analysis.

Specifically, it compares each group of treated countries, denoted by i, to individual countries that have not received the treatment. This matching process is connected to the outcome covariate, Yi, for the treated units. For each treated country, the matched outcome is determined by the estimated coefficient, b, applied to Yi. This result is then weighted according to its corresponding neighbor in the comparison group.

$$\widehat{Yi} = \sum_{j\in C^{0}(Pi)} w_{ij}\, y_{j} \qquad (10)$$

C^0(Pi) denotes the set of treated neighbors for an individual i within the group, where D = 0. The term Wij refers to the weight assigned to each untreated individual i when making comparisons with their treated counterparts. In general, the matching estimator for the Average Treatment Effect on the Treated (ATT), denoted as ATT(S_{10}), can be expressed as follows:

$$\widehat{ATT} = \frac{1}{\#[D=1\cap(S10)}\sum_{i\in\{Di=1\}\cap S10}(Yi-\widehat{Yi}) \qquad (11)$$

$E\,\{Y|\text{treated on } S_{10} - E\,\{Y|\text{weighted/untreated}$

4- Results

To evaluate the potential for determining and scaling up offshore solar farm output across the EU27 countries, a normality test was performed on the dataset. The Jarque-Bera normality test was selected to examine both skewness and kurtosis. The results indicated that the data exhibited a statistically significant normal distribution, as demonstrated by a p-value of 0.00. This finding confirms that the residual errors are normally distributed. The detailed results of this analysis are presented in Table 2, which summarizes the EViews output for the Jarque-Bera test. Following the confirmation of normality, the difference-in-differences (DID) estimator was employed to further analyze the data, as shown in Table 3. The DID approach offers several key advantages:

(1) It enables the comparison of directly comparable entities, ensuring methodological consistency. (2) It accounts for both observed and unobserved differences in characteristics among the countries studied. (3) The method is straightforward to implement in data analysis. (4) It adopts a non-parametric approach, providing flexibility in handling various data structures. These features make the DID estimator a suitable choice for analyzing the impact of different factors on offshore solar farm output within the EU27 context.

Table 2 gives a summary of the descriptive statistics of the covariance and normality test. The mean score of the two determinants, ocean acidification (OCN) and fish population (FFP), is the highest among the variables, referring to the sensitive relation of these two variables in this study model. Interestingly, innovation ecosystem (INN) and government effectiveness (GOV) in the countries are relatively low. This indicates that government effectiveness and innovation ecosystem are negligible in the offshore solar power sector of the EU countries. The mean score of economic growth (GDP) is relatively moderate, as offshore solar power contributes to the blue economy, and blue growth is commonly used. The government effectiveness (GOV) figure supports the fact that the working environment and regulations play a crucial role in the development of renewable marine energy and in mitigating the effects of environmental pollution on the planet. As expected, the mean score of offshore solar power is relatively moderate.

Table 2: Summary statistics and normality test

	FFP	GOV	OCN	INN	OSF	GDP
Mean	4.897	0.326	4.726	0.714	3.774	1.528
Median	5.166	0.328	4.737	0.714	3.724	1.540
Maximum	6.310	0.359	5.981	0.720	5.055	1.752
Minimum	2.797	0.071	2.000	0.698	3.000	0.218
Std. Dev.	0.800	0.563	0.563	0.002	0.247	0.082
Observations	918	918	918	918	918	918
Normality Test	Skewness	Kurtosis	Jarque-Bera	Probability		Observation
Residual	0.373	2.626	26.00	0.000		918

Table 3 presents the intercept dummy variable for treated countries and time, as specified in Equation (5). The inclusion of this variable serves to establish a counterfactual framework for evaluating the hypothesis that all countries, regardless of treatment status, receive comparable levels of renewable and sustainable energy policies. The dummy variable is defined as D = 1 for countries that have received the treatment and D = 0 for those that have not. Statistical analysis indicates that the dummy variable is significant, with a p-value of 0.000. The significance of the dummy variable suggests that both treated and untreated countries demonstrate a strong tendency to attract further development of offshore solar farms. Moreover, these countries are actively implementing renewable and sustainable energy policies designed to mitigate environmental impacts and support a transition toward sustainable development. For further details, refer to Figure 2 and Figure 3.

Table 3 Regression with a dummy variable for the intercept (treat*post) t- t-statistic test

Variable	Coefficient	Std. Error	t-Statistic	Prob.
INTERCEPT	1.292	0.036	35.131	0.00
R-squared	0.814	Mean dependent var		3.774
Adjusted R-squared	0.799	S.D. dependent var		0.247
S.E. of regression	0.110	Akaike info criterion		-1.493
Sum squared resid	10.459	Schwarz criterion		-1.146
Log-likelihood	751.308	Hannan-Quinn criteria		-1.360
F-statistic	57.412	Durbin-Watson stat		0.045
Prob(F-statistic)	0.000			

The parallel trend test is an essential prerequisite for applying the time-varying point Difference-in-Differences (DID) method. In this study, the event study approach is employed to conduct the parallel trend test within the time-varying DID framework. Figure 2 presents the dynamic effects observed in the analysis. During the four periods preceding the implementation of the NREAPs policy, the coefficients associated with the dummy variables do not exhibit statistically significant deviations from zero. This outcome suggests that, before the policy intervention, the strategies of both the treatment and control groups followed a relatively stable trend. Following the introduction of the

NREAPs policy, the coefficient of the relevant variable rises above one. This change indicates that the strategies adopted by both the treatment and control groups experienced notable shifts as a direct consequence of the policy's implementation.

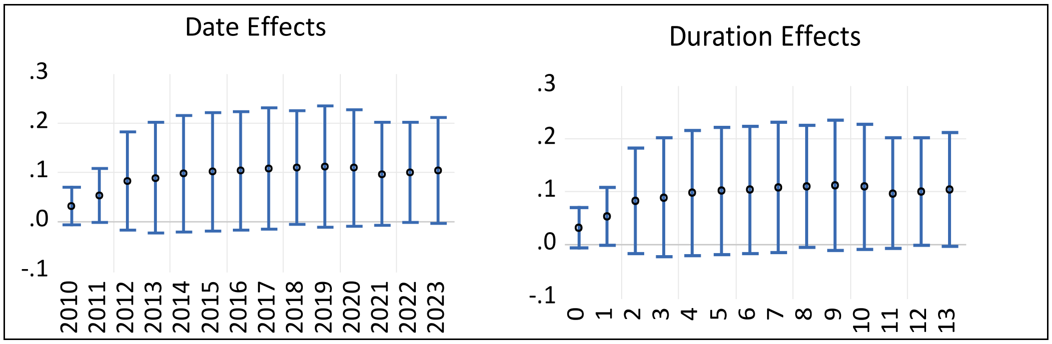

Figure 2: Parallel trend test. The vertical dashed line shows the "event year" of 2010, and the horizontal dashed line shows the zero-value axis.

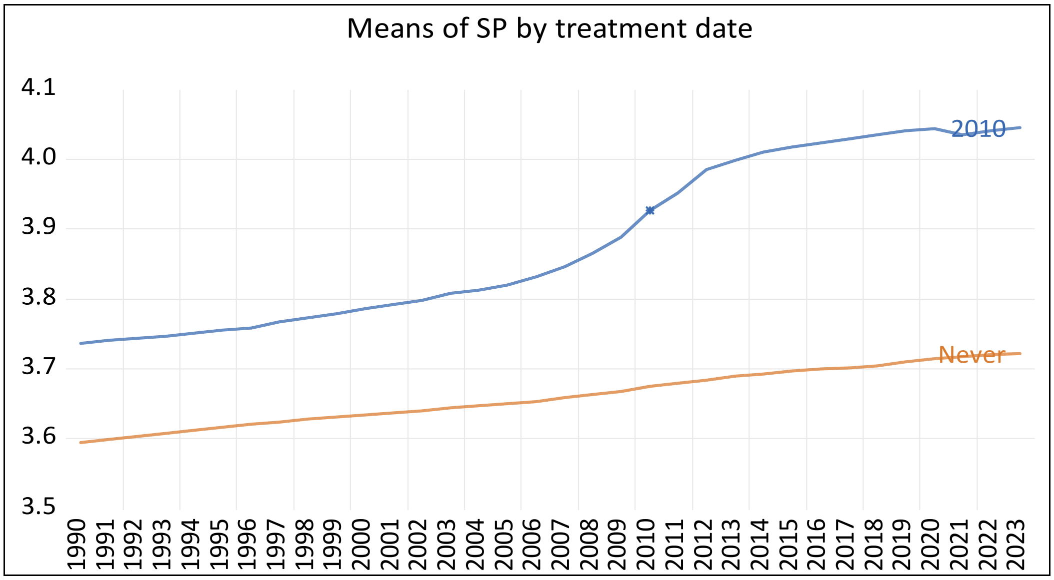

Figure 3 Policy implementation profiles showing the list of adverse events that affected the treatment (in blue) and controlled countries (in red) from 1990 to 2023, before and after the baseline date 2010.

The primary hypothesis of this study was that the effectiveness of the National Renewable Energy Action Plan (NREAP) in promoting offshore solar farm expansion would result in different responses—both negative and positive—compared to those observed in control countries. To assess this, the research examined two hypotheses separately: first, the impact of negative coping strategies under NREAP, and second, the effect of positive adaptive or transformative NREAP strategies. The analysis employed the Ordinary Least Squares (OLS) model, as presented in Table 4, and the Fixed Effect-Ordinary Least Squares (FE-OLS) model as a robustness check in Table 5. The study controlled for Central and Eastern European countries (EU13) and treated Western European countries (EU14) as the primary comparison group. Given the distinct responses among EU27 member states to NREAP policies, the research also considered the specific characteristics of these states, particularly in relation to negative coping strategies. As a result, the focus was placed on three principal models: EU27, EU14, and EU13.

For each of these three models, the study identified countries that reported being affected by NREAP policies at the baseline and analyzed their corresponding coping strategies. The results from the OLS and FE-OLS models, which tested the difference-in-differences (DiD) approach, were not fully conclusive. In Table 4, the DiD (intercept) variable was statistically significant and positive for both the EU27 and EU14 groups, indicating a greater tendency to adopt positive, strengthening NREAP strategies. In contrast, for the EU13 control group, the DiD variable was not significant and was negative.

Similarly, in Table 5, the DiD (intercept) variable remained statistically significant for the EU27 and EU14, again reflecting a higher propensity for positive NREAP strategies. For the EU13 group, the variable did not show statistical significance. The empirical evidence supports the initial hypothesis regarding NREAP strategies. The implementation of these policies has contributed to the expansion of offshore solar farms and is expected to increase the share of marine renewable energy—referred to as blue energy—within the EU27 region. The findings are particularly conclusive for positive responses, as the likelihood of adopting adaptive or transformative NREAP strategies is higher among the EU27 as a whole and among treatment countries (EU14), compared to the control group (EU13).

Table 4 Testing the effect of NREAPs on coping with offshore solar farms, using OLS models. Test completed for the three main models: EU27 States overall (Model 1); Western European Union States EU14 (Model 2); and Central and Eastern European Union States EU13 (Model 3).

Model	EU27		EU14		EU13	
Variable	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error
INTERCEPT	0.200***	0.017	0.232***	0.021	0.006	0.024
FPP	-0.066***	0.008	-0.028*	0.014	-0.117***	0.009
GDP	0.331***	0.028	4.401	4.344	0.2004***	0.020
GOV	0.016	0.890	14.259***	2.826	1.713**	0.692
INN	24.701***	3.305	8.865*	5.095	21.666***	3.687
OCN	-0.110***	0.028	-0.209***	0.022	-0.038**	0.019
Constant	1.494***	2.107	1.761***	5.030	1.281***	2.465
Observation	918		476		442	
Number of groups	27		14		13	
F-statistic	136.701		61.222		47.882	
Prob(F-statistic)	Prob>F=0.000		Prob>F=0.000		Prob>F=0.000	
R-squared	0.473		0.439		0.397	
Control	YES		NO		YES	
Treat	YES		YES		NO	
Intercept	YES		YES		YES	

In Table 4, there is a significant positive influence of NREAPs strategies on offshore solar power. An increase in NREAP applications by 1% will bring about an increase in offshore solar power supply by 0.23% in EU14 states, and 0.20% in the EU27 states overall. In the EU14 states, this research observes that NREAPs policy implementation contributes to an increase in the share of GOV and INN by 14.259 and 8.865 for a 1% increase in offshore solar power production. Among the other variables, a 1% increase in offshore solar power was associated with a decrease in FPP and OCN by 0.028% and 0.209%, respectively.

The DID regression results for the changes in NREAPs policies and the reflection on the offshore solar power production are reported in Table 5; the most influenced group measure is shown to be the EU14 treatment group by 0.194%, the EU27 region by 0.172%, and no significant evidence for EU13 (controlled group). After its treatment, an observed change of -0.197% in FPP, 9.721% in GOV, 35.503% in INN, and -0.244% in OCN was recorded in the years following the treatment for each 1% increase in offshore solar power production in the EU14.

In Table 5, among the three NAREP measures considered, the EU13 controlling group is the least affected by the NREAPs policies implementation. In the year following the NREAPs policies boosting the EU27 region overall, there is an estimated change in FPP and OCN by -0.061% and -0.081% for a 1% increase in offshore solar power production. Moreover, an observed change of 0.305% in GDP and 25.058% in INN was recorded for each 1% increase in offshore solar power production.

Table 5 Testing the effect of NREAPs on coping with offshore solar farms, using FE-OLS models. Test completed for the three main models: EU27 States overall (Model 1); Western European Union States EU14 (Model 2); and Central and Eastern European Union States EU13 (Model 3).

Model	EU27		EU14		EU13	
Variable	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error
INTERCEPT	0.194***	0.021	0.172***	0.024	0.013	0.008
FPP	-0.061***	0.009	-0.197**	0.091	-0.056***	0.006
GDP	0.305***	0.031	0.053	0.060	0.121***	0.009
GOV	0.045	0.919	9.721***	3.006	2.140***	0.274
INN	25.058***	3.357	35.503***	8.009	9.239***	1.754
OCN	-0.081**	0.032	-0.244**	0.095	-0.034***	0.008
Constant	1.853***	2.151	-2.989***	6.081	7.652***	1.190
Observation	918		476		442	
Number of groups	27		14		13	
F-statistic	20.857		55.588		63.946	
Prob(F-statistic)	Prob>F=0.000		Prob>F=0.000		Prob>F=0.000	
R-squared	0.480		0.698		0.468	
Control	YES		NO		YES	
Treat	YES		YES		NO	
Intercept	YES		YES		YES	

5- Discussion

When comparing EU14 western states (treatment group) and EU13 central and eastern states (control group), the greatest augmentation in offshore solar power production policies is achieved in EU14 states (see Table 5). For example, an average annual increase in offshore solar power production of 0.172% and 0.013% is observed in the EU14 and EU13 countries, respectively, following the implementation of the NREAPs policy. The outcome is consistent with earlier studies such as Kasiulis et al (2020) and Kuprat and Huck (2020). NREAP policy and regulation encouraged EU14 member states to formulate relevant policies to support the expansion of renewable marine energy. Many EU14 Western European countries have introduced a series of financial support policies, such as investment subsidies, feed-in tariffs, and tax incentives, to promote the competitiveness of offshore solar power. For instance, the Netherlands has set aside € 44.5 million in a funding program to add 3GW of offshore solar capacity to the country's energy mix.

Due to the promotion of offshore solar power under the NREAP policy led to an average annual mitigation of about -0.244% and -0.034% in OCN for EU14 and EU13, respectively. These results aligned with previous research by Tyka et al. (2023), Chen et al. (2022), and Cai et al. (2023). Western EU14 nations have longer histories of heavy industry, energy production, and maritime traffic (e.g., shipping routes through the English Channel and North Sea), contributing to persistent CO_2 accumulation in coastal waters. Eastern and Central EU13 economies, historically less industrialized and with smaller shipping sectors, have discharged fewer CO_2 pollutants into adjacent seas, leading to slower acidification rates. Despite recent green transitions, Western EU14 countries still host more fossil fuel-dependent industries, while eastern and central states—though transitioning—have smaller carbon footprints in maritime contexts. Eutrophic waters in the Baltic and Black Seas (EU13 nations) support dense phytoplankton blooms, which absorb CO_2 through photosynthesis, temporarily offsetting acidification effects.

Similarly, raising offshore solar power drives an average annual decrease of about -0.197% and -0.056% in FPP for EU14 and EU13, respectively. The outcome aligned with earlier research, such as Benjamins et al. (2024) and Wang et al. (2024). There is a stronger correlation between offshore solar power and fish population decline. Western EU14 countries (e.g., Germany, Denmark) enforce pre-construction ecological impact assessments (EIAs) and post-installation monitoring, prioritizing habitat mitigation (e.g., artificial reef placement alongside solar farms). Offshore solar projects in the North Sea often adopt “blue energy” guidelines, integrating fish-friendly designs (e.g., cable burial to reduce electromagnetic fields). Also, EU14 nations have larger offshore solar (and wind) portfolios, but projects are often sited in deeper waters or away from critical fish habitats, following decades of marine spatial planning. On the other hand, Eastern and Central EU13 states have fewer established offshore renewable energy policies, leading to less standardized habitat protection measures. For example, Baltic Sea projects may lack mandatory fish passage corridors or sediment control during construction. Also, EU13 states are newer to offshore renewables, with projects often located in nearshore zones (e.g., Baltic Sea coasts) that overlap with traditional fish spawning areas, leading to higher habitat disruption.

Expectedly, after boosting offshore solar power under the NREAP umbrella, a significant piece of evidence for an annual increase in GOV is achieved in the EU14. In more detail, an average annual escalation of about 9.721% in GOV for EU14 and 2.140% in GOV for EU13. This result contradicts earlier research by Alsaleh et al. (2020/2024); Wang and Alsaleh (2023); and Alsaleh and Abdul-Rahim (2021/2025) but aligned with Kakoulaki et al. (2024); Khaleel and Elbar (2024). Western EU14 countries' government effectiveness in offshore solar farms is a reflection of proactive policies, efficient regulations, financial systems, and technological leadership, all reinforced by EU-wide collaboration. Eastern EU13 countries, while making progress, struggle with fragmented governance, underinvestment, and reliance on external expertise. Closing this gap requires EU13 governments to prioritize policy stability, grid modernization, and cross-border partnerships, leveraging EU27 frameworks to accelerate offshore solar deployment.

Next, the increase of offshore solar power under the NREAP policy led to an average annual escalation of about 0.053% (insignificant) and 0.121% in GDP for EU14 and EU13, respectively. This was consistent with previous research by Ramos et al. (2022), Bădîrcea et al. (2021), and Tapoglou et al. (2022). Offshore solar power has a more pronounced impact on EU13 Central and Eastern Europe's blue economy due to policy-driven energy transition, favorable resource endowments, cost advantages, and aligned industrial needs. In contrast, EU14 Western Europe's mature offshore solar sector, high transformation costs, and industrial complexity limit offshore Solar's role in the blue economy, though its technological leadership still influences regional development. From another perspective, Central and Eastern European countries, EU13, as they are in the process of economic development, have a greater demand for low-cost and efficient energy sources. Offshore solar power can meet the competitiveness needs to some extent. In addition, compared with Western Europe, EU14, Central and Eastern Europe, EU13 has lower labor costs and land prices, which can reduce the construction and operation costs of offshore solar power projects and improve their competitiveness. Western European countries, EU14, on the other hand, have higher labor costs and more expensive land, which may increase the cost of offshore solar power projects and thus limit their competitiveness and impact on the blue economy.

The promotion of offshore solar power reflects an average annual growth of about 35.503% and 9.239% in INN for EU14 and EU13, respectively. The outcome contradicts previous findings, for example, Gajdzik et al. (2024), Pakulska (2021), and Nichifor et al. (2025). However, the offshore solar power innovation ecosystem in EU14 outperforms that in EU13 due to a combination of historical investment, technological infrastructure, policy frameworks, and industrial collaboration. For example, EU14's decades-long focus on offshore wind (e.g., UK, Germany, Netherlands) created infrastructure, technology, and expertise that directly support floating solar projects (e.g., floating foundations, subsea cabling). Moreover, established R&D hubs (e.g., Fraunhofer Institute, Delft University) drive innovation in durability and maintenance. EU14's offshore solar innovation ecosystem thrives on a foundation of decades of offshore investment, integrated policy frameworks, and mature industrial chains. EU13, while growing, faces hurdles in infrastructure, funding, and talent development (See Chart 1).

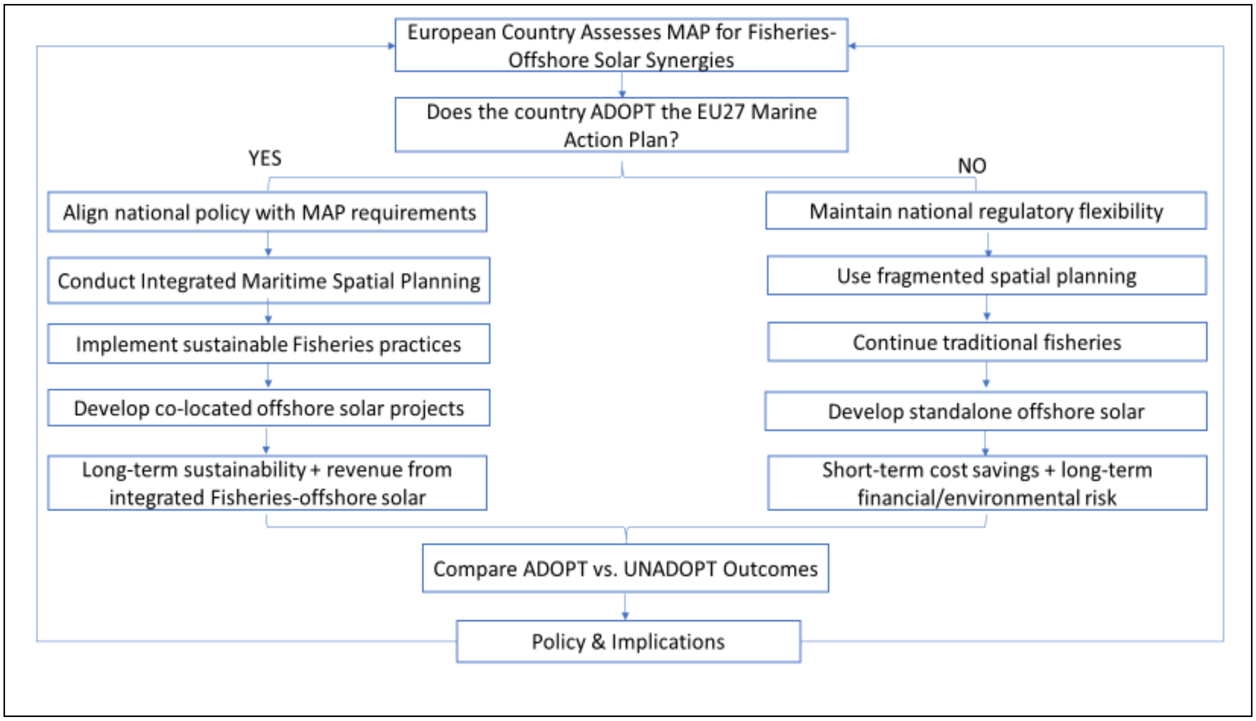

Chart 1 Impact of the Marine Action Plan (Offshore Solar Focus) on Offshore Solar-Fisheries Synergy Projects in European Countries (Adopters vs. Non-Adopters of the Policy)

Table 6 presents the results of a carefully executed placebo test, which was based on a random sample of 27 countries. The estimated coefficients and their corresponding p-values were systematically recorded. These steps were taken to enhance the reproducibility of the findings and to reduce the potential impact of unobserved variables on the regression analysis: (1) All estimated coefficients from the placebo test were consistently less than one; (2) The distribution of these estimates was centered near zero. This outcome suggests that the conclusions drawn from the analysis are unlikely to be driven by other unmeasured factors. Nonetheless, it is important to recognize that this interpretation remains theoretical at this stage. Further research is necessary to thoroughly examine any possible confounding variables that could affect the validity of the regression results.

Table 6 Testing the effect of NREAPs on coping with offshore solar farms, using Placebo tests. Test completed for the three main models: EU27 States overall (Model 1); Western European Union States EU14 (Model 2); and Central and Eastern European Union States EU13 (Model 3).

Model	EU27		EU14		EU13	
Variable	Coefficient	Std. Error	Coefficient	Std. Error	Coefficient	Std. Error
INTERCEPT	-0.226***	0.021	-0.162***	0.023	0.015	0.007*
FPP	-0.056***	0.009	-0.169*	0.091	-0.022	0.008***
GDP	0.230***	0.012	0.099**	0.056	0.102	0.008***

GOV	-0.464	0.360	8.069***	2.991	2.089	0.239***
INN	23.132***	3.23635	40.220***	7.841	-0.300	1.578
OCN	1.306	0.953	-0.165	0.100	-0.021	0.016
Constant	1.880***	2.133	2.790***	5.994	0.858	1.054
Observation	918		476		442	
Number of groups	27		14		13	
F-statistic	20.26		55.26		79.34	
Prob(F-statistic)	Prob>F=0.000		Prob>F=0.000		Prob>F=0.000	
R-squared	0.473		0.697		0.522	
Control	YES		NO		YES	
Treat	YES		YES		NO	
Intercept- Random	YES		YES		YES	

5- Conclusion and Implications

This study examines the strategies for expanding offshore solar farms across the EU27 countries from 1990 to 2023. The primary objective was to assess whether there were notable differences in offshore solar power commitments related to the National Renewable Energy Action Plans (NREAPs) between two distinct periods: 1990–2009 and 2010–2023. To achieve this, a difference-in-differences (DID) approach was applied, utilizing a counterfactual hypothesis and segmenting the countries into two groups based on their regional characteristics. The analysis divided the EU27 into two groups: EU13, comprising Eastern and Central European Union members (control group), and EU14, consisting of Western European Union members (treatment group). The DID method was used to identify the impact of NREAP-related policies by comparing these groups across the two time periods. The results, after controlling for fixed effects, indicated that the regression coefficient for the DID was significantly positive at the 0.00 significance level, as shown in Tables 3, 4, and 5. A placebo test, detailed in Table 6, further confirmed the robustness of these findings.

The empirical results demonstrate that the main objective of NREAP-related policies is to promote offshore solar power production in support of marine ecosystem conservation and the blue economy. The analysis revealed several important trends: (1) Offshore Solar Power Production: The EU14 group experienced the most significant increase in offshore solar power production following the implementation of NREAP policies after 2009. (2) Government Effectiveness and Innovation: Post-2009, the EU14 group also showed greater average annual improvements in government effectiveness and innovation ecosystem compared to the EU13 group. (3) Ocean Acidification: The reduction in ocean acidification was less pronounced in EU14 states, likely due to their longer industrial history and higher energy consumption. (4) Economic Growth: The EU13 group recorded a higher average annual increase in economic growth (GDP) than the EU14 group. (5) Fish Population: The decline in fish population was more significant in the EU13 group compared to the EU14 group.

The study identifies two main mechanisms through which NREAP policies support marine ecosystem conservation in the context of offshore solar power production: (1) Marine Environmental Conservation and Green Energy Strategies: These initiatives stimulate regional blue energy and blue growth, helping the EU27 achieve NREAP goals by 2030. EU14 members, in particular, are encouraged to address historical deficits in marine ecosystem health by implementing changes in the blue economy, reducing ocean acidification, and lowering CO2 emissions. (2) Transformation and Development Plans: EU27 members are exploring strategies for the effective transmission and development of offshore solar power. Key benefits include: (A) Enhancing energy security by reducing dependence on fossil fuel imports and diversifying renewable energy sources. (B) Minimizing ecological impact through marine-friendly designs, such as floating platforms, and reducing pressure on onshore land use. (C) Promoting the integration of multiple renewable energy systems (wind, wave, solar) for more reliable and cost-effective power generation, as exemplified by the EU-SCORES project.

To further advance offshore solar power expansion and consolidate policy achievements, the following recommendations are proposed: (1) For EU13 (Eastern and Central Europe): Increase political support for offshore solar projects by enhancing innovation ecosystems, improving government effectiveness, and restructuring industrial energy systems to facilitate a transition from conventional to renewable energy sources. (2) For EU14 (Western Europe): Implement more proactive marine ecosystem measures and enforce regulations requiring high-pollution industries to transition to offshore solar-powered operations, thereby supporting blue economy growth.

This study acknowledges certain limitations. The sample size may not fully represent the entire European continent, which restricts the generalizability of the findings. The results may also reflect the specific economic structures of EU27 members during the study period and may not apply to non-EU European countries. Further research is necessary to better understand the dynamic effects of NREAP policy upgrades on marine ecosystem strategies. In particular, time series and panel data analyses could clarify whether the observed growth in offshore solar farms is immediate and sustained or subject to change over time. Additionally, behavioral adaptation to new regulations may require a period of adjustment, meaning the full impact of NREAP upgrades on consumption patterns may only become apparent after a significant time lag. Dynamic analysis would also allow for a more detailed examination of potential rebound and pre-bound effects on marine ecosystem factors.

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M.A. (Mohd Alsaleh) gathered the data and estimated the panel cointegration model and the competitive advantage of the external factors on the solar power industry in the EU27 region; M.A. presented the EU27’s health environment and renewable energy sector industry and put together all the numerical results; M.A. contributed with conclusions and recommendations as well as with the limitations of the study and further research; M.A. conducted the literature review; and was responsible for the overall writing process.

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Data is available upon request.

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The authors declare the provided manuscript has not been published before nor submitted to another journal or preprint server for consideration of publication.

Consent to participate:
The authors declare that the manuscript does not report studies involving human (or animal) participants, human (or animal) data, or human (animal) tissue.

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The authors declare that the manuscript does not contain any individual person's data in any form (including any individual details, images or videos).

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