Research Article

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The Role of Intellectual Property Rights in Scaling Offshore Solar Energy: Implications from EU Economics

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Abstract: The 2009 National Renewable Energy Action Plan (NREAP) required EU member states to introduce incentive mechanisms aimed at promoting IPR in offshore solar development. The primary objectives were to increase the proportion of offshore solar energy in the overall energy mix and to reduce environmental pollution. The study utilizes a heterogeneous timing difference-in-differences model, drawing on panel data from 27 EU countries covering the period from 1990 to 2023. This approach enables an assessment of how effective NREAP implementation has influenced offshore solar IPR and its subsequent impact on marine environments and ecosystems. Policy implementation in Western EU countries has had a notably positive effect on the advancement of offshore solar IPR and, as a result, on marine protection. In contrast, Central and Eastern EU states have experienced less pronounced benefits from similar policy measures. The validity of these findings is supported by a placebo test, confirming the robustness of the results. The study concludes by offering recommendations to enhance the competitiveness of offshore solar power projects across the EU. Strengthening IPR frameworks and ensuring consistent policy implementation are identified as key steps toward achieving broader adoption and improved environmental outcomes.

Keywords: offshore solar power; IPR; marine environment; marine ecosystem; blue economy

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1 Introduction

The European Union has set ambitious targets for its energy transition, aiming for a 45 % share of renewable energy by 2030 and achieving carbon neutrality by 2050. In this context, offshore solar energy – particularly floating photovoltaic (PV) systems – has become increasingly important. This technology addresses the challenge of limited land availability while supporting the growing demand for renewable energy across the region. Europe currently holds a leading position in the global offshore PV market. Countries such as the Netherlands and Italy are at the forefront, advancing large-scale offshore solar projects (Wang et al. 2025a). These initiatives demonstrate the region's commitment to expanding renewable energy capacity and leveraging innovative solutions to meet its climate objectives. Intellectual Property Rights (IPR) are essential for the continued development of offshore solar technologies. The sector depends on specialized innovations, including corrosion-resistant modules, platforms designed to withstand marine conditions, and systems for integrating with marine power grids. Effective IPR protection is necessary to encourage investment in research and development, ensuring that new technologies can be brought to market and widely adopted (Wang et al. 2025b).

The European Union has long recognized the significance of IPR in fostering renewable energy innovation. Programmes such as Horizon 2020 require strict IPR protection for outcomes funded by the EU, ensuring that collaborative research projects maintain a balance between commercial incentives and the public interest. Furthermore, public procurement policies in most EU member states typically assign IPR to suppliers to promote commercialization, while public entities retain essential usage rights. This approach has a direct impact on the dissemination and adoption of offshore solar technologies. Despite these supportive frameworks, there are notable regional differences in the EU's photovoltaic patent landscape. Western European countries, particularly Germany and France, are leading applicants for international PV patent families, accounting for approximately 70,000 global filings by 2023 (Alsaleh et al. 2024). In contrast, Central and Eastern European countries have minimal domestic filings related to offshore-specific technologies. This disparity is partly a result of historical industry trends; while EU firms were once global leaders in PV innovation, increased competition from China has highlighted the need for further policy measures to strengthen IPR and maintain competitiveness in offshore solar technologies. The 2009 National Renewable Energy Action Plans (NREAP) required EU member states to establish incentives for IPR in the renewable energy sector. This policy intervention has been instrumental in addressing existing challenges and unlocking the potential of offshore solar energy. Continued focus on robust IPR frameworks will be critical as the EU seeks to achieve its long-term energy and climate goals (Alsaleh 2026).

This study's core problem is evaluating the effectiveness of 2009 NREAP policies (mandating offshore solar IPR incentives) in advancing EU27 offshore solar IPR (amid five critical IPR barriers to scalability/marine integration), and exploring how this policy-driven IPR progress enhances marine environments/ecosystems – with a focus on Western versus Central/Eastern EU comparative effects. Relevant Facts and Statistics: (1) Regional IPR Disparity in European Marine Renewable Energy: Among the top global innovators in marine renewable energy patents, Western EU countries hold prominent positions, with German firm Robert Bosch ranking among the top five players in the field. In contrast, Central/Eastern EU countries have minimal representation in global marine renewable energy patent portfolios, reflecting a significant innovation gap. For adjacent offshore renewable sectors, Western EU nations like Germany and Denmark account for 9 % of global patent families (5 % and 4 % respectively), while Central/Eastern EU countries contribute less than 1 % collectively (Chatzipanagi et al. 2022). (2) EU Leadership in Offshore PV Market and IPR Relevance: Europe is the world's dominant offshore photovoltaic (PV) market, driven by aggressive renewable energy policies, including NREAP. PV-related inventions in Europe have grown seventeenfold over three decades, with 70,000 international patent families (IPFs) in the PV sector by 2023; Western EU countries (Germany, France) are among the top applicants for these IPFs, while Central/Eastern EU nations have negligible domestic patent filings for offshore-specific PV technologies (Chatzipanagi et al. 2022). (3) NREAP Implementation Intensity Disparity: EU member states show significant differences in implementing renewable energy policies tied to IPR incentives. For example, under Next Generation EU (a successor policy framework with similar objectives to NREAP), Western EU countries allocated a larger share of funds to renewable energy innovation (including IPR-related R&D), while Central/Eastern EU nations like Poland, despite receiving €59.8 billion in EU support, directed most renewable energy funds to onshore projects and coal phase-out rather than offshore solar IPR development (Czako 2022). (4) IPR Validity and Commercialization in European Renewables: European patents in renewable energy sectors (relevant to offshore solar) have higher sustainability rates – 68 % of granted European patents in marine renewables remain valid in at least one EU member state, 10 % above the average for all sectors. This highlights the commercial value of IPR in the field, yet the benefit is unevenly distributed: Western EU holds 79 % of international patents in offshore wind (a proxy for offshore solar IPR trends), while Central/Eastern EU relies heavily on imported technologies with minimal local IPR adaptation (Czako 2022). (5) Policy-Driven IPR Growth Timing: Global patent filings for marine renewable energy surged 18 % annually between 2002 and 2022, with a notable acceleration post-2009 (coinciding with NREAP implementation). This timing correlation suggests policy influence, but the growth was concentrated in Western EU – between 2010 and 2023, Western EU's offshore renewable energy patent filings increased by 15 % annually, compared to less than 3 % in Central/Eastern EU (Czako 2022).

This research thus formulates the following questions: (1) How significantly did the large-scale implementation of Directive 2009/28/EC, officially known as the Renewable Energy Directive (RED), impact the IPR in offshore solar power in the European Union from 1990 to 2023? (2) To what degree do the benefits that different EU27 member states reap from implementing Directive 2009/28/EC vary, and how do these differences influence the IPR in the offshore solar power sector? Correspondingly, the research objectives are outlined as follows: (1) To investigate how Directive 2009/28/EC has influenced the IPR in offshore solar power sector in the EU over the period from 1990 to 2023, and to evaluate the extent of this policy's impact on offshore solar power development, taking into account variations among different member states, economic structure, political systems, and geographical regions. (2) To compare the experiences of various EU27 member states in implementing Directive 2009/28/EC, analyze how these experiences affect the IPR in the offshore solar power sector, and determine which implementation models are most effective in promoting marine renewable energy while protecting the marine environment. (3) To analyze the social, economic, and environmental aspects of offshore solar power policies and understand how IPR has shaped the development of marine renewable energy during the 1990–2023 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. Moreover, understanding these differences is essential for the EU27 overall to evaluate and formulate appropriate economic policies in the offshore solar power industry, promote regional economic balance, and enhance the overall offshore solar power competitiveness of the EU markets. 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 France, Germany, Italy, and the Netherlands, are notable for their proactive approach to renewable energy policy, such as the National Renewable Energy Action Plan (NREAP), while these nations have been developing 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 energy economies, which have lower GDP per capita, industrial structures in the process of transformation, and relatively lower innovation capacities. In the EU27 region, the effective implementation of policies like the European Green Deal and the National Renewable Energy Action Plan (NREAP) can strongly influence EU13's newer energy economies. These policies can push for renewable energy adoption and sustainable energy, creating a framework for marine environmental sustainability. Therefore, the increase of EU-wide policies regarding offshore solar power has greatly increased the adoption of renewable energy policies in EU13 economies in recent years. For example, countries within the Central and Eastern European region are beginning to implement offshore solar power projects and are creating legislation to support the growth of the sector. EU13 is a valid "untreated" group because NREAPs' effective treatment – measured by IPR investment, policy ambition, and institutional capacity to drive offshore solar innovation – was negligible compared to EU14. The grouping does not ignore NREAPs' formal EU-wide mandate; instead, it captures the real-world reality that policy impact depends on implementation, not just legislation. This design complies with DID's core logic and is supported by empirical evidence of EU13's structural barriers to translating NREAPs into meaningful IPR integration for offshore solar.

Novelty and significance of the study can be highlighted as follows. (1) Data Construction Novelty: Breaking single-source data limitations, the study builds a 1990–2023 panel dataset covering all EU27, integrating NREAP policy documents, EPO offshore solar patent data, and national energy statistics. This enables cross-regional and long-term policy effect assessment, improving conclusion reliability. (2) Variable Definition Innovation: To address "offshore solar IPR" ambiguity, core variables are defined by offshore-specific tech characteristics. It also quantifies "NREAP effective implementation intensity" (instead of binary indicators), accurately measuring policy impacts by accounting for regional differences. (3) Policy Design Significance: Focusing on the 2009 NREAP, the study explores its heterogeneous effects between Western/Central-Eastern EU, filling the gap of insufficient regional disparity analysis. It provides targeted policy insights (e.g., strengthening Central-Eastern EU IPR incentives) to enhance EU policy synergy. (4) Empirical Insight Novelty: Adopting a heterogeneous timing DID model (validated by placebo tests) avoids endogeneity. It links offshore solar IPR to marine environmental protection, revealing the "policy → IPR → tech → ecosystem" mechanism and enriching interdisciplinary research.

The remainder of the study is structured as follows. The Section Literature review elaborates on the recent studies in this field from empirical and theoretical perspectives. Section data methodology describes the model specification and panel data estimators. The section's empirical results show the estimation outputs of the panel data estimators. Discussion on findings and implications with conclusion is provided in the Section on discussions and conclusion.

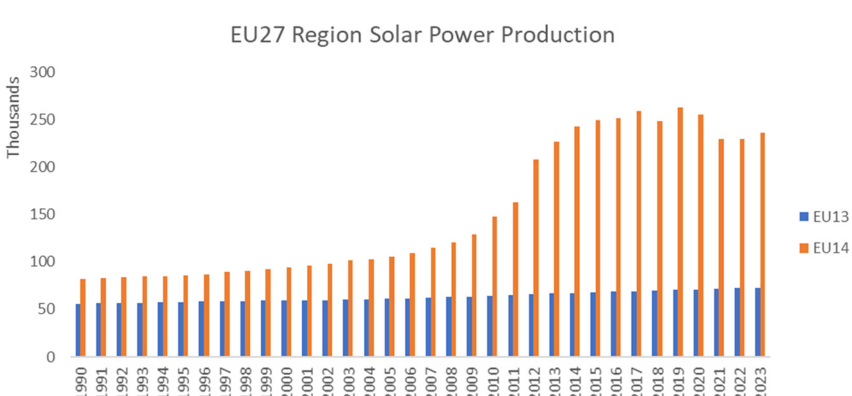

Figure 1: Offshore solar power generation in the EU27 region (1990–2023), including a comparison of offshore solar power production between the EU13 and EU14 groups over the same period (1990–2023).

2 Literature Review

Recent studies on offshore solar power and the development of Intellectual Property rights (IPR) have primarily addressed four key areas: the technical status of offshore solar power, the application of IPR within these systems, the effects of offshore solar power on the marine environment, and its broader impact on marine ecosystems. In the British Isles, Diesing et al. (2023) examined the transition towards a fully renewable energy system by 2050. Their findings suggest that moving to 100 % renewable energy is more economically advantageous than strategies relying on nuclear power and fossil carbon capture and storage. The study estimates that annualized system costs could be reduced to 63 billion euros, with a levelized cost of electricity at 40 euros per megawatt-hour, provided that onshore wind and solar photovoltaic installations are expanded.

In Portugal, Onea and Rusu (2022) analyzed a decade of data to assess the complementarity between offshore solar, offshore wind, and wave resources. Their research indicates that offshore solar and wind power are more prominent in the southern regions, while wave power diminishes from north to south. In China, Crijns-Graus et al. (2022) compared China's advancements in new renewable energy technologies, such as floating solar, with those of the European Union. Their work highlights China's emergence as a major global player in mainstream renewable electricity, attributed to its industrial policies and emphasis on effectiveness over cost efficiency.

Oloruntobi et al. (2023) addressed the evolving challenges in maritime shipping and the sector's increasing expectations amid technological advancements. The study suggests that marine renewable energy, particularly floating solar, can reliably power desalination plants due to its abundance and uncontaminated supply. Furthermore, future vessels may utilize offshore solar energy to charge batteries for both propulsion and auxiliary functions. In the same manner, Simoes and Lima (2023) quantified the requirements for concrete, steel, and flat glass in constructing offshore solar photovoltaic and concentrated solar power panel foundations. Their analysis underscores that a sustainable transition to marine renewables is only feasible if resource extraction and material production are managed intensively and sourced locally.

In the North Sea, Vlaswinkel et al. (2023) investigated the environmental implications of offshore solar installations alongside initial pilot projects. Their findings indicate no significant changes in water quality or seabed characteristics, while the documentation of bird activity on floating platforms represents a novel observation. Following an earlier study, Vagiona et al. (2022) evaluated potential offshore solar farm locations in the Aegean Sea, considering various constraints and assessment criteria. The study identified nine suitable marine areas, with the North Aegean emerging as the most favorable site for maximizing energy output while minimizing environmental impact.

Also, Alsaleh and Abdul-Rahim (2024) and Rahman et al. (2022) conducted a comprehensive review of the environmental impacts of renewable energy sources in power plants, including offshore solar thermal and photovoltaic systems. Their analysis emphasizes the importance of careful selection of renewable energy sources, as improper deployment can have detrimental environmental effects. Moreover, Costoya et al. (2022) and Delbeke et al. (2023) assessed marine offshore energy resources along the coasts of Portugal, Spain, and Belgium. Although offshore wind resources generally surpass offshore solar photovoltaic resources on an annual basis, both exhibit considerable spatial and temporal variability, enhancing resilience to climate change.

In the same manner, Russo et al. (2023) evaluated the impact of climate change on solar resource availability and variability for renewable electricity production. The study found the most significant differences during winter, with solar photovoltaic generation changes ranging from a 10 kWh decrease to a 20 kWh increase, depending on the scenario and season. Also, Vinichenko et al. (2023) analyzed the diffusion of nuclear, wind, and solar power technologies. Their research demonstrates that wind and solar power have been adopted more rapidly and extensively across major economies compared to nuclear power, further supporting climate resilience.

While Kastanaki and Giannis (2022), Ramos et al. (2022), Keller et al. (2022), and Giannopoulos (2023) have highlighted the need to advance the commercialization of multi-use offshore solar power systems. These systems integrate solar energy generation with other marine activities, such as aquaculture, tourism, transportation, port operations, and desalination, but require targeted attention and further research.

From another perspective, Jamroen et al. (2023) developed a water quality monitoring system for aquaculture in Thailand, powered by photovoltaic energy and narrowband IoT technology. Their evaluation shows that the system achieves both high reliability and a low levelized cost of energy. Related studies by Koričan et al. (2022; 2023), Pires Manso et al. (2023), and Asgher and Iqbal (2023) explored the integration of fully electric fishing vessels with photovoltaic power systems. Their findings indicate that charging electric fishing vessels at ports can help reduce surplus electricity production, lower operational costs, and decrease carbon dioxide emissions.

Recent empirical research has contributed significantly to understanding the connections among environmental policy, energy economics, and financial sustainability, considering both national and global perspectives. For example, Tan et al. (2025) utilize textual analysis to examine the effects of China's environmental protection tax law on green innovation within firms that generate high levels of pollution. Their findings indicate that targeted environmental taxes can encourage these firms to adopt environmentally friendly technologies and comply with regulations. This evidence has important implications for shaping environmental policies, particularly in emerging economies. Likewise, Li et al. (2022) present a comparative study of the traditional energy sector's role in the global market. By analyzing the relationships among environmental, social, and governance (ESG) activities, free cash flow, and capital market performance, the authors provide insight into how traditional energy industries may align sustainability efforts with financial objectives during the ongoing global energy transition. Also, Fu et al. (2025) focus on the financial risks associated with climate change, specifically the impact of sea-level rise (SLR) on mortgage credit access. Their research demonstrates that increased SLR risk correlates with lower loan approval rates. This finding highlights the importance of developing climate-resilient financial regulations and risk assessment frameworks, especially in coastal areas. Similarly, Zhu et al. (2025) assess the progress and effectiveness of China's wind power sector. The study traces the industry's development and evaluates the influence of policy support, technological advancements, and market mechanisms. The results offer valuable lessons for expanding renewable energy industries globally. Together, these studies address key aspects of environmental policy implementation, energy sector transformation, and financial risk management. They provide a solid empirical basis for literature reviews on sustainable energy transitions and the development of climate-resilient economic systems.

Alsaleh et al. (2024) examine the influence of intellectual property rights (IPR), intellectual capital, and market size on geothermal power exploration. Their findings identify IPR as a significant factor in promoting technological innovation and improving exploration efficiency within renewable energy industries. The study emphasizes that well-developed IPR frameworks encourage research and development investment in specialized, resource-specific technologies, such as those used in geothermal reservoir exploration. This perspective is relevant to offshore solar energy, which also depends on specialized technological advancements, including corrosion-resistant modules. Offshore solar faces similar requirements for IPR-driven research and development incentives, which align with the primary objectives of National Renewable Energy Action Plan (NREAP) policy evaluations in the European Union's offshore solar sector.

In related research, Alsaleh et al. (2024) investigate the impact of IPR on the development of aquaculture production networks. Their analysis demonstrates that IPR supports technological diffusion, standardization, and the restructuring of marine-related industrial chains. Although this work focuses on aquaculture, it highlights the broader significance of IPR in economic activities compatible with marine ecosystems. Specifically, just as IPR contributes to balancing industrial growth and environmental sustainability in aquaculture, it is also essential for aligning offshore solar energy development with marine environmental protection. Together, these studies establish a foundational connection between IPR and innovation across renewable and marine-related sectors. However, they do not address the specific context of offshore solar energy or consider regional differences in IPR implementation, such as those between Western and Central-Eastern European Union member states. These gaps are the focus of the current study on NREAP and IPR in EU offshore solar energy (Alsaleh and Wang 2023).

H1: The treated policies promote the IPR in offshore solar power, which leads to an increase in the share of marine renewable energy and achieves blue economy growth.

H2: The controlled policies do not promote the IPR in offshore solar power, which leads to a decrease in the share of marine renewable energy and achieves blue economy growth.

While the EU and some member states have introduced policies related to IPR in offshore solar power, such as France and Germany. However, there is a lack of in-depth research using the Difference in Differences approach to analyse the impact of these policies on the IPR development level in offshore solar power. The current literature did not precisely measure how these policies affect the IPR in offshore solar power in the EU27 region. Without this evaluation, it is difficult to provide an empirical basis for policy optimization in the EU market. Moreover, there is no research applying the DID method to compare EU27 members that have adopted specific photovoltaic technologies with those that have not. Without such research, it is impossible to determine the actual effects of these technologies in practice. This restrains the further quality improvement of these IPR in the field of offshore solar energy in the EU. Lastly, the offshore solar power approach involves the interests of multiple parties, including energy developers, landowners, stakeholders, and aquaculture 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.

Offshore solar power offers unique advantages in resource utilization and sustainability, while the DID method provides a rigorous framework to quantify its competitive edge by isolating causal effects from confounding factors. Therefore, the novelty of energy economic analysis via the DID method is as follows: (1) Define treatment groups (regions/projects with offshore solar) and control groups (similar regions without), ensuring comparable natural and economic conditions. (2) Gather pre- and post-development data on indicators like power generation cost, efficiency, environmental impact, and economic benefits. (3) Verify that indicators for both groups followed similar trends before the intervention to ensure DID validity. (4) Compare policy implementation pre-post differences between groups to estimate the causal impact of IPR in offshore solar power. (5) Conduct statistical inference and sensitivity tests (e.g., using different control groups or periods) to ensure result reliability.

The temporal structure of the Difference-in-Differences (DID) design, which spans the period from 1990 to 2023 with the treatment commencing in 2010, is both theoretically and methodologically robust. This assessment is based on two principal considerations: the justification for the extended pre-treatment period and the implicit validity of the parallel trends assumption throughout the analysis window. Both aspects are consistent with the research context and established DID methodology. The selection of 1990–2009 as the pre-treatment period is well-founded in relation to the study's objectives, which include evaluating the impact of the 2009 National Renewable Energy Action Plans (NREAP) on offshore solar intellectual property rights (IPR) within the EU27, as well as examining disparities between Western-Central and Eastern EU regions. This timeframe aligns with significant phases of European integration, such as the post-Cold War transition and the 2004–2007 enlargement, allowing for the establishment of stable pre-policy baselines across both regions. In particular, it captures the gradual integration of Central and Eastern European countries into the EU energy system. Furthermore, the extended pre-treatment period accommodates the inherently long development cycles associated with offshore solar IPR, enabling the identification of slow-moving trends and minimizing the risk of bias from short-term fluctuations. This deliberate choice supports the reliability of the analysis and should be viewed as a methodological strength rather than a limitation. The parallel trends assumption is implicitly supported over the 1990–2009 period. Before the introduction of the NREAP, EU renewable energy policies were broad in scope and did not include targeted incentives for offshore solar IPR. This created a uniform policy environment for both Western-Central and Eastern EU regions, reducing the likelihood of differential shocks. Additionally, as EU members or candidate countries, all regions operated under common market regulations and technological diffusion mechanisms, which fostered similar trends in IPR development. The application of a heterogeneous timing DID model further strengthens the analysis by accounting for minor differences in pre-treatment trends. These contextual and methodological safeguards collectively uphold the validity of the parallel trends assumption.

3 Method and Data

3.1 Data Collection

To evaluate the level of Intellectual Property right (IPR) development in offshore solar power across the EU27 countries, the difference-in-differences (DID) analytical approach was employed. This method involved analyzing data spanning from 1990 to 2023. The designated treatment period for the countries identified as treated extended from 2010 to 2023. For the empirical analysis, datasets from both EU24 and EU27 countries were utilized, covering the years 1990–2023. The selection of this approach was based on the suitability of the difference-in-differences methodology for comparative policy analysis. (Intercept): A dummy variable indicating whether a country was part of the treatment group (=1) during the effective policy implementation intensity of the National Renewable Energy Action Plan (NREAP) in 2010, or part of the control group (=0). Offshore Solar Power (OSP), as operationalized by Eurostat's renewable energy statistical framework, refers to the total gross surface area of solar thermal collectors deployed in marine/offshore environments (coastal waters, offshore zones ≥ 1 km from shore), quantified in thousands of square meters (thousand m^2). This definition is rooted in Eurostat's historical data collection standards for renewable energy, where solar thermal technology was the primary measurable offshore solar application before the widespread adoption of floating photovoltaic (PV) systems. (IPR) Intellectual property right: Measured by the number of trademark applications filed with national or regional Intellectual Property (IP) offices, Eurostat's intellectual property rights (IPR) database for resident patent applications is a harmonized dataset sourced from the European Patent Office (EPO), centered on EPO filings by EU/EEA residents, with clear definitions, breakdowns, and standardized metrics for innovation tracking.

(ENV) Marine Environment: Describes the complex, reciprocal relationship with atmospheric carbon dioxide (CO_2). Oceans serve as a significant sink for CO_2, but rising levels due to human activity are altering marine chemistry and ecosystems. (ECO) Marine Ecosystem Interaction: Refers to aquaculture production (in metric tons) and related operational activities, which serve as indicators of the impact of renewable energy on marine ecosystems, encompassing both sustainable resource use and ecological conservation.

(GDP) Gross Domestic Product: Calculated as the sum of gross value added by all resident producers, plus product taxes, and minus subsidies not included in product values. All variables were sourced from the World Development Indicators and Eurostat. For further details, refer to Table 1.

When intellectual property rights (IPR) are treated as an independent variable, it suggests that IPR influences dependent outcomes such as sectoral development. However, the study in question aims to assess how policy interventions affect the development of IPR. This approach requires IPR to be considered as an outcome variable, shaped by the implementation of specific policies. Moreover, within the difference-in-differences (DID) framework, it is essential to clearly define the treatment (policy intervention), the outcome (IPR), any mediators, and relevant control variables. Such clarity is necessary to establish valid causal relationships. If the role of IPR remains ambiguous, it becomes difficult to accurately determine the effects of policy interventions, as potential confounding relationships – such as whether policy influences IPR or vice versa – are not adequately addressed. Finally, if IPR is simultaneously positioned as both a driver and an outcome, the study cannot reliably determine whether policies are effective in promoting IPR and subsequent outcomes, or if existing levels of IPR influence the evaluation of policy effectiveness. This lack of distinction undermines the ability to draw clear conclusions about the direction and magnitude of policy impacts.

Table 1: Variable explanation list and data sources: Offshore solar power; intellectual property rights; marine environment; marine ecosystem; and economic growth.

Variable	Symbol	Source	Variable	Unit of measurement
Dummy variable	Intercept	WBD	Independent	Treated = 1, controlled = 0
Offshore solar power	OSP	Eurostat	Dependent	Thousand square meters
Intellectual property rights	IPPR	Eurostat	Independent	Patent applications, residents
Marine environment	ENV	WBD	Independent	A metric ton of CO_2 per capita
Marine ecosystem	ECO	WBD	Independent	Aquaculture production metric tons
Economic growth	GDP	Eurostat	Independent	Current US dollars

Theoretical Motivation and Roles of ENV/ECO Variables in the DID Model. (1) Core Theoretical Motivation: Inclusion aligns with the study's focus on NREAP policy → offshore solar IPR → sustainable energy transition. ENV/ECO variables reflect the policy's environmental sustainability goals (e.g., EU 2050 carbon neutrality), verifying if IPR-driven offshore solar achieves energy-environment win-wins. (2) Typical roles: (A) Outcome variables: Evaluate policy's final environmental impacts (e.g., marine water quality, carbon reductions), testing if NREAP-induced IPR improves ENV/ECO outcomes. (B) Control variables: Eliminate confounding bias (e.g., pre-existing environmental quality affects policy intensity and IPR investment), ensuring policy effect estimates on core outcomes (IPR) are reliable. (C) Channels (mediators): Mediate policy/IPR and energy outcomes (e.g., eco-friendly offshore solar tech from policy-supported IPR improves ECO resilience, enabling larger-scale deployment).

This study provides a transparent account of the data sources used in constructing the EU27 panel dataset covering the years 1990–2023. The sources are both clear and authoritative, comprising: EU NREAP reports accessed through the European Commission Energy Portal; EPO offshore solar patent data; Eurostat energy and environmental statistics. Each source is cited with specific access paths and data categories, supporting the reproducibility of the research. The methodology for dataset construction is thoroughly detailed. In addressing EU24 and EU27 coverage, the study adopts a dynamic approach that reflects the timeline of EU enlargement, from the period before 2004 through to 2013 and beyond. Clear criteria for the inclusion of new member states and consistent regional classification are applied, effectively managing issues related to changes in coverage over time.

The study outlines comprehensive protocols for managing missing data and interpolation. For short-term gaps in intellectual property rights (IPR) data, defined as two years or less, linear interpolation is employed. In cases of long-term missing data, zero-imputation is used, with justification provided where there is no evidence of offshore solar research and development activity. The proportion of interpolated data is reported at 3.2 percent, and sensitivity analyses confirm that these methods do not distort the main trends in the dataset. Variable harmonization is conducted through a systematic three-step process: (1) Unifying measurement standards using EU-harmonized indicators. (2) Normalizing variables by economic and R&D scale. (3) Cross-checking data with national yearbooks. (4) This approach ensures comparability across countries and time periods, supporting the reliability and methodological rigor of the dataset.

3.2 Theoretical Background

Sustainable development theory (Brundtland Framework) is centered on meeting "current needs without compromising the ability of future generations to meet their own needs." It bridges economic development (e.g., offshore solar as a renewable energy source) with environmental stewardship (protecting marine ecosystems and the marine environment) and social equity (e.g., ensuring coastal communities benefit from IPR/marine resource use). In our study, using IPR to design offshore solar farms that coexist with the marine ecosystem or marine environment aligns with sustainable development principles.

By using IPR to design offshore solar farms that coexist with marine ecosystems, this research embodies the Brundtland Framework's "triple bottom line": (1) Economic: Offshore solar reduces energy costs and carbon liabilities, supporting long-term growth. (2) Environmental: Marine ecosystems remain intact, preserving their services for future generations. (3) Social: Coastal communities gain agency, jobs, and a stake in sustainable resource use. In essence, this approach transforms offshore solar from a mere energy solution into a tool for intergenerational justice – a hallmark of sustainable development.

The Difference-in-Differences (DID) method provides a systematic approach to evaluating how the Brundtland Framework influences offshore solar power generation. Specifically, it enables an assessment of whether the framework enhances production efficiency and resource utilization when compared to the independent operation of offshore solar power under the NAREAP initiative. To conduct this analysis, the DID technique is employed, following the methodologies outlined by Upton and Snyder (2017) and Abadie (2018). This method is suitable for both cross-sectional and panel data, and is applied to datasets from EU14 and EU13 countries across two distinct periods: 1990–2010 and 2011–2023.

The principal advantage of the DID approach lies in its ability to provide unbiased estimates of the impact of offshore solar power within the EU27 region. This reliability makes it a preferred choice for policy evaluation in this context. In this framework, let $y(i, t)$ represent the outcome of interest for country i at time t. Observations are made for each country both before ($t = 0$) and after ($t = 1$) the implementation of the Brundtland Framework. Countries exposed to the policy intervention during the treatment period are identified by the indicator $D(i, t) = 1$, while those not exposed are denoted by $D(i, t) = 0$.

Treated countries: EU14 countries, where $D(i, t) = 1$ during the treatment period.

Control countries: Countries not exposed to the intervention, where $D(i, t) = 0$.

The DID estimator is typically implemented using a linear parametric model, consistent with the procedures described by Card (1985) and Abadie (2018). The outcome variable is assumed to follow a variance process as specified in the relevant econometric literature.

$$Y_i, t = \mu_i, t = \delta(t) + \alpha \cdot D_i, t + \eta(i) + v_i, t \tag{1}$$

Equation (1) includes several key elements, each representing a distinct aspect of the model: $\delta(t)$: This term captures the component that varies over time, reflecting factors that are specific to each period. α: This parameter measures the effect of the treatment within the model. $\eta(i)$: This component accounts for characteristics that are unique to each country. $v(i, t)$: This term represents country-specific shocks. These shocks have an average value of zero within each period ($t = 0, 1$) and are directly correlated over time. $y(i, t)$ and $D(i, t)$: These are the observable variables in the model.

$$P\left(D_i, t = 1 \mid -\mu_i, t\right) = P\left(D_i, 1\right) = 1 \tag{2}$$

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

$$Y_i, t = \delta(t) + \alpha D_i, t + E\left[\eta(i) \mid D_i, 1\right] + \varepsilon i, t \tag{3}$$

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

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 δ=$(\delta(1) - \delta\ (o)$.

Equation (4) is derived below (Nawaz et al. 2021):

$$Y_i, t = \mu + \tau D_i, 1 + \delta t + \delta D_i, t + \varepsilon i, t \tag{4}$$

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 ensures that the model's assumptions are satisfied for these time periods. The variables presented in Equation (4), along with the parameter δ, can be estimated using the ordinary least squares (OLS) method. This statistical approach allows for efficient estimation of the model parameters. Furthermore, the structure of the equation enables the identification of treated countries based on their level of dependence, provided that $D(i, 1) = 1$ and considering the country-specific variable $\eta(i)$. This selection criterion is essential for distinguishing between the treated and control groups within the analysis. Equation (4) may also be simplified further, as outlined below.

$$Y_{\text{it}} = \delta + \delta_i \times \text{TREAT}_i + \delta_{\text{it}} \times \text{POST}_t + \beta_t^{2\times2}\text{TREAT}_i \times \text{POST}_t + U_{\text{it}} \tag{5}$$

In this analysis, $\boldsymbol{Y_{\text{it}}}$ denotes the outcomes for several key indicators, including offshore solar power (OSP), the intercept, environmental factors (ENV), intellectual property rights (IPR), economic conditions (ECO), and gross domestic product (GDP). The term $\boldsymbol{\delta_i}$**TREAT**$_{\boldsymbol{i}}$ identifies countries that have been exposed to the treatment at a specific point in time. Similarly, $\boldsymbol{\delta_{\text{it}}}$**POST**$_{\boldsymbol{t}}$ refers to countries that have experienced the treatment after its implementation. The interaction term, $\boldsymbol{\beta_{2\times2t}}$**TREAT**$_{\boldsymbol{i}}$ $\times$ **POST**$_{\boldsymbol{t}}$ $+$ $\boldsymbol{U_{\text{it}}}$, captures the combined effect of the treatment dummy variable for a group of countries and the post-treatment dummy variable within the regression model. This component is essential for assessing the impact of the treatment across different groups and time periods. This section specifically examines both EU13 and EU14 member states that have been exposed to the treatment before and after its implementation. The objective is to determine the influence of IPR as a determinant of offshore solar power development. The variable $\boldsymbol{U_{\text{it}}}$ represents the country-specific, time-varying component that is unrelated to the main explanatory variables, reflecting transitional changes in IPR investment levels 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.

$$\delta = \{E[Y_i, 1 \mid D_i, 1 = 1] - E[Y_i, 1 \mid D_i, 1 = 0]\} - \{E[Y_i, 0 \mid D_i, 1 = 1] - E[Y_i, 0 \mid D_i, 1 = 0]\} \tag{6}$$

Developing an appropriate model is essential when analyzing cross-sectional data pairs, specifically ($Y(i, t)$, $D(i, 1)$) for time periods $t = 0$ and $t = 1$. 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 comparison between $Y(i, 1)$ and $Y(i, 0)$. To estimate the parameter δ, the analysis employs the ordinary least squares (OLS) method, which is a standard approach for obtaining reliable estimates in such settings.

$$\delta = E[Y_i, 1 - Y_i, 0 \mid D_i, 1 = 1] - E[Y_i, 1 \mid Y_i, 0, D_i, 1 = 0] \tag{7}$$

Based on 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, if none of the countries receive treatment, the mean outcomes would exhibit the same variations as those observed in the treated countries. Abadie (2018) notes that this modeling approach may be restrictive, particularly when the treated and untreated groups possess different, unbalanced exploratory variables that influence the dynamics of the outcomes. This limitation can affect the validity of comparisons between groups. Drawing an analogy to the foundational work of Ashenfelter (1978), it is important to address these variations and account for heterogeneity among the countries under study. To manage these concerns, the model developed by Ashenfelter and Card (1984) is introduced, as it is designed to accommodate such differences effectively.

$$D_i, 1 = \begin{cases} 1, \text{if } y_i, 1 - k + u_i < Y \\ 0, \text{otherwise} \end{cases} \tag{8}$$

In this model, K represents a positive integer, Y is a constant, and $u(i)$ denotes a random variable. The scenario considers countries with relatively low levels of IPR development in the offshore solar power sector. Following the treatment period, these countries are expected to implement new policies aimed at expanding their offshore solar power capabilities. This response is primarily driven by the requirements of the Paris Agreement and the concerns raised by environmental advocacy groups. The Difference-in-Differences (DID) approach is applicable under the condition $(i, 1 - k)$. Under these circumstances, the effect on the group receiving the intervention is outlined below:

$$f(\theta, D_i 1) = \begin{cases} -Y_i 1, D_i 1 = 1 \\ |Y_i 0|, D_i 1 = 0 \end{cases} - [E(Y_i 0 \mid X_i, D_i 1 = 1) - E(Y_i 0 \mid X_i, D_i 1 = 0)] \tag{9}$$

The equation $X(i) = (i, 1 - k)$ defines a vector, $X(i)$, which represents the observable characteristics of individual countries. As outlined both in this article and in the work of Abadie (2018), these characteristics are established at the initial time point, $t = 0$. Equation (7) addresses the sequence in which countries are matched for analysis. Specifically, it compares each group of treated countries, denoted by i, to individual countries that have not received the treatment. In this context, the outcome covariate, Y_i, for each treated country is considered. The matched outcome, estimated by b Y_i, is then weighted according to its similarity to a neighboring country in the comparison group. This approach ensures that the analysis accounts for differences in observable characteristics when comparing outcomes between treated and untreated countries.

$$\widehat{Y}_i = \sum_{j \in C^0(P_i)} w_{ij} y_j \quad (10)$$

$C^0(P_i)$ denotes the set of treated neighbors i within the group where $D = 0$. The term W_{ij} refers to the weight assigned to each untreated individual i when making comparisons with treated individuals.

In general, the matching estimator for the Average Treatment Effect on the Treated (ATT), denoted as ATT(S_{10}), can be expressed as follows:

$$\widehat{\text{ATT}} = \frac{1}{\#[D = 1 \cap (S10)]} \sum_{i \in \{D_i = 1\} \cap S10} \left(Y_i - \widehat{Y_i}\right) \quad (11)$$

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

4 Results

To assess the potential for scaling up the offshore solar power sector across the EU27 countries, a normality test was performed on the dataset. The Jarque-Bera test was selected to evaluate the skewness and kurtosis of the data. The results indicated statistical significance, with a p-value of 0.00, confirming that the data are normally distributed. Based on these findings, it can be concluded that the residual errors exhibit a normal distribution. The results of the Jarque–Bera test, as analyzed using Eviews, are summarized in Table 2. Following the confirmation of normality, the difference-in-differences (DID) estimator was utilized to further analyze the data. The DID approach offers several advantages: It enables comparison between entities with similar characteristics, ensuring valid and meaningful analysis. It accounts for both observed and unobserved differences among countries. It is straightforward to implement and does not rely on parametric assumptions. Table 2 also provides a summary of the descriptive statistics related to covariance and the normality test. Among the variables examined, the mean GDP score is the highest. In contrast, the indicator for intellectual property rights (IPR), measured by the number of individuals engaged in technological innovation, is relatively low. This suggests that innovation within the offshore solar power sector remains limited in the EU27 region. Additionally, both aquaculture and carbon dioxide emissions display high mean values, reflecting significant emissions within the aquaculture sector. As anticipated, the mean value for offshore solar power is also relatively high.

Table 3 presents the intercept dummy variable applied to both treated countries and time periods, as defined in Equation (5). This variable is included to establish a counterfactual framework for evaluating the hypothesis that all countries, regardless of treatment status, would receive similar levels of renewable and sustainable energy policies. The dummy variable is assigned a value of $D = 1$ for treated countries and $D = 0$ for those that are untreated. Statistical analysis indicates that this variable is highly significant, with a p-value of 0.000. These results suggest that both treated and untreated countries demonstrate a strong tendency to attract offshore solar power projects and to implement renewable and sustainable energy policies. Such measures are directed at mitigating environmental impacts and supporting a transition toward sustainable development. Further details can be found in Figures 2 and 3.

The parallel trend test is an essential prerequisite for applying the time-varying point Difference-in-Differences (DID) methodology. 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 throughout the analysis. Specifically, during the four periods preceding the implementation of the NREAP policy, the coefficients associated with the dummy variables do not display statistically significant deviations from zero. This outcome suggests that, before the policy's introduction,

Table 2: Summary statistics and normality test results, including indicators of mean, median, maximum, minimum, standard deviation (std. dev.), and number of observations.

	AQU	CO_2	GDP1	IPR	OSP
Mean	4.095	4.726	11.112	0.714	3.774
Median	4.144	4.737	11.161	0.714	3.724
Maximum	5.638	5.981	12.648	0.720	5.055
Minimum	2.025	2.000	9.406	0.698	3.000
Std. dev.	0.823	0.563	0.735	0.002	0.247
Observations	918	918	918	918	918
Normality test	Skewness	Jarque-Bera	Probability		Observation
Residual	3.155	2.547		0.000	918

Table 3: Regression analysis incorporating a dummy variable for the intercept term (treat*post), with t-statistic tests: Coefficient, standard deviation, t-statistic, and probability (prob.).

Variable	Coefficient	Std. error	t-Statistic	Prob.
INTERCEPT	3.691	0.051	71.614	0.000
R-squared	0.810	Mean dependent var.		3.774
Adjusted R-squared	0.796	SD dependent var.		0.247
S.E. of regression	0.111	Akaike info criterion		−1.475
Sum squared resid.	10.662	Schwarz criterion		−1.134
Log-likelihood	742.461	Hannan–Quinn criteria		−1.345
F-statistic	57.008	Durbin–Watson stat.		0.039
Prob. (F-statistic)	0.000			

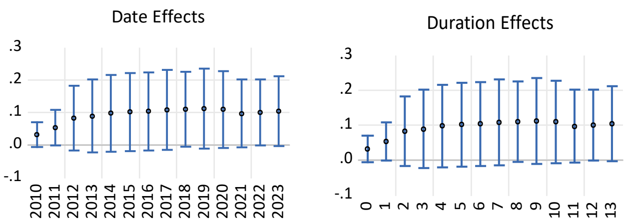

Figure 2: Parallel trend test. The vertical dashed line denotes the “event year” of 2010, while the horizontal dashed line represents the zero-value axis.

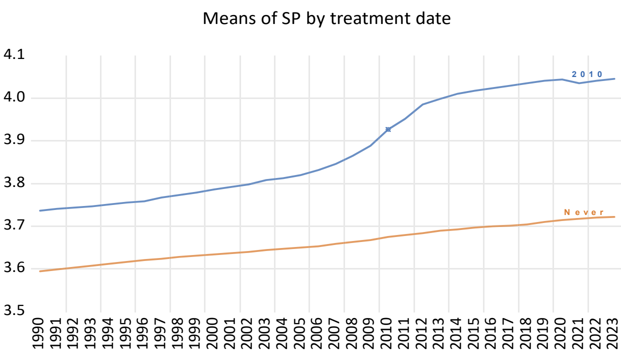

Figure 3: Policy implementation profiles illustrating the list of adverse events affecting treatment countries (shown in blue) and control countries (shown in red) from 1990 to 2023, both before and after the baseline year of 2010.

the trends in the NREAP strategies for both the treatment and control groups remained relatively stable. Following the effective implementation of the NREAP policy, the coefficient of the relevant variable rises above one. This result indicates that the strategies of both the treatment and control groups experienced notable changes attributable to the policy intervention.

The primary hypothesis of this study examined whether the initiatives under the National Renewable Energy Action Plan (NREAP) that support advancements in intellectual property rights (IPR) for offshore solar power would lead to different responses – both negative and positive – compared to those observed in control countries. To address this hypothesis, the research assessed two aspects separately: first, the negative coping strategies associated with NREAP, and second, the positive adaptive or transformative strategies. The analysis employed the Ordinary Least Squares (OLS) model, as presented in Table 4, and used the Fixed Effect-Ordinary Least Squares (FE-OLS) model as a robustness check in Table 5. Throughout the analysis, the study controlled for the group of Central and Eastern European countries, referred to as EU13. Given that the responses of EU27 member states to the Monitoring and Assessment Plans (MAPs) are distinct, it was necessary to consider the specific characteristics of these countries, particularly when analyzing negative coping strategies under NREAP. Consequently, the authors concentrated on the three most commonly referenced models: EU27, EU14, and EU13.

This paper examined the three primary models presented in Tables 4 and 5 to identify the countries that reported being affected by the relevant policies at the baseline. Subsequently, the study analyzed the coping strategies adopted under the National Renewable Energy Action Plans (NREAPs). The Ordinary Least Squares (OLS) and Fixed Effects OLS (FE-OLS) models, which tested the difference-in-differences (DiD) approach, yielded non-conclusive results as shown in Tables 4 and 5. In Table 4, the DiD variable (intercept) is statistically significant for both the EU27 and EU14 groups, indicating a greater tendency to implement positive and strengthening NREAP strategies. In contrast, for the EU13 control group, the DiD variable (intercept) does not reach statistical significance. Table 5 reflects a similar pattern: the DiD variable (intercept) remains significant for the EU27 and EU14, while it is not significant for the EU13 group. These findings support the initial hypothesis regarding NREAP strategies. Specifically, the results indicate that the implementation of targeted NREAP policies encourages the development of intellectual property rights (IPR) within offshore solar power farm projects. This, in turn, contributes to an increased share of marine renewable energy, thereby promoting environmental sustainability in the EU27 region. Furthermore, the evidence is more robust for positive outcomes, as the propensity to adopt adaptive or transformative NREAP strategies is higher among the EU27 region as a whole and among the treatment group countries (EU24), compared to the control group (EU13).

In Table 4, there is a significant positive influence of NREAP strategies on offshore solar power; an increase in NREAP effective application by 1 % will bring about an increase in offshore solar power supply by 0.29 % in EU14 states, and 0.28 % in the EU27 states overall. In the EU14 states, this research observes that NREAP effective policy implementation contributes to an increase in the share of IPR and AQU by 13.76 and 0.038 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 CO_2 by 0.314 %. The DID regression results for the changes in NREAP effective policies are reported in Table 5. The most influential group measure is shown to be the EU14 treatment group. After its treatment, an observed change of 0.275 % in INTERCEPT, 0.037 % in AQU, 0.066 % in GDP, and 13.82 % in IPR was recorded in the years following the treatment for each 1 % increase in offshore solar power production in the EU14. Among the other variables, a 1 %

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	0.288***	0.017	0.290***	0.027	−0.024	0.027
AQU	0.037***	0.009	0.038***	0.0131	0.064***	0.0169
CO_2	−0.190***	0.013	−0.314***	0.059	−0.110***	0.021
GDP	2.547*	1.464	0.0731	0.057	0.167***	0.024
IPR	5.924**	2.829	13.768***	5.200	12.363***	4.082
Constant	4.857**	2.169	12.721***	3.579	10.960***	2.817
Observation	918		476		442	
Number of groups	27		14		13	
F-statistic	120.870		67.421		24.102	
Prob. (*F*-statistic)	Prob. > *F* = 0.000		Prob. > *F* = 0.000		Prob. > *F* = 0.000	
R-squared	0.398		0.417		0.216	
Control	Yes		No		Yes	
Treat	Yes		Yes		No	
Intercept	Yes		Yes		Yes	

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	0.275***	0.009	0.010	0.008
AQU	0.061***	0.009	0.037***	0.000	0.004	0.010
CO_2	−0.081**	0.032	−0.304***	0.004	−0.031*	0.018
GDP	0.306***	0.031	0.066***	0.002	0.114***	0.009
IPR	25.004***	3.171	13.820***	0.192	0.009	0.015
Constant	18.851***	2.150	12.747***	0.133	2.601***	0.137
Observation	918		476		442	
Number of groups	27		14		13	
F-statistic	21.430		43.720		32.587	
Prob. (*F*-statistic)	Prob. > *F* = 0.000		Prob. > *F* = 0.000		Prob. > *F* = 0.000	
R-squared	0.480		0.978,698		0.928	
Control	Yes		No		Yes	
Treat	Yes		Yes		No	
Intercept	Yes		Yes		Yes	

***1 %, **5 %, and *1 %.

increase in offshore solar power was associated with a decrease in CO_2 by 0.304 % (Table 5).

In Table 5, among the three NREAP measures considered, the EU13 controlling group is not affected by the NREAP policies. In the year following the NREAP, effective policies boosting the EU27 region overall, there is an estimated reduction in CO_2 emissions of 0.031 % for a 1 % increase in offshore solar power production. Moreover, an observed change of 2.601 % in GDP was recorded for each 1 % increase in offshore solar power production in EU13. On the other hand, no significant outcomes were recorded between the independent variables: Intercept, AQU, and IPR for each 1 % increase in offshore solar power production in EU13.

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 0.275 % and 0.010 % is observed in the EU14 and EU13 countries, respectively, following the implementation of the NREAPs policy (effective/ineffective). The outcome is consistent with earlier studies, such as Apolonia et al. (2021), O'Hagan (2011) and Portman (2010). The Western EU14 countries exhibit stronger support for offshore solar power compared to the Central and Eastern EU13 due to a convergence of economic, geographical, political, and technological factors. In a more detailed analysis, the Western EU14 members set aggressive renewable targets. For example, Germany aims for 80 % renewable electricity by 2030, with offshore solar as a key pillar. The EU's RepowerEU plan further incentivizes Western EU14 nations to diversify energy sources away from fossil fuels. From another perspective, Western EU14 benefits from strong public backing for climate action. In Ireland, 81 % of citizens support solar deployment, creating political momentum. While Central and Eastern EU13 nations face entrenched fossil fuel interests (e.g., Poland's coal industry) and weaker environmental advocacy, slowing transitions. While EU27 funds (e.g., the €36.6 billion Modernization Fund) aid Central and Eastern EU13's energy transition, these are often earmarked for grid upgrades or coal phase-outs rather than offshore innovation. Western nations leverage their economic clout to shape EU policies favoring offshore solar.

Also, promoting offshore solar power reflects an average annual growth of about 13.820 % and 0.009 % in IPR for EU14 and EU13, respectively. The outcome agrees with previous findings of Mueller and Wallace (2008); Corsatea (2014); and Cui and Zhao (2023) point to the higher innovation level of offshore solar power in Western EU14 countries compared to Eastern and Central EU13 countries can be attributed to several factors, including differences in R&D investment, technological foundation, talent pool, and industry-university - research cooperation. Western EU14 members have more advanced IPR integration in offshore solar power than Central and Eastern EU13 members due to four key factors: (1) Digital Infrastructure: Western nations have robust 5G, IoT networks, and smart grids that enable real-time monitoring, AI-driven optimization, and seamless integration of offshore solar into energy systems, whereas Central and Eastern EU13 lacks comparable digital grid maturity. (2) Policy and Funding: Western EU14 aligns with EU digital and renewable policies (e.g., REPowerEU, Digital Europe Programme), directing significant funds to IPR R&D and public-private partnerships. Central and Eastern EU13 face policy fragmentation and underinvestment in digital energy integration. (3) Innovation Ecosystems: Western regions host global tech and renewable giants (e.g., Siemens, Oceans of Energy) and high R&D spending, driving advancements like IoT sensors, AI analytics, and standardized offshore systems. Central and Eastern EU13 lack comparable industry collaboration and R&D capacity. (4) Skilled Talent: Western EU14 has specialized workforces in energy informatics and offshore engineering, supported by targeted education programs, while Central and Eastern EU13 face skill shortages in renewable energy IPR (Alsaleh et al. 2025; Alsaleh and Yang 2023).

In the year after boosting offshore solar power under the NREAP umbrella, an average annual escalation of about 0.037 % and 0.004 % in AQU for EU14 and EU13, respectively. For example, Koričan et al. (2022) and Mohammed et al. (2024) suggest Western EU14's leadership in IPR-aquaculture connections with offshore solar stems from integrated digital infrastructure, forward-looking policies, R&D-intensive ecosystems, and skilled workforces. Central and Eastern EU13 face structural gaps in infrastructure, policy alignment, and innovation capacity, despite EU funding and nearshoring trends. While Central and Eastern EU13 could leverage EU initiatives like the European Grids Package (2025) and Baltic Sea potential, Western EU14 is likely to maintain its lead for decades. The key for Central and Eastern EU13 lies in aligning national strategies with EU IPR standards, attracting specialized talent, and prioritizing digitalized offshore projects.

Unexpectedly, due to the promotion of offshore solar power under the NREAP effective policy led to an average annual reduction of about −0.304 % and −0.031 % in CO_2 for EU14 and EU13, respectively. This harmonized with earlier studies by Soukissian et al. (2017), Sgobbi et al. (2016) and Theodora and Piperis (2022), who referred to that EU14 Western European countries, such as the Netherlands, Germany, and France, have a long-standing maritime tradition and a highly developed maritime industry. They have a large number of ports, and Rotterdam in the Netherlands is one of the largest ports in Europe. These ports handle a large volume of cargo and passenger traffic, with numerous ships coming and going, resulting in high CO_2 emissions from ship fuel combustion. In contrast, although many EU13 Eastern European countries also have a coastline, but overall maritime industry scale and activity level are relatively lower than those of Western European countries, which causes lower CO_2 emissions.

Next, increasing offshore solar power showed an average annual rise of about 0.066 % and 0.114 % in GDP for EU14 and EU13, respectively. This is consistent with previous research by Taveira-Pinto et al. (2020) Fratila et al. (2021), and Bădîrcea et al. (2021) showing that the development of marine renewable energy provides an opportunity for EU13 Eastern European Members to catch up. It can attract a large amount of investment in related infrastructure construction, stimulate the growth of related industries such as manufacturing and

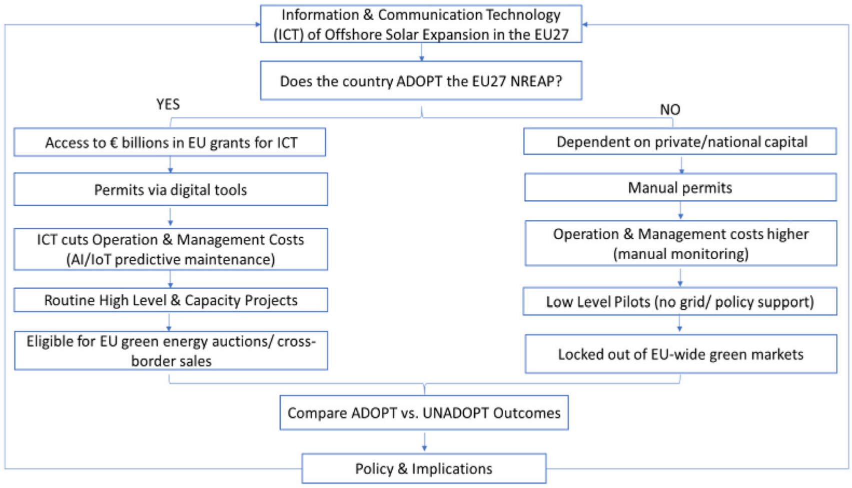

Chart 1: The impacts of the NREAP on the intellectual property rights (IPR) of offshore solar power in European countries: A comparison between policy adopters and non-adopters.

installation, create a large number of jobs, and thus promote overall economic development. For example, countries like Poland and Romania can use the development of offshore solar to enhance their industrial capabilities and economic strength. In contrast, Western EU14 countries already have relatively mature economies and industrial systems, so the marginal impact of offshore solar on their economies may be relatively small (see Chart 1).

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. The results of the placebo test indicate that all estimated coefficients were consistently less than one, with the distribution centered near zero. This observation suggests that the conclusions drawn from the analysis are unlikely to be driven by other unexamined factors. Nevertheless, it is important to emphasize that this interpretation remains theoretical at this stage. Further research and detailed examination are necessary to fully assess 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	−0.227***	0.022	−0.159***	0.0237	0.020**	0.010
AQU	0.053***	0.009	0.006	0.042	0.048***	0.011
CO_2	0.150***	0.014	0.051	0.095	−0.113***	0.020
GDP	0.090	0.091	−0.047	0.052	0.046*	0.026
IPR	−8.446***	2.835	−41.429***	8.023	−0.036*	0.018
Constant	8.694***	1.982	−26.161***	5.671	3.796***	0.106
Observation	918		476		442	
Number of groups	27		14		13	
F-statistic	17.780		56.640		23.995	
Prob. (*F*-statistic)	Prob. > *F* = 0.000		Prob. > *F* = 0.000		Prob. > *F* = 0.000	
R-squared	0.434		0.693		0.905	
Control	Yes		No		Yes	
Treat	Yes		Yes		No	
Intercept-random	Yes		Yes		Yes	

***1 %, **5 %, and *1 %.

6 Conclusions

This study examines the influence of intellectual property rights (IPR) development and relevant macroeconomic factors on the offshore solar power sector within the EU27 countries, covering the period from 1990 to 2023. The primary objective was to determine whether there are notable differences in offshore solar power commitments and National Renewable Energy Action Plan (NREAP) strategies across two distinct time periods. To assess these differences, the study employed a difference-in-differences (DID) approach. This method involved formulating a counterfactual hypothesis and dividing the countries into two groups for comparative analysis. The control group, referred to as EU13, consists of Eastern and Central European Union members, while the treated group, EU14, comprises Western European Union members. This grouping enabled a structured evaluation of policy impacts over time. After accounting for fixed effects, the regression coefficient for the DID analysis was found to be significantly positive at the 0.00 significance level, as reported in Tables 3, 4, and 5. A placebo test was conducted to further validate these results, with findings presented in Table 6. The empirical evidence indicates that policies and regulations associated with NREAPs have effectively promoted offshore solar power production. Furthermore, the results highlight the importance of advanced IPR and robust macroeconomic conditions in supporting the economic benefits of blue growth within the European Union.

When comparing EU14 western states (treatment group) and EU13 central and eastern states (control group), the greatest augmentation in offshore solar power production is achieved in EU14 states. Leading that in the year after boosting NREAPs policy implementation, an average annual escalation of the dependent variable, offshore solar power, and independent variables, IPR, and the aquaculture sector are higher in the EU14 treatment group in comparison with the EU13 control group. While the year after boosting NREAPs policy implementation, an average annual reduction of carbon dioxide emission was observed more in EU13 states in comparison to those in the EU14 states. On the other hand, an average annual increase in economic growth is observed to be higher in the EU13 states in comparison with those in the EU14 states.

This study shows that the National Renewable Energy Action Plans (NREAPs) have two core focuses in promoting the application of Intellectual Property rights (IPR) in offshore solar power generation: the protection of marine ecosystems and the maintenance of the marine environment. In terms of marine ecosystem protection, NREAPs have forced offshore solar projects to introduce advanced IPR technologies during the planning, construction, and operation phases by setting strict ecological assessment standards. For example, remote sensing monitoring technology is used to track the impact of projects on marine habitats in real-time, and big data analysis is employed to predict IPR trends in ecological chain changes. This achieves precise protection of marine ecosystems and lays a solid ecological foundation for the sustainable development of offshore solar power generation.

In the aspect of marine environment maintenance, NREAPs aim to reduce pollution and damage to the marine environment caused by blue growth marine economic development, promoting the in-depth application of IPR in environmental monitoring and management. Sensor networks are deployed to collect real-time environmental data such as seawater quality and marine meteorology. Through Internet of Things (IoT) technology, real-time transmission and analysis of data are realized, enabling timely detection and handling of potential environmental problems, thus effectively maintaining the stability of the marine environment.

Based on the above conclusions, the following policy implications are proposed to further strengthen the role of NREAPs in promoting the application of IPR in offshore solar power generation in EU27 members: (1) Improve IPR incentive policies oriented to ecology and environment in EU14 members: The government should increase financial support and tax incentives for the research, development, and application of IPR technologies used in marine ecosystem protection and marine environment maintenance. Special funds should be established to encourage enterprises and research institutions to develop more accurate and efficient IPR technologies for ecological monitoring and environmental management. Additional rewards should be given to enterprises that successfully apply relevant technologies in projects and achieve significant marine ecological and environmental benefits. (2) Establish a unified IPR data sharing and supervision platform in EU14 members: Under the framework of NREAPs, build a national IPR data sharing and supervision platform for offshore solar power generation. Integrate ecological monitoring data and environmental management data from various projects to achieve inter-regional and inter-departmental data interconnection among all EU27. At the same time, use the platform to conduct real-time supervision of the ecological and environmental impacts of projects to ensure that policy requirements are implemented and improve supervision efficiency and transparency between EU14 and EU13. (3) Strengthen international cooperation and technical exchanges between EU14 and EU13: Actively participate in international cooperation projects on the integration of offshore solar power generation and IPR, and learn from advanced policy experiences and technological achievements in ecological protection and environmental maintenance from other countries. Through international exchanges and cooperation, introduce advanced foreign IPR technologies and management models, and innovatively apply them in combination with national conditions to improve the overall level of IPR in China's offshore solar power generation and promote NREAPs to play a role in a broader international perspective. (4) Promote industry-university-research collaborative innovation mechanisms among EU14 and EU13: Encourage universities, research institutions, and enterprises to establish industry-university-research cooperation alliances to conduct joint research on IPR needs for marine ecosystem protection and marine environment maintenance. The government should play a bridging role, provide policy support and resource matching services for these alliances, accelerate the transformation and application of technological achievements, and form a virtuous cycle of "research and development–application - feedback - re-research and development" to continuously improve the application efficiency of IPR in offshore solar power generation.

This research is not without limitations; this study focuses on the mechanism by which NREAPs promote IPR applications in offshore solar power generation, primarily from the perspectives of marine ecosystems and the environment. However, it may lack in-depth analysis of specific cases across different regions or country levels. While the study emphasizes the role of IPR technologies, it pays insufficient attention to the technical constraints in their application. For example, the high cost of some advanced IPR technologies, technical bottlenecks in data transmission and analysis in complex marine environments, and difficulties in popularizing technologies among small and medium-sized enterprises may affect the actual effectiveness of NREAPs' promotion. Future research directions to be considered by other scholars: (1) Future research can select offshore solar power projects in different regions or countries with distinct NREAPs implementations. (2) Establish long-term monitoring mechanisms to collect data on IPR applications, ecological and environmental changes, and policy adjustments in offshore solar power projects over extended periods. (3) Focus on technical constraints in the application of IPR in offshore solar power generation under the NREAPs framework. (4) Study how to coordinate NREAPs with energy policies, environmental policies, and technological innovation policies to create synergies and avoid policy conflicts. (5) With the continuous development of emerging technologies such as artificial intelligence, 5G, and blockchain, future research can explore how these technologies integrate with IPR in the context of NREAPs to better promote ecological protection and environmental maintenance in offshore solar power generation.

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