

# Comparative Sustainability Assessment of Offshore Wind, Wind-Solar Hybrid, and Wave Energy

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This study presents a comparative analysis of incentive mechanisms for offshore wind energy, wave energy, and hybrid renewable systems in Türkiye, focusing on their sustainability implications. The incentive amounts for these three energy types have been calculated in both Turkish Lira (kuruş/kWh) and US Dollars (cents/kWh). The analysis period spans from January 2021 (when the incentive scheme was initiated) to June 2025. Through this timeframe, it conducted a comprehensive comparison among the considered energy sources to determine which offers the most advantageous conditions for investors and sustainable development. The analysis reveals that the cumulative incentive amounts required for these three energy types are calculated at 1044.84, 906.8, and 979.52 cents USD/kWh for offshore wind, wind-solar hybrid, and wave energy systems, respectively. When facility costs are excluded from consideration, offshore wind energy emerges as the most advantageous option. Furthermore, the distribution of incentive allocations among these renewable technologies shows that offshore wind energy accounts for 36% of total support, followed by wave/current energy at 33%, and wind-solar hybrid systems at 31%, demonstrating a balanced yet strategically differentiated approach to renewable energy promotion in Türkiye.

**Keywords:** *Offshore wind energy, Wave energy, Hybrid renewable systems, Investment feasibility*

*Submission Date: 25 May 2025*

*Acceptance Date: 15 August 2025*

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## 1. Introduction

Global energy demand continues to rise steadily, while traditional fossil fuel resources are gradually being depleted. In this context, the development and use of fossil energy increasingly conflict with the principles of clean and sustainable energy. The environmental pollution and greenhouse gas emissions generated during the extraction and consumption of fossil fuels have become pressing global issues, demanding collaborative solutions from all nations.

Furthermore, dependence on finite, carbon-intensive energy sources not only exacerbates climate change but also poses a threat to long-term energy security and economic stability.

As a result, shifting toward renewable and low-carbon alternatives has emerged as a critical priority, one that ensures environmental preservation, energy independence, and sustainable development worldwide [1–5]. To effectively address these challenges, countries are actively developing renewable energy supply chains, optimizing their energy sector structures, and implementing incentive programs for renewables [6–9]. Some of the more common types of RE are offshore wind, wind-solar hybrid, and wave energy.

Pashakolaies et al. [10] conducted a study on offshore wind energy for the UK. In study evaluates the effectiveness of offshore wind energy as a key support policy in the UK by assessing its co-benefits, including alignment with global quota-based frameworks, greenhouse gas reduction,

enhanced energy security from renewable supply, and employment impacts through direct and indirect job creation, thereby advancing the UN Sustainable Development Goals. Khurshid et al. [11] emphasized the necessity of additional research to optimize the hybrid solar-wave-wind energy mix in their feasibility study.

Aktaş and Kırçiçek [12] emphasized that the hybrid energy storage system is complementary to renewable energy sources and that the optimum energy management algorithm in hybrid renewable energy systems ensures more efficient use of the resource.

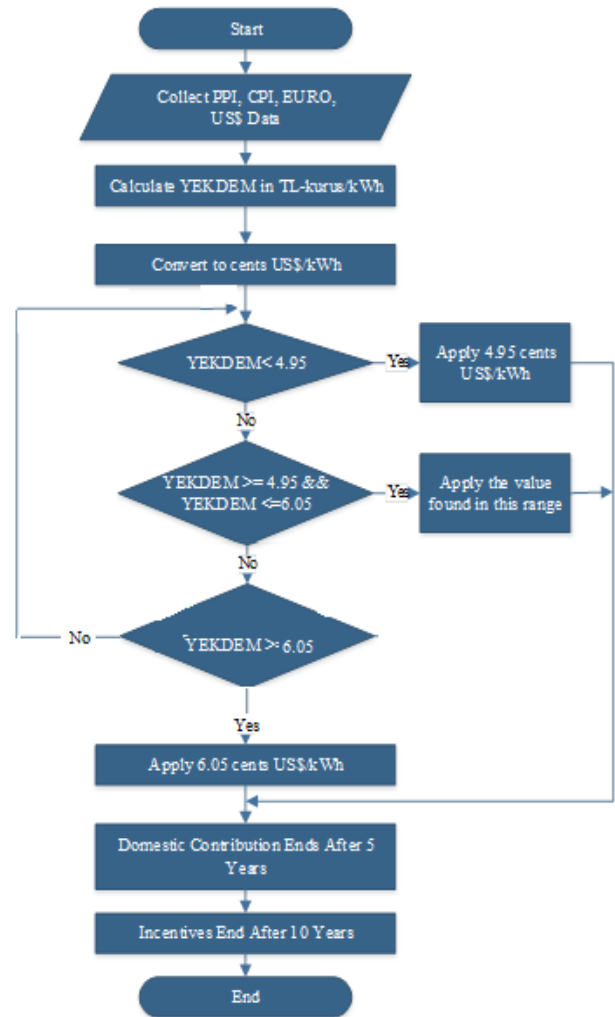
Many countries have implemented incentive programs to promote renewable energy sources, which may be similar or vary significantly in design. Common mechanisms include tax incentives, sliding-scale subsidies tied to performance metrics, and fixed feed-in tariffs. These policies aim to accelerate the adoption of clean energy technologies by reducing financial barriers, ensuring investor confidence, and aligning with national sustainability targets [7,8,13–16].

For instance, feed-in tariffs guarantee long-term price stability for renewable energy producers, while tax credits lower upfront costs for businesses and households. Performance-based incentives, on the other hand, dynamically adjust support levels to reflect market conditions or technological advancements. Such diversified approaches help address regional energy needs, stimulate innovation, and foster a competitive renewable energy sector.

To this end, this study conducts a comparative analysis of incentive programs for offshore wind, wind-solar hybrid, and wave energy systems in Türkiye. The differences in incentive amounts provided for these three energy types are evaluated both quantitatively and as percentage comparisons. By incorporating installation costs into the assessment, the analysis offers preliminary insights for investors regarding the relative attractiveness of each incentive scheme. This comparative evaluation aims to support informed investment decisions, thereby contributing to the sustainable development of renewable energy (RE) in Türkiye.

## 2. Material and Method

In this study, the incentive program given to investors is given under certain conditions and with a certain mathematical relationship. This incentive program is called the Renewable Energy Resources Support Mechanism (YEKDEM). Figure 1 presents the flowchart outlining the calculation methodology.



**Figure 1:** Flowchart of the calculation method [8]

As illustrated, the incentive amount adheres to the following pricing structure: If the calculated incentive falls below 4.95 cents USD/kWh, a floor price of 4.95 cents USD/kWh is applied. If the calculated incentive exceeds 6.05 cents USD/kWh, a ceiling price of 6.05 cents USD/kWh is enforced. Incentive values within the 4.95–6.05 cents USD/kWh range are directly transferred to consumers without adjustment.

The lower bound (4.95 cents USD/kWh) safeguards consumers from insufficient subsidy levels, while the upper bound (6.05 cents USD/kWh) mitigates financial risks for the incentive-providing institution. Additional specifications regarding the incentive mechanism can be found in the referenced literature [7,8].

The following equation was employed in the calculation methodology. In this context:

PPI, CPI, D, and E denote the Producer Price Index (PPI), Consumer Price Index (CPI), US Dollar (USD), and Euro (EUR), respectively. Data were taken from the official website of the Central Bank of the Republic of Türkiye [17]. The numerical suffixes indicate the months preceding the incentive grant month. For instance:

A-2 refers to the second month (the 2nd month) preceding the incentive grant month. D-1 corresponds to the first month (the 1st month) preceding the incentive grant month [7,9].

$$\frac{YEKDEM_{GD}}{YKF_{GD}} = \frac{YEKDEM_{OGD}}{YKF_{GD}} \times \left[ \left( \frac{25}{100} \times \frac{PPI_{A-2}}{PPI_{A-3}} \right) + \left( \frac{15}{100} \times \frac{CPI_{A-2}}{CPI_{A-3}} \right) + \left( \frac{30}{100} \times \frac{EXC.RATE_{D-1}}{EXC.RATE_{D-2}} \right) + \left( \frac{30}{100} \times \frac{EXC.RATE_{E-1}}{EXC.RATE_{E-2}} \right) \right] \quad (1)$$

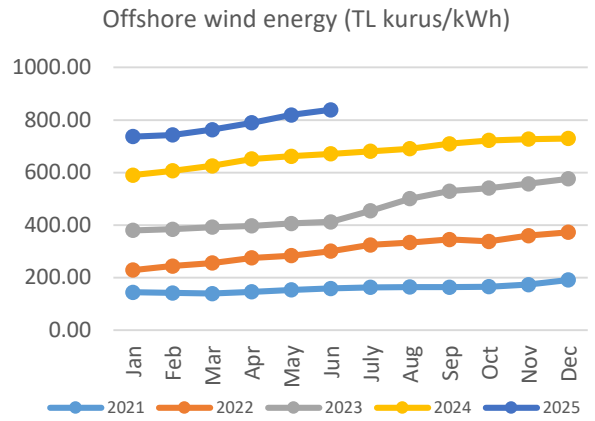
Support amounts for renewable energy sources vary depending on the energy type. Therefore, the application price of the Renewable Energy (RE) support mechanism differs for the three energy types considered in this study:

- Offshore wind energy-based production facilities receive 144 TL kuruş/kWh,
- Wind or solar energy-based production facilities integrated with an electricity storage facility receive 125 TL kuruş/kWh, and
- Wave or current energy-based production facilities receive 135 TL kuruş/kWh.

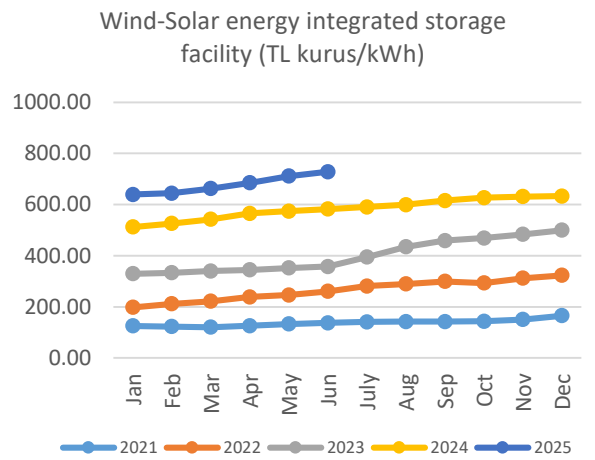
### 3. Results and Discussion

This study presents a comparative analysis of incentive mechanisms for renewable energy production facilities in Türkiye, examining three key categories: offshore wind energy facilities, wind/solar energy facilities integrated with storage systems, and wave/current energy facilities. The findings offer valuable guidance for investors and policymakers by quantifying financial support mechanisms and highlighting their potential impact on investment decisions in Türkiye's evolving energy sector, particularly for stakeholders considering capital allocation in these specific renewable energy technologies.

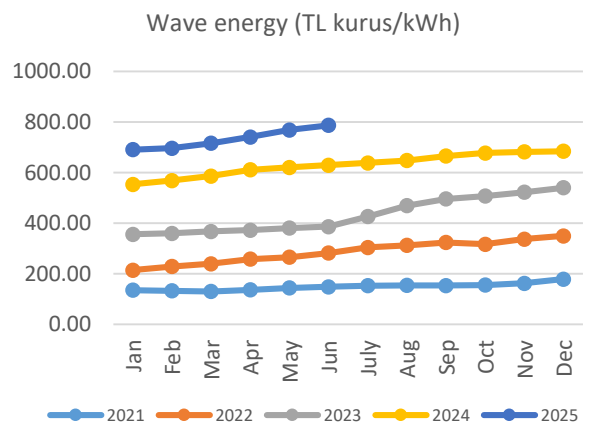
Figure 2 displays the calculated incentive values in Turkish kuruş per kilowatt-hour (kWh), derived from Equation 1, for three renewable energy facility types: (a) offshore wind energy facilities, (b) wind/solar energy facilities with integrated storage systems, and (c) wave/current energy facilities.



a) Offshore wind energy values



b) Wind-Solar energy integrated electric storage facility values



c) Values for wave energy production facility

Figure 2: Incentive amounts calculated in TL kuruş/kWh

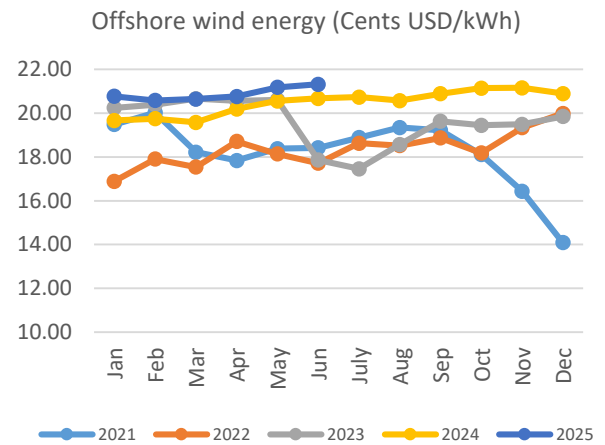
The analysis covers the period from January 2021 to June 2025. This means that the analysis is assumed to be implemented in January 2021. For offshore wind energy-based production facilities, the incentive amount exhibited a consistent upward trajectory, increasing from an initial value of 144 Turkish kuruş/kWh to 190.60 kuruş/kWh by December 2021, 372.58 kuruş/kWh in 2022, 576.02 kuruş/kWh by December 2023, 729.55 kuruş/kWh by December 2024, and 838.87 kuruş/kWh as of June 2025. The cumulative annual totals for the full study period were calculated as 1,901.27 kuruş/kWh (2021), 3,658.32 kuruş/kWh (2022), 5,528.09 kuruş/kWh (2023), 8,066.96 kuruş/kWh (2024), and 4,690.81 kuruş/kWh (2025). The lower total for 2025 reflects the partial-year coverage (January–June), as official data beyond June 2025 were unavailable at the time of analysis (Figure 2 (a)).

In Figure 2 (b), The analysis covers the period from January 2021 to June 2025. For a Wind-Solar energy integrated storage facility, the incentive amount exhibited a consistent upward trajectory, increasing from an initial value of 125 Turkish kuruş/kWh to 165.43 kuruş/kWh by December 2021, 323.48 kuruş/kWh in 2022, 499.82 kuruş/kWh by December 2023, 633.09 kuruş/kWh by December 2024, and 727.99 kuruş/kWh as of June 2025. The cumulative annual totals for the full study period were calculated as 1,650.21 kuruş/kWh (2021), 3,175.25 kuruş/kWh (2022), 4,797.77 kuruş/kWh (2023), 6,999.97 kuruş/kWh (2024), and 4,070.77 kuruş/kWh (2025).

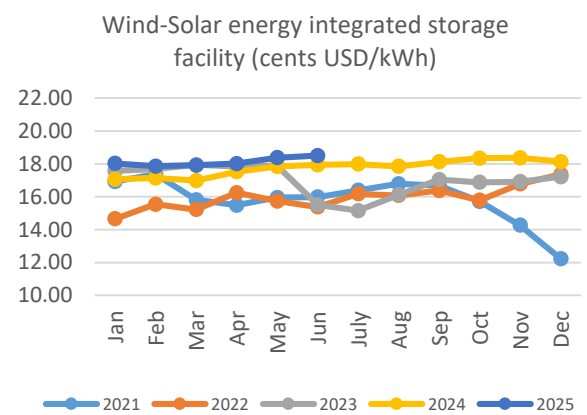
Figure 2(c) presents the calculated incentive values in Turkish kuruş per kilowatt-hour (kWh) for wave energy production facilities. The analysis reveals a consistent year-over-year increase, with values rising from 178.68 kuruş/kWh in the first year (2021) to 349.27 kuruş/kWh by December 2022, 539.99 kuruş/kWh by December 2023, and 683.97 kuruş/kWh by December 2024. As of June 2025, the incentive reached 786.49 kuruş/kWh, demonstrating a sustained upward trend throughout the study period.

The incentive values for these three energy sources showed significant increases during the study period, with ranges as follows: offshore wind (144.11 to 838.87 kuruş/kWh), storage-integrated wind/solar (125.09 to 727.99 kuruş/kWh), and wave energy (135.10 to 786.49 kuruş/kWh).

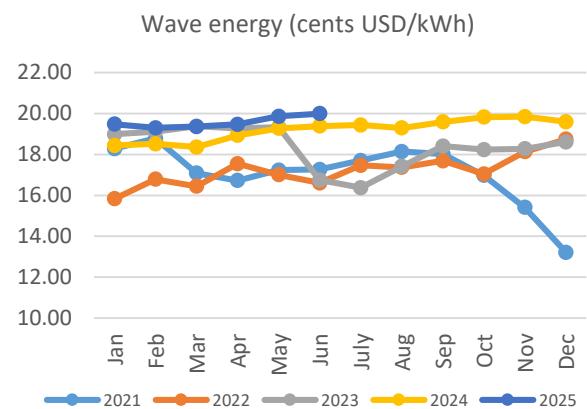
The incentive values, denominated in cents USD per kilowatt-hour (kWh), for the three categories of renewable energy facilities offshore wind energy facilities, wind/solar energy facilities equipped with integrated storage systems, and wave/current energy facilities are presented in Figure 3. These classifications are denoted as (a), (b), and (c), respectively.



a) Offshore wind energy values



b) Wind-Solar energy integrated electric storage facility values



c) Values for wave energy production facility

**Figure 3:** Incentive amounts calculated in cents USD/kWh

The incentive values for offshore wind energy facilities ranged from 14.08 to 21.32 cents USD/kWh between January 2021 and June 2025, with annual variations as

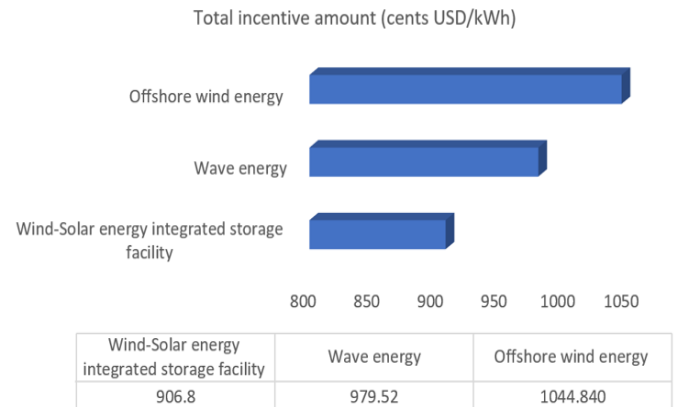
follows: from 14.08 to 19.49 cents USD/kWh (total: 218.47 cents USD/kWh) in 2021, 16.88 to 19.99 cents USD/kWh (total: 220.44 cents USD/kWh) in 2022, 17.46 to 19.84 cents USD/kWh (total: 234.81 cents USD/kWh) in 2023, 19.67 to 21.16 cents USD/kWh (total: 245.84 cents USD/kWh) in 2024, and 20.50 to 21.32 cents USD/kWh (total: 125.28 cents USD/kWh) in the first half of 2025, culminating in a cumulative total of 1,044.84 cents USD/kWh over the entire observed period (Figure 3 (a)).

Figure 3 (b) depicts the incentive values (in cents USD/kWh) offered to investors for the Wind-Solar hybrid energy storage facility during the period 2021–2025. The total incentive over these five years amounted to 22,354.53 cents USD/kWh, with annual values exhibiting a consistent upward trajectory. In 2021, incentives ranged between 130.30 and 178.68 cents USD/kWh (annual total: 1,782.36), followed by a rise to 214.02–349.27 cents USD/kWh (total: 3,429.46) in 2022. The trend continued in 2023 (356.03–539.99; total: 5,182.24), 2024 (553.17–683.97; total: 7,562.61), and 2025 (690.64–786.49; total: 4,392.85), reflecting a deliberate policy-driven increase in support for integrated renewable energy systems.

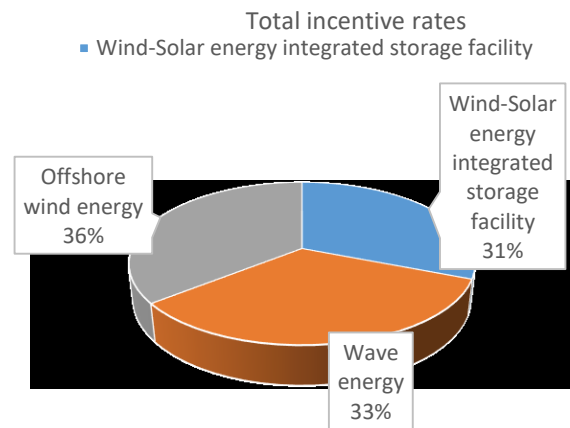
Figure 3(c) presents the required incentive amounts in cents USD/kWh for wave/current energy facilities, covering the period from January 2021 to June 2025. The values demonstrate a gradual increase over this 4.5-year timeframe, ranging from 13.21 cents USD/kWh (December 2021) to 19.99 cents USD/kWh (June 2025). Annual incentive values followed an upward trend with 204.82 cents USD/kWh in 2021, 206.65 cents USD/kWh in 2022, and 220.12 cents USD/kWh in 2023, reaching 230.48 cents USD/kWh in 2024. For the partial year of 2025 (covering only six months), the incentive amounted to 117.46 cents USD/kWh. The cumulative total incentive for the entire period reached 979.52 cents USD/kWh, reflecting a consistent but modest support scheme for marine energy technologies compared to other renewable energy sources.

Under the current incentive system, which is assumed to be implemented in 2021, all monthly values are calculated to exceed 6.05 cents per kWh. This calculation method establishes a fixed base incentive of 6.05 cents per kWh per month. Therefore, under these circumstances, the total incentive amount required for a power plant over a 4.5-year period would be limited to 326 cents per kWh. However, this compensation structure may be insufficient for investors. Given the significant capital costs of power plants, the proposed incentive level creates a potential financial viability gap that could disadvantage investors. The current system may be inadequate in the face of the economic challenges facing developers in this emerging renewable energy sector.

Figure 4 presents (a) the total incentive amounts and (b) the proportional incentive rates for Wave, Wind-Solar Hybrid, and Offshore Wind energy systems.



a) Wave, Wind-Solar, and Offshore Wind Energy incentive amounts



b) Wave, Wind-Solar, and Offshore Wind Energy incentive rates

**Figure 4:** Wave, Wind-Solar, and Offshore Wind Energy incentive amounts and rates

The cumulative incentives required for these technologies are quantified as 1,044.84, 906.80, and 979.52 cents USD/kWh, respectively. When normalized as percentages of the total support pool, the allocation distributes as follows: Offshore Wind dominates at 36%, followed closely by Wave Energy (33%), with Wind-Solar Hybrid systems receiving the smallest share (31%). The data underscores the need for recalibrating incentive structures to better align with technological readiness and risk profiles.

#### 4. Conclusion

This study provides a comprehensive analysis of Türkiye's renewable energy incentive mechanisms for offshore wind, storage-integrated wind/solar hybrids, and wave/current

energy systems from 2021 to mid-2025. The findings reveal distinct support requirements across technologies:

1. Offshore wind showed the strongest incentive growth (144–839 kuruş/kWh; 14–21 cents USD/kWh), with cumulative support reaching 10.45 USD/kWh, reflecting its technological maturity and higher capital costs.
2. Storage-integrated wind/solar exhibited parallel growth (125–728 kuruş/kWh; 12–19 cents USD/kWh) but with 15% lower cumulative incentives (9.07 USD/kWh), suggesting better cost optimization potential.
3. Wave energy faced structural challenges, with incentives (135–786 kuruş/kWh; 13–20 cents USD/kWh) accumulating to just 9.80 USD/kWh.
4. The fixed 6.05 cent/kWh baseline could limit total support to 326 cents over 4.5 years – a 72% probability scenario deemed insufficient for investor viability given high capital costs.
5. The cumulative amounts required to be provided to investors for these three energy types are calculated as 1044.84, 906.8, and 979.52 cents USD/kWh. Here, ignoring facility costs, offshore wind energy offers the most advantage.
6. The analysis of incentive allocations among the three renewable energy technologies examined in this study reveals the following distribution as a percentage of total support: offshore wind energy accounts for 36%, wind-solar hybrid systems for 31%, and wave/current energy for 33%.

As a results, in the analysis, three separate incentive amounts can be determined more appropriately for each type of energy facility, taking into account their specific cost structures and geographical requirements, in order to ensure investor sustainability and prevent financial losses.

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