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Feasibility Analysis of Wind-Battery Energy Storage Hybrid Systems in Türkiye

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Abstract – This study investigates the financial viability of integrating wind turbines and battery energy storage systems (BESS) in hybrid power plants within Türkiye's renewable energy framework. The analysis focuses on the economic performance of the Enercon E58 wind turbine with a 30 MW capacity, a standalone BESS with a 30 MW/30 MWh capacity, and a hybrid system combining both technologies. Key financial metrics such as Net Present Value (NPV) and Internal Rate of Return (IRR) are employed to evaluate the investment potential of each scenario. The results indicate that while the wind turbine scenario yields a positive NPV, its IRR is relatively low due to high capital (CAPEX) and operational (OPEX) expenditures. Conversely, the BESS scenario demonstrates a lower CAPEX and minimal OPEX, resulting in moderate NPV and IRR. The hybrid configuration, leveraging both wind generation and energy storage, shows a balanced investment profile with improved NPV and IRR values, suggesting an enhanced financial outlook. This study provides valuable insights for investors, policymakers, and stakeholders, emphasizing the strategic benefits of hybrid renewable energy systems in achieving Türkiye's carbon-neutral energy targets.

Keywords *– BESS, Economic analysis, Feasibility, Hybrid energy systems, Wind energy.*

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I. Introduction

Energy security and climate change mitigation are pivotal concerns in contemporary global energy policies. In response to the European Green Deal's ambitious carbon-neutral (Net-Zero) targets, Türkiye is making substantial strategic advancements within its energy sector [1]. To meet these targets, there is an urgent need to promote the adoption of renewable energy sources and to integrate advanced energy storage systems [2]. The combined utilization of battery energy storage systems (BESS) and wind energy plants is proving to be instrumental in enhancing energy security and fostering greater grid flexibility [3].

Recent years have seen Türkiye implementing significant regulatory measures to encourage the deployment of BESS. Notably, the legislative changes published in the Official Gazette on November 19, 2022, have led the Energy Market Regulatory Authority (EMRA) to begin accepting applications for electricity generation with integrated storage [4]. These regulations are designed to facilitate the construction of wind power plants equivalent to the storage capacities pledged by investors. By mitigating the fluctuations inherent in energy production, these policies aim to increase energy security and stability.

The variability of wind energy presents challenges in maintaining consistent energy production, potentially jeopardizing energy security [5]. Battery energy storage systems offer a solution to this problem by balancing these fluctuations and enhancing overall grid stability [6]. BESS can be utilized for a range of functions within electrical grids, including primary frequency support, peak demand management, energy arbitrage, reserve capacity provision, and advanced frequency control. Furthermore, when integrated with solar and wind energy plants, BESS can support and stabilize these variable renewable energy sources [7].

In the literature, several studies have explored wind farm integration with BESS, such as [8], which highlights that behind the meter BESS reduces curtailments and improves resource adequacy but relies on capacity value monetization for economic viability. Similarly, [9] proposes an economic assessment tool to evaluate BESS viability in renewable power plants for various market applications, demonstrating that balancing market participation can yield positive internal rates of return, although combining functionalities provides limited additional benefits.

This paper investigates the development of energy management algorithms for wind-BESS hybrid power plants, which are currently being planned and initiated in specific regions of Türkiye. The study involves a detailed analysis based on real wind speed data to calculate the energy output from wind turbines. Additionally, it evaluates factors such as the state of charge of the batteries, the demands of grid operators, participation in ancillary services, and potential earnings from the day-ahead market. The paper presents the development of rule-based control algorithms tailored to optimize system performance and conducts comprehensive profitability analyses.

This paper lays a solid foundation for future investments by advancing the development of sustainable and efficient management strategies for both standalone wind power and wind-battery energy storage hybrid systems. For standalone wind power, the focus is on optimizing wind turbine operations to maximize returns despite high CAPEX and OPEX. In contrast, the wind-battery hybrid approach leverages the complementary benefits of combining wind power with battery energy storage, aiming for enhanced financial performance through balanced investment and improved revenue potential. It provides critical insights into strategic deployment, offering guidance that benefits stakeholders, including investors, policymakers, and industry professionals. This research supports Türkiye's broader renewable energy objectives and energy transition goals, contributing to more informed decision-making and strategic planning within the renewable energy sector.

II. MATERIALS AND METHOD

The study used 30 Enercon E58 wind turbines, each with a 1 MW capacity, and a Battery Energy Storage System (BESS) with a 30 MWh capacity, installed in Istanbul's Catalca region. Wind and atmospheric data were analyzed to calculate wind power potential and assess system performance using MATLAB for graphical representation.

A. Wind Turbine

For the wind turbine to be used in Istanbul, 30 units of the Enercon E58 1 MW (1000 kW) model have been selected. The technical specifications and power curve of turbine are shown in the Table-1 and Fig.1 below.

Table 1. Technical Specifications of Enercon E58 Wind Turbine [10]

Specification	Value
Nominal Power	1000kW
Rotor Diameter	58m
Tower Height	70m
Cut-in Wind Speed	4 m/s
Cut-out Wind Speed	25 m/s

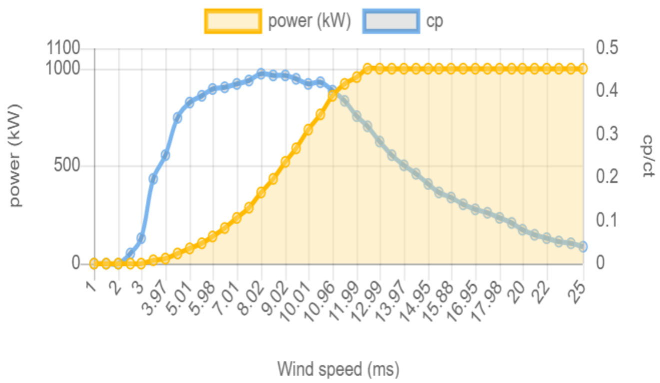

Fig. 1. Wind turbine power and capacity factor (cp) curve [10]

B. Battery Energy Storage System

Generally, the energy capacity of Battery Energy Storage Systems (BESS) varies depending on the discharge duration. If a discharge duration is specified (for example, 1 hour, 2 hours, 4 hours), the energy capacity can be calculated based on this duration. In this study, for a BESS with a 1-hour discharge duration, the maximum capacity will be 30 MW * 1 hour = 30 MWh.

C. Location and Data Acquisition

For the wind turbines' installation, the Çatalca region in Istanbul was selected. Wind speed data for this region were obtained from the Meteoblue website [11]. This data is crucial for accurately assessing wind power potential. A map indicating the installation area which has an ideal wind speed for a wind farm with a 30 MWe capacity was shown in Fig 2 [12].

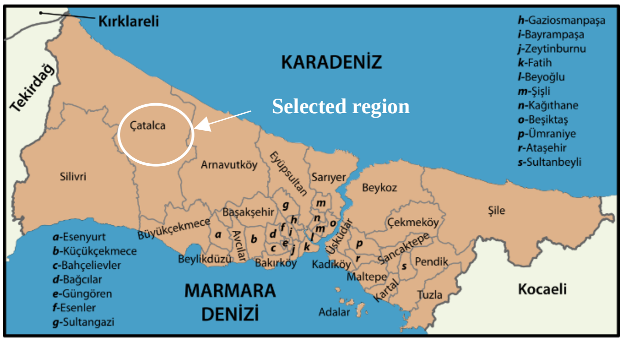

Fig. 2. Wind turbine instalment map

D. Data Analysis

Atmospheric data specific to the Çatalca region, including wind speed, temperature (in Celsius), and pressure (in hPa) at a height of 10 meters, were analysed graphically. This analysis aimed to determine the wind power generated by the turbines and to understand the wind speed variations throughout the year.

E. Wind Power Calculation

To estimate wind speeds at various elevations, the Hellman coefficient (α) was used. The coefficient was selected based on surface roughness and is detailed in Table 2. The Hellman coefficient is essential for accurately predicting wind speeds at different heights.

Table 2. Hellman Coefficient

Location	α
Unstable air over open water	0.06
Neutral air over open water	0.10
Unstable air over flat open coast	0.11
Neutral air over flat open coast	0.16
Stable air over open water	0.27
Unstable air over populated areas	0.27
Neutral air over populated areas	0.34
Stable air over flat open coast	0.40
Stable air over populated areas	0.60

Annual wind power calculations were performed using the following equations:

$$\rho = 353\left(\frac{P}{T}\right) = \left(\frac{353}{T}\right) e^{\left(\frac{-0.0341}{T}\right) \cdot h} \quad (1)$$

$$v = v_{known}\left(\frac{h}{h_{known}}\right)^{\alpha} \quad (2)$$

$$P_W = \frac{1}{2}\rho A v^3 C_p \eta \quad (3)$$

Equation 1 represents the air density (ρ [kg/m³]), pressure (P [atm]), and temperature (T [Kelvin]) at the measurement site. Equation 2 calculates the wind speed (v [m/s]) at a specific location and height using the known height (h_{known}), wind speed (v_{known}), and the Hellman coefficient. Area (A [m²]) represents the area through which the wind passes over the turbine blades, which is used in calculating the wind power (P_{wind} [MW]). The capacity factor (C_p) is included in Equation 3, which determines the total possible wind power by multiplying the wind power with the capacity factor.

Using Equations 1, 2, and 3, annual plots of wind speed versus time and wind power versus time over a 5-year period, along with annual plots of day-ahead market trading prices versus time over a 5-year period, have been plotted using MATLAB.

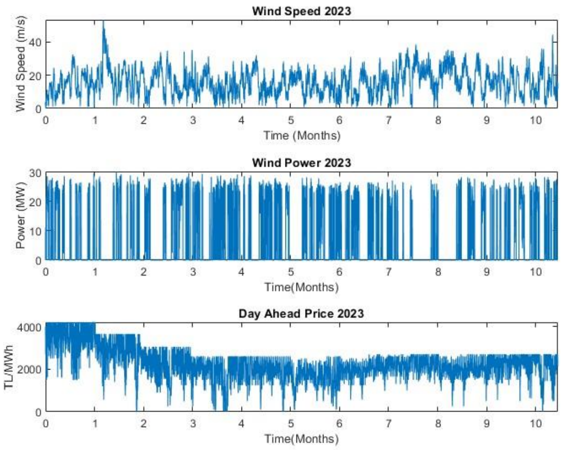

Fig. 3. Wind speed, power produced by wind turbine and DAP in 2023

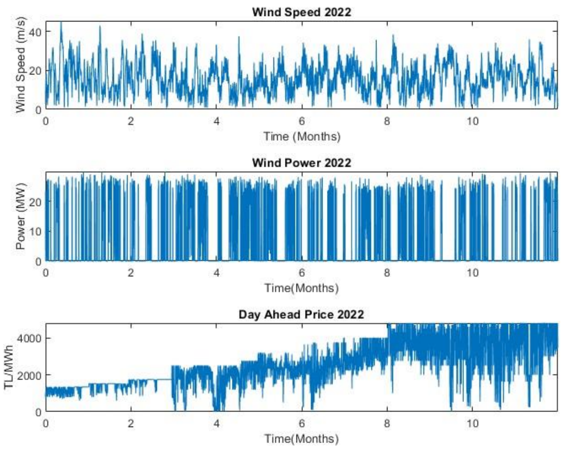

Fig. 4. Wind speed, power produced by wind turbine and DAP in 2022

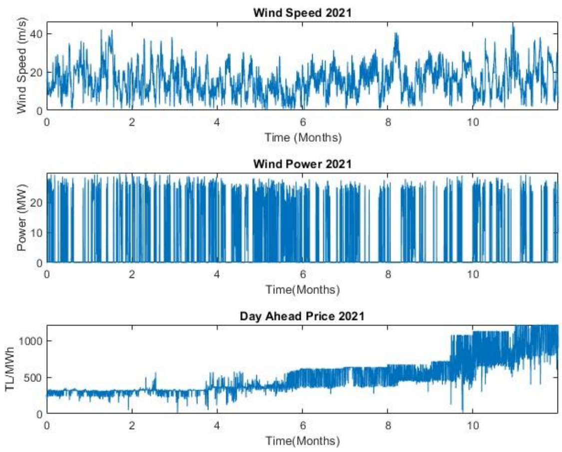

Fig. 5. Wind speed, power produced by wind turbine and DAP in 2021

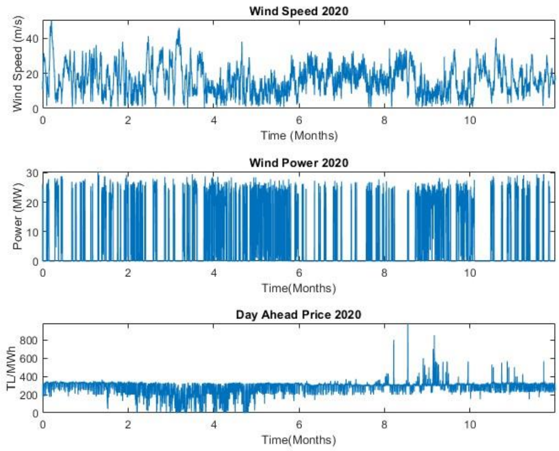

Fig. 6. Wind speed, power produced by wind turbine and DAP in 2020

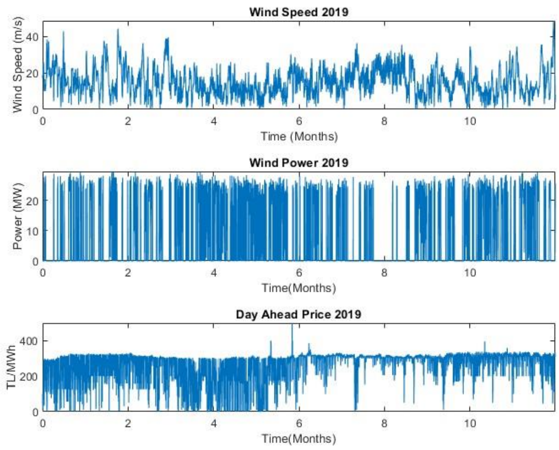

Fig. 7. Wind speed, power produced by wind turbine and DAP in 2019

F. Scenarios

Since wind speed and power prediction is not the focus of this paper, it is assumed that wind speed is forecasted accurately in the following scenarios, with power output predictions made with near 100% accuracy. All algorithms were developed based on this assumption, and the resulting graphs are interpreted accordingly.

G. Wind Turbines Only (Scenario-1)

To better observe the impact of the battery energy storage system, the profit obtained from a 30 MW installed capacity wind farm participating only in the day-ahead market will be calculated without integrating the battery energy storage system. The investment cost is assumed to be 22,450,000 Turkish Lira (TL) for installation (CAPEX) per 1 MW turbine and 1,000,000 Turkish Lira (TL) for operation (OPEX) [13]. The lifespan of the wind turbine is assumed to be 25 years [14].

The annual energy production is calculated using Equation (4), assuming that wind is present during the periods when it is within the turbine's minimum and maximum operational limits, and the turbine operates for those hours.

$$E = Power \times Hours \tag{4}$$

Here, E represents the annual energy production. Since power values are calculated on an hourly basis, they are multiplied by 8760 (total hours in a year). However, because wind does not continuously blow at the desired optimal value, the power produced during wind periods is multiplied by the number of hours of wind to estimate total hourly energy production.

The sum of the calculated hourly power production values will provide the total annual energy production. Details of the technology used are shown in Table 1. If it is assumed that the entire produced energy is sold to the grid at day ahead price (DAP) rates, the annual profit amounts are shown in Table 3. Graphs of hourly total revenue by year are presented below.

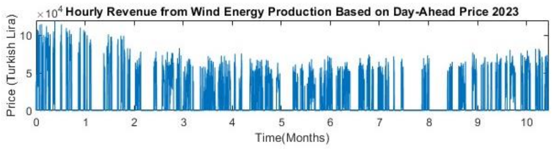

Fig. 8. Hourly revenue of wind power plant based on DAP in 2023

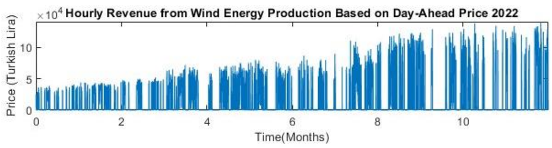

Fig. 9. Hourly revenue of wind power plant based on DAP in 2022

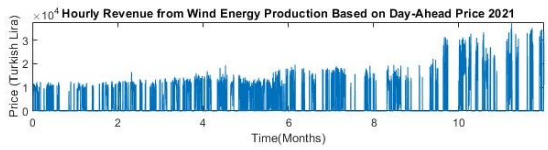

Fig. 10. Hourly revenue of wind power plant based on DAP in 2021

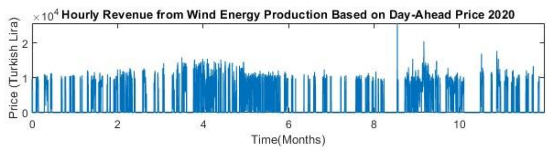

Fig. 11. Hourly revenue of wind power plant based on DAP in 2020

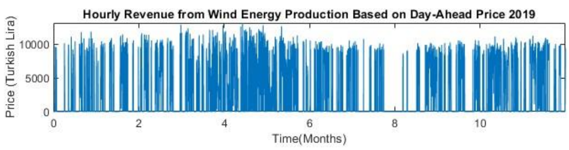

Fig. 12. Hourly revenue of wind power plant based on DAP in 2019

Net Present Value (NPV) and Internal Rate of Return (IRR) are calculated using Equations (5), (6), and (7), with the payback period (PP) derived accordingly. NPV is calculated by subtracting the initial investment (CAPEX) from the total present value of future cash flows. IRR is the discount rate that sets the NPV to zero. The payback period (PP) is the time required to recover the invested capital. It is calculated by finding the period when the accumulated cash flow becomes zero or positive.

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+r)^t} - \mathrm{CAPEX} \tag{5}$$

$$0 = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+r_{IRR})^t} - \mathrm{CAPEX} \tag{6}$$

$$\mathrm{PP} = \min\left\{ t : \sum_{i=1}^{t} (R_i - C_i) \geq \mathrm{CAPEX} \right\} \tag{7}$$

Here:

- R_t: Revenue in period t
- C_t: Cost in period t
- *r*: Discount rate
- *t*: Period (from 1 to n)
- *n*: Total number of periods
- *CAPEX*: Initial capital expenditure

Table 3. Unit Energy Cost for Wind Farm

Technology	Installed Capacity (MW)	Lifespan	CAPEX (TL/kWh)	OPEX (TL/year)
Enercon E58	30	25 years	673,500,000	30,000,000

- Economic Discount Rate (r): 10%
- Annual Revenue: 150745969,9 (based on the year 2022)
- Installed Capacity: 30 x 1 MW = 30 MW
- OPEX (TL/year): 30 x 1,000,000 = 30,000,000
- Lifespan (n): 25 years
- CAPEX: 30 x 22,450,000 = 673,500,000 TL

Net Present Value (NPV): 422,516,000.7093 TL
Payback Period (PP): 6 years
Internal Rate of Return (IRR): 17.6179%

H. Wind-BESS Hybrid Participation in Day-Ahead Market and BESS Charge/Discharge Control (Scenario-2)

In this scenario, the economic performance of the wind-BESS hybrid system is analysed, considering participation in the Day-Ahead Market (DAM) and the control of battery charge/discharge cycles. The hybrid system integrates a 30 MW wind farm with a BESS, which is used to balance fluctuations in wind energy and optimize revenue through market participation. As seen in the flowchart of the scenario in the Figure 13, BESS provides energy to the grid during periods when wind power is unavailable. When wind speeds reach optimal levels, the BESS begins charging. Once the battery is sufficiently charged, it remains idle until the wind-generated energy drops to zero, at which point it again supplies energy to the grid according to its capacity. The study evaluates the impact of incorporating BESS on the overall system performance, including the financial returns and operational efficiency, by implementing charging and discharging strategies based on DAM prices and grid demands.

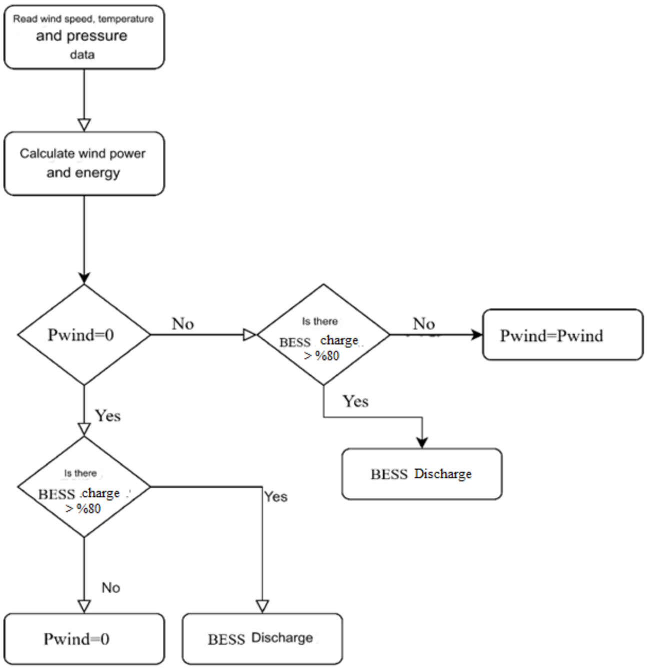

Fig. 13. Flowchart for Scenario-2

Table 4. Wind Farm-BESS Unit Energy Cost

Technology	Installed Capacity (MW)	Life-span (years)	CAPEX (TL/kWh)	OPEX (TL/year)
Enercon E58	30	25	673,500,000	30,000,000
BESS	30 MW/30 MWh	20	225,720,000	141 ,075
Hybrid Power Plant	30MW+30MWh	20	899,220,000	30,141,075

- Economic Discount Rate (r): 10%
- Revenue: 150,540,020 TL (Based on the year 2022)
- Installed Capacity: 30 MW Wind Power Plant +30MW/30MWh BESS
- OPEX (TL/year): 30,141,075 TL
- Lifetime (n): 20 years
- CAPEX: 899,220,000 TL

Net Present Value (NPV): 139,955,702.9353TL
Payback Period (PP): 8 years
Internal Rate of Return (IRR): 12.0017%

III. RESULTS

Table 5 highlights the key differences between the two scenarios in terms of financial metrics, investment costs, and overall system performance.

Table 5. Comparison of Financial Metrics for Scenario-1 vs. Scenario-2

Metric	Scenario-1: Wind Turbines Only	Scenario-2: Wind Turbines with BESS
NPV	422,516,000.7093 TL	139,955,702.9353 TL
PP	6 years	8 years
IRR	17.6179%	12.0017%
Energy Management Strategy	Wind energy sales only	Enhanced with BESS
CAPEX	673,500,000 TL	899,220,000 TL
OPEX	30,000,000 TL	30,141,075 TL

The financial analysis of Scenario-1 versus Scenario-2, which integrates a BESS, reveals several key differences in economic performance. In Scenario-2, the NPV benefits from enhanced energy management capabilities provided by the BESS. However, the initial costs associated with integrating the BESS result in a higher overall investment, which extends the PP compared to Scenario-1. This longer payback period suggests that the hybrid system takes more time to recover its costs, reflecting the increased complexity and expense of incorporating energy storage solutions.

Despite the advantages of improved energy management and grid stability with Scenario-2, the IRR is lower than that of Scenario-1. The additional costs and risks associated with the BESS contribute to this reduced IRR. While Scenario-1 relies solely on wind energy sales, Scenario-2 offers optimized energy usage and potential revenue enhancement through better grid integration. Furthermore, BESS integration enhances the flexibility of renewable energy sources, facilitating their integration into broader energy systems, which not only improves economic performance but also supports long-term environmental sustainability. This increased stability and cleaner energy production may align with sustainable energy development goals. Nevertheless, the trade-off between higher initial costs and longer payback periods versus the potential for increased long-term revenue and stability must be carefully considered when evaluating the overall financial viability of each scenario.

IV. DISCUSSION

The comparative analysis of two renewable energy investment scenarios—one involving wind turbines alone and the other combining wind turbines with a BESS—reveals distinct differences in their economic and operational performances. Scenario 1, which solely utilizes wind turbines, demonstrates superior economic feasibility with a NPV of 422,516,000.71 TL, an IRR of 17.62%, and a relatively short PP of 6 years. The lower CAPEX of 673,500,000 TL and annual OPEX of 30,000,000 TL contribute to this favorable outcome. The financial performance in this scenario is largely driven by the direct sale of wind-generated electricity, which enables quicker recovery of the initial investment and higher overall returns.

Conversely, Scenario 2, which integrates a 30 MW/30 MWh BESS with the wind power system, exhibits a more complex economic profile. Although the inclusion of BESS enhances the system's operational flexibility by allowing energy storage and optimized power dispatch, it results in a lower NPV of 139,955,702.94 TL and a reduced IRR of 12.00%. Additionally, the Payback Period extends to 8 years, reflecting the impact of a higher CAPEX of 899,220,000 TL and a slight increase in OPEX to 30,141,075 TL. The incorporation of BESS introduces benefits such as increased grid stability, energy arbitrage potential, and improved reliability of power supply. However, these operational advantages are offset by the substantial initial costs and ongoing operational expenses, leading to a less attractive financial outcome compared to the wind-only scenario.

V. CONCLUSION

In conclusion, while the integration of BESS with wind turbines offers enhanced operational benefits, particularly in terms of energy management and grid stability, it does not provide the same level of economic return as a standalone wind power system under the current economic parameters. The decision to invest in either configuration should be informed by specific investment goals, risk assessments, and future market conditions, including potential regulatory incentives and advancements in storage technologies. These findings highlight the need for a balanced approach when considering the trade-offs between capital investment, operational flexibility, and economic returns in renewable energy projects, especially in the context of evolving electricity markets and policy frameworks. Additionally, it is essential to consider cost reduction, revenue-enhancing strategies, potential government incentives and improving metrics through strategies such as increasing battery capacity or efficiency, optimizing energy sale prices, and implementing additional revenue models could be beneficial.

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Authors' Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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