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An Arbitrage Study with Wind-Solar-BESS Hybrid Power Plant

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Anahtar Kelimeler

Batarya Enerji Depolama Sistemleri (BEDS)
Enerji Arbitrajı
Enerji Depolama
Melez Enerji Sistmleri

Graphical/Tabular Abstract (Grafik Özet)

This study analyzes the economic feasibility of integrating a Battery Energy Storage System (BESS) into a wind-solar hybrid power plant in Türkiye, demonstrating that energy arbitrage enhances profitability with an 8-year amortization period. / Bu çalışma, Türkiye'de bir rüzgar-güneş hibrit santraline BESS entegrasyonunun ekonomik uygulanabilirliğini analiz etmekte ve enerji arbitrajının 8 yıllık geri ödeme süresi ile kârlılığı artırdığını göstermektedir.

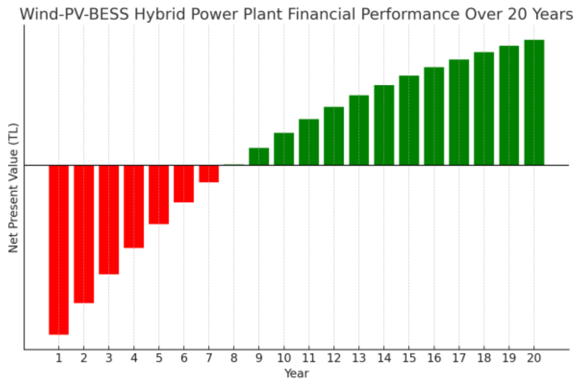

***Figure A**: Wind-Solar-BESS Hybrid Power Plant Financial Performance Over 20 Years /*
***Şekil A**:. Rüzgar-Güneş-BEDS Melez Güç Santrali 20 Yıllık Finansal Performansı*

Highlights (Önemli noktalar)

- *The integration of a Battery Energy Storage System (BESS) with a hybrid wind-solar power plant enhances profitability by enabling energy arbitrage. / Batarya Enerji Depolama Sistemi (BESS) ile hibrit rüzgar-güneş santralinin entegrasyonu, enerji arbitrajı yoluyla kârlılığı artırmaktadır.*
- *Market Clearing Price (MCP) analyses indicate that storing energy during low-price hours and selling during peak-price hours optimizes financial returns. / Piyasa Takas Fiyatı (PTF) analizleri, düşük fiyatlı saatlerde enerji depolamanın ve yüksek fiyatlı saatlerde satış yapmanın finansal getirileri optimize ettiğini göstermektedir.*
- *A one-year analysis of arbitrage scenarios resulted in an additional revenue of 5,872,081 TL, with an overall impact of 1.81%. / Bir yıllık arbitraj senaryoları analizi, 5.872.081 TL ek gelir sağlamış ve toplamda %1,81'lik bir etki yaratmıştır.*
- *Net Present Value (NPV) analysis confirms an amortization period of 8 years for the 40 MWh BESS. / Net Bugünkü Değer analizi, 40 MWh BESS için 8 yıllık bir amortisman süresini doğrulamaktadır.*

Aim (Amaç): *This study aims to analyze the economic impact of integrating a BESS into a wind-solar hybrid power plant for energy arbitrage in Türkiye. / Bu çalışma, Türkiye'de bir rüzgar-güneş hibrit santraline BESS entegrasyonunun enerji arbitrajı açısından ekonomik etkisini analiz etmeyi amaçlamaktadır.*

Originality (Özgünlük): *This research provides one of the first detailed analyses of BESS-based arbitrage in Türkiye's hybrid renewable energy market. / Bu çalışma, Türkiye'nin hibrit yenilenebilir enerji piyasasında BESS tabanlı arbitraj üzerine yapılan ilk detaylı analizlerden birini sunmaktadır.*

Results (Bulgular): *The study demonstrates that arbitrage with a BESS increases the profitability of hybrid power plants, with revenue gains varying by season. / Çalışma, BESS ile yapılan arbitrajın hibrit enerji santrallerinin kârlılığını artırdığını ve gelir artışlarının mevsimsel olarak değiştiğini göstermektedir.*

Conclusion (Sonuç): *Integrating BESS into hybrid wind-solar power plants in Türkiye proves economically viable, with a payback period of 8 years and a positive revenue impact. / Türkiye'de hibrit rüzgar-güneş santrallerine BESS entegrasyonu ekonomik olarak uygulanabilir olup, 8 yıllık geri ödeme süresi ve olumlu bir gelir etkisi sağlamaktadır.*

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An Arbitrage Study with Wind-Solar-BESS Hybrid Power Plant

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Abstract

Today, the demand for energy is increasing due to reasons such as technological advancements, population growth, industrialization, and globalization. The insufficiency and exhaustibility of fossil resources are enhancing the use and importance of renewable energy sources. Hybrid energy systems have been developed to make better use of renewable energy sources. Solutions that effectively employ several sources are known as hybrid systems. In many areas with sufficient potential for wind and solar energy, the implementation of hybrid energy systems is of great importance. In this study, under the conditions in Türkiye, scenarios will be examined in which a battery energy storage system (BESS) is installed in a wind-solar hybrid power plant. The scenarios involve storing energy during hours when energy prices are low and selling both the production from the hybrid plant and the energy stored in the BESS to the electricity market during hours when energy prices are high. It is shown that, the integration of the BESS significantly enhanced the profitability of the hybrid power plant, yielding an additional 5,872,081 TL in revenue over nearly a year, with an overall revenue impact of 1.81%. Specifically, the BESS contributed 1,745,374 TL in summer (2.11% impact), 1,420,917 TL in autumn (1.54%), 1,814,786 TL in winter (2.15%), and 891,004 TL in spring for just 2 months (1.38%). With a 20-year battery lifespan, the Net Present Value (NPV) analysis confirms an 8-year amortization period.

Rüzgâr-Güneş-BEDS Melez Güç Santrali ile Bir Arbitraj Çalışması

Makale Bilgisi

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Öz

Günümüzde teknolojik gelişmeler, nüfus artışı, sanayileşme ve küreselleşme gibi faktörler nedeniyle enerji talebi artmaktadır. Fosil kaynakların yetersizliği ve tükenebilirliği, yenilenebilir enerji kaynaklarının kullanımını ve önemini artırmaktadır. Yenilenebilir enerji kaynaklarının daha verimli kullanılmasını sağlamak amacıyla melez enerji sistemleri geliştirilmiştir. Birden fazla kaynağın etkin bir şekilde kullanıldığı çözümler melez sistemler olarak adlandırılmaktadır. Rüzgâr ve güneş enerjisi potansiyelinin yeterli olduğu birçok bölgede melez enerji sistemlerinin uygulanması büyük önem taşımaktadır. Bu çalışmada, Türkiye koşulları altında, bir rüzgâr-güneş melez enerji santraline batarya enerji depolama sistemi (BEDS) entegrasyonu senaryoları incelenmiştir. Senaryolar, enerji fiyatlarının düşük olduğu saatlerde enerjinin depolanması ve melez santral üretimi ile birlikte BEDS'te depolanan enerjinin, enerji fiyatlarının yüksek olduğu saatlerde elektrik piyasasına satılmasını içermektedir. Çalışma sonucunda, BEDS entegrasyonunun melez santralin kârlılığını önemli ölçüde artırdığı gösterilmiş, yaklaşık bir yıl içinde ek 5.872.081 TL gelir elde edilmiş ve toplam gelir üzerinde %1,81 oranında bir etki sağlanmıştır. Özellikle BEDS'in katkısı yaz aylarında 1.745.374 TL (%2,11), sonbaharda 1.420.917 TL (%1,54), kış aylarında 1.814.786 TL (%2,15) ve ilkbaharda yalnızca 2 ayda 891.004 TL (%1,38) olarak gerçekleşmiştir. Yirmi yıllık batarya ömrü dikkate alındığında, Net Bugünkü Değer (NPV) analizi, 8 yıllık bir amortisman süresini doğrulamaktadır.

1. INTRODUCTION (GİRİŞ)

According to the report by the International Energy Agency (IEA), while the world currently has a primary energy demand expressed as 14 million tons of oil equivalent (Mtoe), this demand is expected to increase by 45% over the next 20 years, reaching 20.3 billion Mtoe [1-3]. The depletion of fossil fuel energy sources, their environmental impacts, and concerns over global warming have led the world to seek innovative energy sources. Developing countries are increasing their interest in renewable energy sources to reduce their dependency on external energy. Renewable energy sources are becoming increasingly attractive due to their environmental friendliness and inexhaustibility compared to fossil fuels. According to statistical data, the average annual increase in

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demand for renewable energy over the past fifty years is approximately five times higher compared to other energy sources [4].

Although each country's energy demand varies, the global demand for energy is increasing year by year [1]. Türkiye's installed capacity has also increased over the years, in line with the global trend. While Türkiye's installed capacity has increased over the years, there has also been an increase in installed capacity by primary sources [5]. This increase in installed power capacity has been rapid due to factors such as the rise in private sector investments, the removal of bureaucratic barriers, the provision of necessary incentive mechanisms, the reduction of energy dependency, and government policies, and it is expected to continue to increase in the future. In the Turkish National Energy Plan report by the Ministry of Energy and Natural Resources, it is stated that the share of renewable energy sources is projected to gradually increase to 61.4% by 2053, within the forecasts for 2035-2053 [6].

The Regulation on Storage Activities in the Electricity Market, published in the Official Gazette on May 9, 2021, and numbered 31479, has paved the way for storage investments in Türkiye [7]. Within the scope of the regulation, a total of 5,968 pre-license applications for wind and solar with storage, exceeding 260,000 MW in installed capacity, were received for the 2023-2028 connection capacities announced by TEIAS. Regulation on Storage Activities in the Electricity Market states, "The amount of energy that integrated electricity storage units within power plants with storage-based electricity generation facilities will provide to the system on a settlement period basis cannot exceed the production amount that can be made with the electrical installed capacity stated in the license of the power plant". While the storage of electrical energy is beneficial, it also presents a high-cost investment. Since there is no precedent in Türkiye, our study has been concluded based on the assumption that a BESS installation suitable for the example hybrid energy system and the clause stating that it will not exceed the existing installed capacity in the regulation has been made.

A hybrid power plant is a facility where two or more power generation plants provide energy to the grid together. Renewable energy sources, due to generating energy from natural phenomena, cannot provide continuous and uninterrupted energy supply to the system. In wind turbines, since the wind does not blow at the same speed and direction continuously, electricity production will not be the same every hour at the existing capacity. In solar power plants, solar radiation will not be provided consistently to the grid due to various parameters such as the angle of sunlight, sunshine durations, day and night conditions, and summer and winter variations.

In today's world, due to high energy demand, studies on storing energy and supplying it to the grid from this storage system when needed are increasing both in Türkiye and globally. Especially the irregularity of energy produced from renewable sources has highlighted the necessity of providing energy to the grid in a more regular and suitable manner. While a wind power plant has the capacity to generate electricity even when it is not needed, instead of cut-off the plant and decreasing the energy production, storing it in a BESS during non-essential times and supplying it to the grid when needed would be a more optimal solution.

Energy arbitrage involves purchasing electricity during periods of low prices and selling it when prices are high. Specifically, the Battery Energy Storage System (BESS) is charged during times of low demand, leading to lower prices, and discharged during periods of high demand, which results in higher prices. This service relies on the BESS to store energy for extended periods [8]. Consequently, BESS can provide benefits both to the system owner and the grid by mitigating high electricity prices by supplying energy during peak demand periods, which typically correspond to higher energy costs [9].

The suitability of different Energy Storage System (ESS) types varies based on the specific application. For instance, the effectiveness of various storage methods may depend on the timescale of storage (short-term versus long-term) and the energy return on investment. [10] Lithium-ion batteries are generally the most suitable type of BESS for arbitrage due to several key factors [11]. They have a high energy density, allowing them to store more energy compared to other battery types and feature a more compact design [12]. Additionally, their long cycle life enables them to withstand numerous charge-discharge cycles, making them more economical in the long run [13]. Lithium-ion batteries also offer high efficiency in energy conversion processes, which aids in achieving greater profits from arbitrage strategies [14]. Their fast charging and discharging capabilities allow them to quickly respond to rapid price changes in the energy market, making them ideal for arbitrage [15]. Furthermore, they are flexible and suitable for both small and large-scale energy storage projects, with applications across various scenarios. These attributes make lithium-ion batteries the most advantageous option for arbitrage applications. In this study Li-ion battery type is preferred to integrate to the hybrid power plant. However, investment decisions should always consider project requirements, cost analysis, and long-term strategic goals.

One of the main challenges in integrating renewable energy into the power system is its inconsistency and variability due to weather conditions. Solar energy production fluctuates with sunlight, while wind energy varies with wind speed, leading to irregular power output. BESS for energy arbitrage provide a crucial solution by enabling the purchase of electricity at low prices and its sale at high prices. This approach maximizes economic benefits, supports grid stability, and enhances the integration of solar and wind energy sources. Many researches have been made recently with the common aim of demonstrating the positive effects of BESS on energy arbitrage. In [16] techno-economic analysis of a grid-scale battery providing energy arbitrage is performed. By applying a cycle-counting degradation model, they found that battery degradation significantly impacts the profitability of BESS, leading to a yearly net profit reduction in the range of 13–24%. In [17], a grid-connected hybrid energy system was designed to meet the electricity needs of the industrial zone in İzmir. Considering annual emission values and unit electricity cost criteria, it was concluded that the most efficient system is the battery-integrated hybrid energy system design. The system design reduced the unit electricity cost to $0.0730 and decreased annual emission values related to electricity consumption by 82%. In [18] different arbitrage strategies from the literature, such as seasonal, statistical, and neural networks-based models are compared for Colombian electricity market. In the study conducted by Hu et al, the aim was to analyze the potential utilization of BESS in the major European electricity markets. According to their results battery systems with a 1 MWh capacity are currently not feasible for energy arbitrage in European electricity markets. [19]. In [20], it is demonstrated that participating in the Single Electricity Market (SEM) alone is not profitable for BESS on the island of Ireland. However, the proposed methodology under a stacked revenues arrangement can enhance BESS revenues. This study aims to explore the benefits of BESS arbitrage within Türkiye's specific conditions and regulatory framework. The contribution of this study is its pioneering research on energy arbitrage in Türkiye using solar, wind, and BESS. It provides practical information for BESS arbitrage by leveraging Türkiye's energy market regulations. The study delivers a comprehensive analysis of integrating solar and wind energy with BESS for effective energy arbitrage, assessing the economic benefits specific to Türkiye's energy market. This research will benefit various stakeholders by enhancing revenue opportunities for energy producers, informing regulatory authorities on supportive frameworks, improving reliability and potentially reducing costs for energy consumers, offering investment insights to investors.

2. EXAMINATION OF TÜRKİYE MARKET CLEARING PRICES (MCP) (TÜRKİYE PİYASA TAKAS FİYATLARININ (PTF) İNCELENMESİ)

In the study, it is assumed that a hybrid power plant with 44.4 MW wind energy, 40 MW solar energy, and an 80 MW battery energy storage system is established under the conditions in Türkiye. An arbitrage study will be applied to the hybrid power plant to examine its effects on costs. According to the regulation, the amount of energy provided from the BESS cannot exceed the total installed capacity of wind and solar power stated in the power plant's license, so a BESS with the same installed capacity as the existing hybrid power plant is chosen. All calculations in the continuation of the study are based on these installed capacities.

Firstly, the production trend of the hybrid power plant is examined. The energy data for the PV-Wind hybrid power plant system, downloaded from Türkiye open-source electricity market transparency platform, is shown in Figure 1 [21]. A sample production graph for 3 months is shown below. The production of the solar power plant starts at 07:00, reaches its peak at 12:00, and then decreases until 18:00. The production graph of the wind power plant, on the other hand, does not show significant fluctuations, and it is determined that it provides stable production.

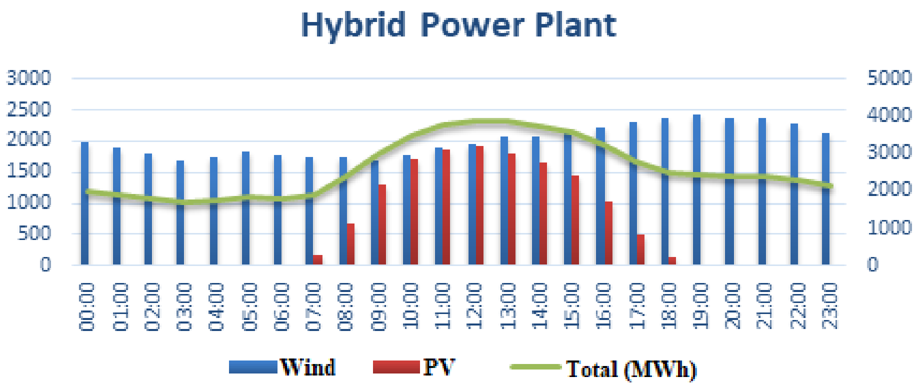

Figure 1. An Example of a Hybrid Power Plant Production Graph (Melez Bir Güç Santraline Ait Üretim Grafiği Örneği)

Secondly, an analysis of market clearing prices was conducted. An essential factor in executing energy arbitrage is predicting future market behavior to maximize potential profits. As seen in Figure 2, prices in the free market are always higher during peak hours [22]. This is due to the high level of demand between 18:00 and 23:00, when energy consumption from industrial and commercial establishments is complemented by household energy demand. Daytime and nighttime prices are relatively close to each other, with one sometimes being slightly lower or higher than the other.

Based on the analyses, it is forecasted the hours during which the energy produced over a four-month period should be stored and the hours during which it should be sold [22]. (Figure 2) By storing the energy produced during the day or night and selling both the generated and stored energy during high-demand hours, it is possible to maximize profits. To support the argument mentioned above, average energy prices since 2019 have been examined, broken down by daytime, peak, and night periods. In Figure 3, it is observed that in 2019, unlike in previous years, the prices during the peak period exceeded the average daytime prices [22]. Nighttime prices remained below both the daytime and peak period prices.

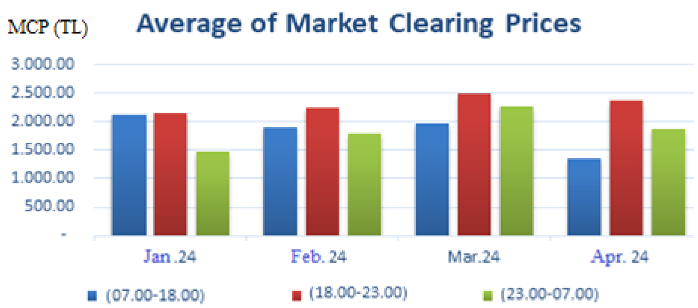

Figure 2. EPIAS, Market Clearing Prices Day-Peak-Night Price Formation Examination (EPİAŞ Piyasa Takas Fiyatları (PTF) Gündüz-Tepe-Gece Fiyat Oluşumunun İncelenmesi)

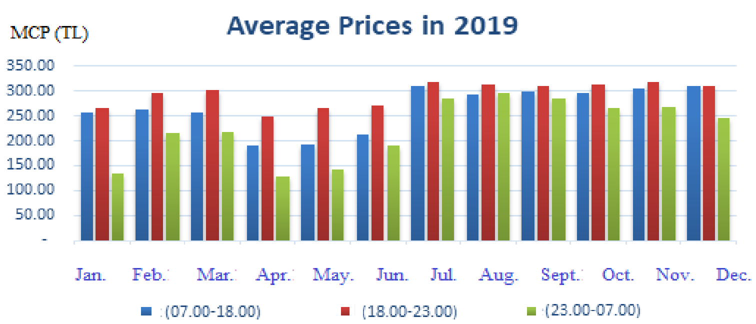

Figure 3. Average Market Clearing Prices in 2019 received from EPIAS Transparency Platform (2019 Yılı Ortalama Piyasa Takas Fiyatları (PTF) – EPİAŞ Şeffaflık Platformu Verileri)

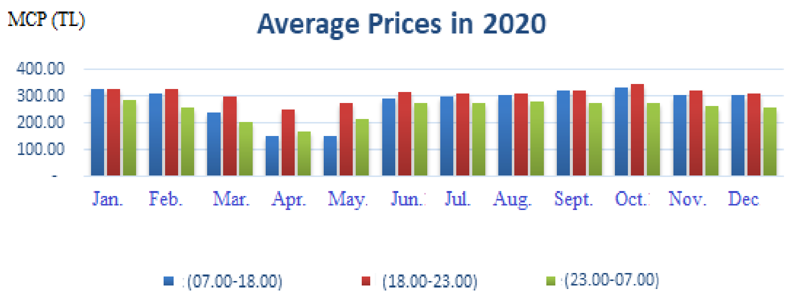

Figure 4. Average Market Clearing Prices in 2020 received from EPIAS Transparency Platform (2020 Yılı Ortalama Piyasa Takas Fiyatları (PTF) – EPİAŞ Şeffaflık Platformu Verileri)

In Figure 4, the effect observed in 2019 is also seen in 2020 [22]. Peak period prices exceeded the average daytime prices, while nighttime prices remained below both the daytime and peak period prices. However, due to the impact of the pandemic in 2020, nighttime prices were observed to be higher than daytime prices. Nonetheless, peak period prices were higher than both daytime and nighttime prices.

In Figure 5, the impact of the pandemic is also observed in 2021 [22]. However, starting from the summer months, increases in energy demand, inflation, and exchange rates led to a rise in energy prices. Nonetheless, the primary area of focus is the consistent pattern of high peak prices and low nighttime prices, supporting the above argument. Therefore, storing energy at night and selling it during peak hours will maximize profits.

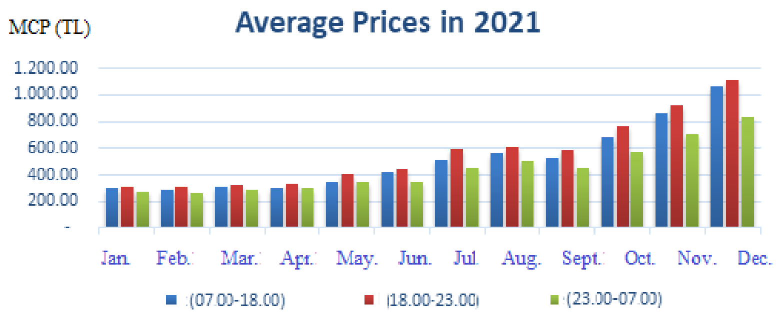

Figure 5. Average Market Clearing Prices in 2020 received from EPIAS Transparency Platform (2021 Yılı Ortalama Piyasa Takas Fiyatları (PTF) – EPİAŞ Şeffaflık Platformu Verileri)

In Figure 6, the global impacts, and inflationary pressures in 2022 led to even higher energy prices [22]. Despite this, as seen in the graph, daytime prices remain lower than peak period prices. Nighttime prices are consistently the lowest.

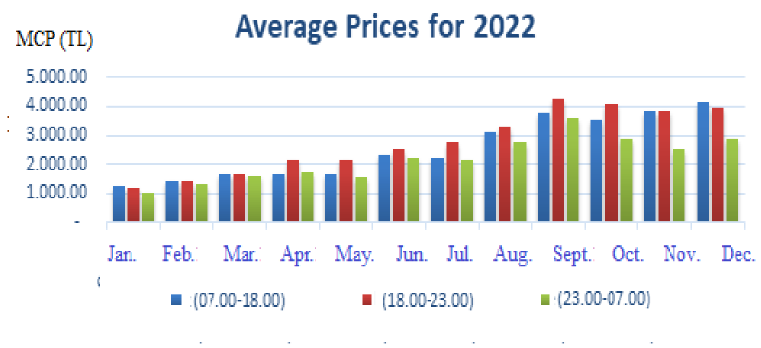

Figure 6. Average Market Clearing Prices in 2022 received from EPIAS Transparency Platform (2022 Yılı Ortalama Piyasa Takas Fiyatları (PTF) – EPİAŞ Şeffaflık Platformu Verileri)

In Figure 7, the resolution of the crisis in natural gas power plants in 2023 led to a relaxation in prices [22]. However, as always, nighttime prices remain low, and peak period prices are high.

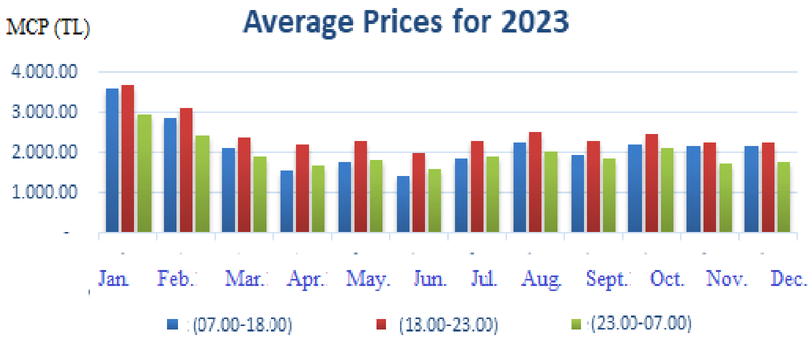

Figure 7. Average Market Clearing Prices in 2023 received from EPIAS Transparency Platform (2023 Yılı Ortalama Piyasa Takas Fiyatları (PTF) – EPİAŞ Şeffaflık Platformu Verileri)

When looking at the daytime-peak-night prices in Figure 8 in past years, nighttime prices are always low, while peak period prices are high [22]. Therefore, storing energy generated at night and selling it during peak hours will maximize profits. Energy storage and sales scenarios will be developed accordingly.

In Figure 8 the average production of the hybrid plant is shown for daytime-peak-night hours [22]. It is evident that the consumption during daytime hours is always higher when considering wind and solar production. Based on this, it can be assumed that a portion of daytime production and all or part of nighttime production can be stored in the BESS, taking advantage of lower prices. Consequently, during peak hours when prices are high, both energy sales from the BESS and production from the plant can be sold to the electricity market.

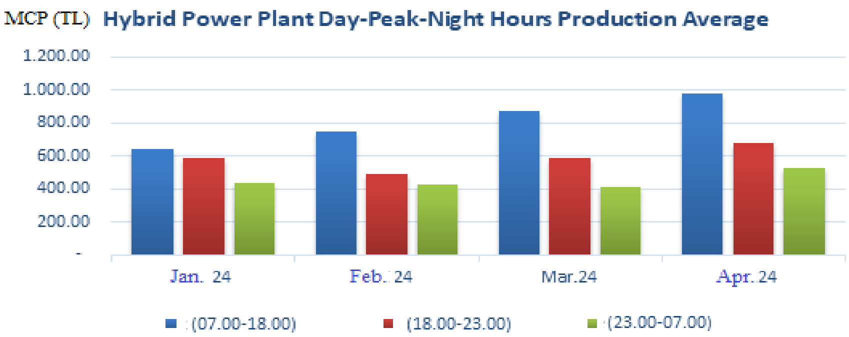

Figure 8. Daytime-peak-night Electricity Prices of 2024 (2024 Yılı Gündüz-Tepe-Gece Elektrik Fiyatları)

3. HYBRID ENERGY POWER PLANT ARBITRAGE SCENARIOS (MELEZ ENERJI SANTRALI ARBITRAJ SENARYOLARI)

According to the arbitrage scenarios, the energy produced during the hours when the power plant operates at lower costs will be stored in the BESS instead of being sold to the market. During the peak hours, defined as 18:00 - 23:00, the stored energy will be sold. The storage process will begin at midnight when the prices are relatively lower. Depending on the production of the hybrid plant, which consists of wind and solar power, the charging time for the BESS will be determined, typically being 2 hours or longer. The assumed installed capacity of the hybrid plant is 44.4 MW for wind and 40 MW for solar. Batteries will primarily be charged with wind energy overnight, but in cases where wind power is insufficient, the charging process will continue throughout the day with the contribution of solar power. In this study, a degradation-unaware model has been used for the BESS. As a result, the effects of degradation from rapid charging/discharging required for like frequency support, as well as the impact of temperature changes on battery life, have not been considered. Battery efficiencies were selected based on the literature on battery technologies in general [23,24]. Fantham's experimental calculations of efficiency using the Open Circuit Voltage (OCV) method for batteries in a 2 MW BESS system found an average efficiency of 95.9934% for lithium batteries [25]. In [15] which included energy arbitrage, the efficiency of lithium batteries was estimated to be around 90% based on various references. The calculations will be as follows:

- Starting from midnight, the BESS will begin to charge, and the energy produced by the hybrid plant will not be sold to the market until the BESS is fully charged at 80 MW. The excess energy will be sold to the market.
- The stored energy in the BESS will be sold to the market during the peak hours (18:00 - 23:00) with a 90% efficiency rate.
- No energy will be sold to the market while the BESS is being charged.

Battery Charge Status = Previous Charge Status + Charged Energy-Produced Energy (1)

Energy Stored in the Battery = (Charged Energy×Efficiency)×Charging Time (2)

Where, previous charge status means the charge status of the BESS in the previous hour, charged energy means the amount of energy charged by the power plant, produced energy represent the amount of energy produced by the hybrid plant, efficiency is taken as the efficiency of energy storage in the BESS, charging time is account for the time taken to charge the BESS in (1) and (2). While energy is stored in the BESS, there will be no sales to the market in (3) and (4). Sales from the BESS will be calculated with (5) during peak hours.

$$\text{Total Revenue}_1 = \text{Total Production x MCP} \quad (3)$$

$$\text{Total Revenue}_2 = (\text{Total Production} - \text{Energy Stored in Battery}) \text{ x MCP} \quad (4)$$

Battery Energy Revenue = Energy Stored in Battery x MCP (5)

Table 1. An arbitrage scenario for January 3, 2024. (3 Ocak 2024 tarihine ait bir arbitraj senaryosu)

Hour	Total Energy (MWh)	Wind	PV	Batt. Char -ge	Batt. Disch-arge	MCP (TL/ MWh)	Total Revenue (TL)	Total Revenue -BESS	Batt. Revenue (TL)
00:00	-	-	-	-		2,325.00	-	-	-
01:00	4.76	4.76	-	4.76		2,248.00	10,700.48	-	-
02:00	1.23	1.23	-	1.23		2,188.00	2,691.24	-	-
03:00	4.03	4.03	-	4.03		2,188.00	8,817.64	-	-
04:00	1.25	1.25	-	1.25		2,098.00	2,622.50	-	-
05:00	1.98	1.98	-	1.98		1,449.98	2,870.96	-	-
06:00	8.14	8.14	-	8.14		1,349.99	10,988.92	-	-
07:00	3.87	3.87	-	3.87		2,110.66	8,168.25	-	-
08:00	4.69	3.29	1.40	4.69		2,649.00	12,423.81	-	-
09:00	15.40	-	15.40	15.40		2,690.02	41,426.31	-	-
10:00	15.40	-	15.40	15.40		2,379.99	36,651.85	-	-
11:00	28.38	-	28.38	19.25		2,288.00	64,933.44	20,889.44	-
12:00	30.75	-	30.75			1,349.99	41,512.19	41,512.19	-
13:00	30.74	-	30.74			1,449.99	44,572.69	44,572.69	-
14:00	27.61	-	27.61			2,146.78	59,272.60	59,272.60	-
15:00	24.50	4.20	20.30			2,288.01	56,056.25	56,056.25	-
16:00	24.14	11.64	12.50			2,380.00	57,453.20	57,453.20	-
17:00	22.19	20.33	1.86			2,600.00	57,694.00	57,694.00	-
18:00	31.12	31.12	-		14.40	2,594.00	80,725.28	80,725.28	37,353.60
19:00	36.34	36.34	-		14.40	2,299.98	83,581.27	83,581.27	33,119.71
20:00	35.31	35.31	-		14.40	1,968.00	69,490.08	69,490.08	28,339.20
21:00	38.11	38.11	-		14.40	2,288.01	87,196.06	87,196.06	32,947.34
22:00	36.62	36.62	-		14.40	2,185.01	80,015.07	80,015.07	31,464.14
23:00	26.82	26.82	-			1,998.00	53,586.36	53,586.36	-
							973,450.44	792,044.49	163,224.00
								Profit and Loss	**- 18,181.96**

In Scenario 2, the date March 4, 2024, was examined in Table 2. Due to the low energy production of the hybrid plant, the BESS was charged until 11:00, and no energy was sold to the market. When this stored energy was sold to the system during peak hours, a loss of 11,054,38 TL was incurred. If this energy had been sold directly to the system without being stored, this loss would not have occurred.

Table 2. An arbitrage scenario for March 4, 2024 (4 Mart 2024 tarihine ait bir arbitraj senaryosu)

Hour	Total Energy (MWh)	Wind	PV	Batt. Char-ge	Batt. Dis-charge	MCP (TL/ MWh)	Total Revenue (TL)	Total Revenue -BESS	Batt. Revenue (TL)
00:00	2.64	2.64	-	2.64		2,200.01	5,808.03	-	-
01:00	2.57	2.57	-	2.57		2,245.00	5,769.65	-	-
02:00	1.90	1.90	-	1.90		2,278.98	4,330.06	-	-
03:00	0.38	0.38	-	0.38		2,200.00	836.00	-	-
04:00	-	-	-	-		2,100.00	-	-	-
05:00	-	-	-	-		2,243.00	-	-	-
06:00	-	-	-	-		2,278.99	-	-	-
07:00	0.86	-	0.86	0.86		2,300.00	1,978.00	-	-
08:00	8.60	-	8.60	8.60		2,690.00	23,134.00	-	-
09:00	19.22	-	19.22	19.22		2,612.12	50,204.95	-	-
10:00	27.09	-	27.09	27.09		2,340.28	63,398.19	-	-
11:00	25.37	-	25.37	16.74		2,393.91	60,733.50	20,659.44	-
12:00	19.80	0.94	18.86			2,098.99	41,560.00	41,560.00	-
13:00	15.97	1.29	14.68			2,199.00	35,118.03	35,118.03	-
14:00	6.95	0.93	6.02			1,997.18	13,880.40	13,880.40	-
15:00	17.31	-	17.31			2,097.00	36,299.07	36,299.07	-
16:00	17.13	-	17.13			2,278.98	39,038.93	39,038.93	-
17:00	2.74	-	2.74			2,549.01	6,984.29	6,984.29	-
18:00	0.47	-	0.47		14.40	2,649.01	1,245.03	1,245.03	38,145.74
19:00	-	-	-		14.40	2,690.00	-	-	38,736.00
20:00	0.08	0.08	-		14.40	2,690.00	215.20	215.20	38,736.00
21:00	2.17	2.17	-		14.40	2,502.00	5,429.34	5,429.34	36,028.80
22:00	2.28	2.28	-		14.40	2,280.00	5,198.40	5,198.40	32,832.00
23:00	4.48	4.48	-			2,186.00	9,793.28	9,793.28	-
							410,954.34	215,421.42	184,478.54
								Profit and Loss	**- 11,054.38**

In the third scenario, the date June 6, 2023, was examined in Table 3. Due to high energy production by the BESS at 00:00 and 01:00, it was fully charged within 2 hours. When this stored energy was sold to the system during peak hours, a loss of 31,119.28 TL was incurred. If this energy had been sold directly to the system without being stored, this loss would not have occurred. Upon examining the cause of the loss, it can be observed that the MCP during the charging periods was 2,188.22 TL and 2,059.08 TL, while the prices during the sales were 1,699.99, 1,775.01, 2,134.28, 2,299.98, and 1,756.97 respectively, resulting in selling energy to the market at lower prices.

Table 3. An arbitrage scenario for June 6, 2023. (6 Haziran 2023 tarihine ait bir arbitraj senaryosu)

Hour	Total Energy (MWh)	Wind	PV	Batt. Char-ge	Batt. Dis-charge	MCP (TL/ MWh)	Total Revenue (TL)	Total Revenue -BESS	Batt. Revenue (TL)
00:00	43.26	43.26	-	43.26		2,188.22	94,662.40	-	-
01:00	42.56	42.56	-	36.74		2,059.08	87,634.44	11,983.85	-
02:00	43.25	43.25	-			1,600.00	69,200.00	69,200.00	-
03:00	43.31	43.31	-			1,133.60	49,096.22	49,096.22	-
04:00	43.31	43.31	-			1,600.00	69,296.00	69,296.00	-

05:00	39.92	39.92	-			1,348.99	53,851.68	53,851.68	-
06:00	31.86	31.86	-			1,133.60	36,116.50	36,116.50	-
07:00	42.92	42.92	-			1,000.00	42,920.00	42,920.00	-
08:00	44.35	44.35	-			1,349.00	59,828.15	59,828.15	-
09:00	44.98	44.98	-			1,700.00	76,466.00	76,466.00	-
10:00	45.48	45.48	-			1,249.99	56,849.55	56,849.55	-
11:00	45.48	45.48	-			1,133.59	51,555.67	51,555.67	-
12:00	45.43	45.43	-			750.00	34,072.50	34,072.50	-
13:00	44.89	44.89	-			980.00	43,992.20	43,992.20	-
14:00	44.84	44.84	-			1,249.99	56,049.55	56,049.55	-
15:00	45.30	45.30	-			1,250.00	56,625.00	56,625.00	-
16:00	44.68	44.68	-			1,348.98	60,272.43	60,272.43	-
17:00	43.92	43.92	-			1,600.01	70,272.44	70,272.44	-
18:00	34.65	34.65	-		14.40	1,699.99	58,904.65	58,904.65	24,479.86
19:00	23.39	23.39	-		14.40	1,775.01	41,517.48	41,517.48	25,560.14
20:00	15.07	15.07	-		14.40	2,134.28	32,163.60	32,163.60	30,733.63
21:00	15.17	15.17	-		14.40	2,299.98	34,890.70	34,890.70	33,119.71
22:00	8.56	8.56	-		14.40	1,756.97	15,039.66	15,039.66	25,300.37
23:00	5.03	5.03	-			1,348.98	6,785.37	6,785.37	-
							1,258,062.19	1,087,749.19	139,193.71
								Profit and Loss	**- 31,119.28**

In Scenario 4, the date November 1, 2023, was examined in Table 4. The BESS was charged at 00:00 and 10:00. When this stored energy was sold to the system during peak hours, a profit of 10,831.09 TL was obtained. The fact that the MCP was 2700 TL during peak hours seems to have contributed to this additional profit. It appears that a higher price was obtained during peak hours compared to the price at which the BESS was charged during the night.

Table 4. An arbitrage scenario for November 1, 2023 (1 Kasım 2023 tarihine ait bir arbitraj senaryosu)

Hour	**Total Energy (MWh)**	**Wind**	**PV**	**Batt. Char -ge**	**Batt. Dis-charg e**	**MCP (TL/ MWh)**	**Total Revenue (TL)**	**Total Revenue -BESS**	**Batt. Revenue (TL)**
00:00	1.19	1.19	-	1.19		2,498.19	2,972.85	-	-
01:00	1.40	1.40	-	1.40		2,294.18	3,211.85	-	-
02:00	4.28	4.28	-	4.28		2,155.99	9,227.64	-	-
03:00	1.97	1.97	-	1.97		2,000.00	3,940.00	-	-
04:00	1.46	1.46	-	1.46		1,754.64	2,561.77	-	-
05:00	1.98	1.98	-	1.98		1,685.00	3,336.30	-	-
06:00	0.99	0.99	-	0.99		1,999.46	1,979.47	-	-
07:00	2.34	2.34	-	2.34		1,999.12	4,677.94	-	-
08:00	3.40	3.40	-	3.40		2,700.00	9.180,00	-	-
09:00	4.08	4.08	-	4.08		2,700.00	11,016.00	-	-
10:00	4.33	4.33	-	4.33		2,666.65	11,546.59	-	-
11:00	15.37	15.37	-	15.37		2,394.19	36,798.70	-	-
12:00	18.07	18.07	-	18.07		2,094.19	37,842.01	-	-
13:00	18.07	18.07	-	18.07		2,345.81	42,388.79	-	-
14:00	21.34	21.34	-	1.07		2,700.00	57,618.00	54,729.00	-
15:00	25.69	25.69	-			2,700.00	69,363.00	69,363.00	-
16:00	24.47	24.47	-			2,700.00	66,069.00	66,069.00	-
17:00	18.35	18.35	-			2,700.00	49,545.00	49,545.00	-
18:00	19.99	19.99	-		14.40	2,700.00	53,973.00	53,973.00	38,880.00

19:00	16.98	16.98	-		14.40	2,700.00	45,846.00	45,846.00	38,880.00
20:00	11.92	11.92	-		14.40	2,700.00	32,184.00	32,184.00	38,880.00
21:00	8.98	8.98	-		14.40	2,700.00	24,246.00	24,246.00	38,880.00
22:00	6.58	6.58	-		14.40	2,700.00	17,766.00	17,766.00	38,880.00
23:00	5.51	5.51	-			2,498.19	13,765.03	13,765.03	-
							611,054.94	427,486.03	194.400,00
								Profit and Loss	**10,831.09**

The data for the summer and autumn months of 2023 has been examined. Since the solar energy part of the hybrid power plant was put into operation from the middle of October, the contribution of solar energy production to the total revenue began to be realized from mid-October onwards.

4. RESULT ANALYSIS OF SEASONAL ENERGY ARBITRAGE (MEVSİMSEL ENERJİ ARBİTRAJI SONUÇ ANALİZİ)

A hybrid power plant's production data and the actual market prices were analyzed between June 1, 2023, and April 30, 2024. During this period, the BESS was charged during off-peak hours and discharged during peak hours. Below are the calculations for summer, autumn, winter, and spring in three-month periods, as well as an analysis of the calculations for the entire period. All calculations have been formulated and executed in MS Excel, which forms the basis for many programs used in energy calculations, such as RETScreen.

Table 5. Summer Season Energy Arbitrage Revenue (Yaz Mevsimi Enerji Arbitraj Geliri)

01.06.2023 – 31.08.2023 Total Revenue (Summer Season)		
Total Revenue with only from Wind-PV Hybrid Power Plant	82,681,377	
Total Revenue without BESS Charging		69,420,565
Total Revenue only from BESS		15,006,186
Total Revenue	82,681,377	84,436,752
Revenue Difference (TL)		1,745,374
Revenue Difference (%)		2.11%

In Table 5, covering the summer period from June 1, 2023, to August 31, 2023, the revenues from storing energy in the BESS and selling energy were calculated for all days. If there were no BESS system, and the hybrid plant sold the generated energy directly to the market, the revenue would have been 82,681,377 TL. The hybrid plant does not sell energy to the market during the hours when the BESS is being charged and only stores energy, resulting in a total revenue of 69,420,565 TL during the non-storage hours. The energy stored in the BESS during the low-price night hours and sold during the peak hours resulted in an additional revenue of 15,006,186 TL. This integration of the BESS created a total additional revenue of 1,745,374 TL for the given period. Therefore, the BESS had a positive revenue impact of 2.11%.

Table 6. Autumn Season Energy Arbitrage Revenue (Sonbahar Mevsimi Enerji Arbitraj Geliri)

01.09.2023 – 30.11.2023 Total Revenue (Autumn Season)		
Total Revenue with only from Wind-PV Hybrid Power Plant	92,197,827	
Total Revenue without BESS Charging		77,708,924
Total Revenue only from BESS		15,909,820
Total Revenue	92,197,827	93,618,744
Revenue Difference (TL)		1,420,917
Revenue Difference (%)		1.54%

In Table 6, covering the autumn period from September 1, 2023, to November 30, 2023, the revenues from energy storage and energy sales from the BESS were calculated for all days. If there were no BESS system, the revenue generated from selling energy to the market as produced by the hybrid plant would have been 92,197,827 TL. During the hours when the BESS is being charged, the hybrid plant will not sell energy to the market but only store it. Thus, the total revenue generated, excluding the hours when energy is not sold due to storage, amounts to 77,708,924 TL. Energy stored in the BESS during hours when night prices are low is sold to the system during peak hours, resulting in revenue of 15,909,820 TL. With the BESS, a total of 1,420,917 TL additional revenue was generated during this period. Therefore, the BESS had a positive revenue impact of 1.54%.

Table 7. Winter Season Energy Arbitrage Revenue (Kış Mevsimi Enerji Arbitraj Geliri)

01.12.2023 – 29.02.2024 Total Revenue (Winter Season)		
Total Revenue with only from Wind-PV Hybrid Power Plant	84,405,029	
Total Revenue without BESS Charging		71,500,233
Total Revenue only from BESS		14,719,582
Total Revenue	84,405,029	86,219,814
Revenue Difference (TL)		1,814,786
Revenue Difference (%)		2.15%

In Table 7, covering the winter period from December 1, 2023, to February 29, 2024, the revenues from energy storage in the BESS and energy sales from the BESS were calculated for all days. If there were no BESS system, the revenue generated from selling energy to the market as produced by the hybrid plant would have been 84,405,029 TL. The total revenue generated, excluding the hours when energy is not sold due to storage, amounts to 71,500,233 TL. Energy stored in the BESS during hours when night prices are low is sold to the system during peak hours, resulting in revenue of 14,719,582 TL. With the BESS, a total of 1,814,786 TL additional revenue was generated during this period. Therefore, the BESS had a positive revenue impact of 2.15%.

Table 8. Spring Season Energy Arbitrage Revenue (İlkbahar Mevsimi Enerji Arbitraj Geliri)

01.03.2023 – 30.04.2024 Total Revenue (Spring Season)		
Total Revenue with only from Wind-PV Hybrid Power Plant	64,506,015	
Total Revenue without BESS Charging		54,599,653
Total Revenue only from BESS		10,797,366
Total Revenue	64,506,015	65,397,019
Revenue Difference (TL)		891,004
Revenue Difference (%)		1.38%

In Table 8, covering the spring period from March 1, 2023, to April 30, 2024, the revenues from energy storage in the BESS and energy sales from the BESS were calculated for all days. If there were no BESS system, the revenue generated from selling energy to the market as produced by the hybrid plant would have been 64,506,015 TL. When the BESS system is integrated, during the hours when the BESS is being charged, the hybrid plant will not sell energy to the market but only store it. Thus, the total revenue generated, excluding the hours when energy is not sold due to storage, amounts to 54,599,653 TL. Energy stored in the BESS during hours when night prices are low is sold to the system during peak hours, resulting in revenue of 10,797,366 TL. With the BESS, a total of 891,004 TL additional revenue was generated during this period. Therefore, the BESS had a positive revenue impact of 1.38%. As of now, May 2024 has not yet been completed; only two months have been calculated.

Table 9. Total Energy Arbitrage Revenue (Toplam Enerji Arbitraj Geliri)

01.06.2023 – 30.04.2024 Total Revenue (Approximately One Year Period)		
Total Revenue with only from Wind-PV Hybrid Power Plant	323,790,248	
Total Revenue without BESS Charging		273,229,375
Total Revenue only from BESS		56,432,954
Total Revenue	323,790,248	329,662,329
Revenue Difference (TL)		5,872,081
Revenue Difference (%)		1.81%

In Table 9, covering approximately one year from June 1, 2023, to April 30, 2024, the revenues from energy storage in the BESS and energy sales from the BESS were calculated for all days. The total benefit amounted to 5,872,081 TL, resulting in a positive revenue impact of 1.81%.

When arbitrage through integrating the BESS into the hybrid plant was examined on selected days across four seasons, it was observed that both profits and losses occurred. The most significant factor was found to be related to market trading prices, whether low or high, along with the duration of charging spread across hours, affecting the potential for losses. These analyses were based on actual production and prices; thus, scenarios were employed in the study. However, other models for maximizing revenue, such as storing and selling at different prices or solely storing and participating in the Balancing Market on the following day, utilizing the dispatch center's available capacity, can also be explored, or implemented. Additionally, the seasonal effect, not often observed, was evident in this study where price was more influential. Instances of low production or maintenance periods of the plant were identified during the analyses.

5. ECONOMIC INDICATORS (EKONOMİK GÖSTERGELER)

This section begins by discussing the revenue generated solely from the BESS through arbitrage over approximately one year (from 2023 to 2024), as shown in Table 9 of the previous section, and proceeds to calculate the net present value (NPV) using the CAPEX (capital expenditure), which includes the investment cost of the BESS, and the OPEX (operational expenses), which covers the operation and maintenance expenses. This will allow us to evaluate the economic feasibility of the proposed system. The NPV is calculated using (6). Although CAPEX and OPEX values for BESS differ in various sources, they have been converted to Turkish Lira using the most recent exchange rate and based on the latest report published for Türkiye [26]. Table 10 provides an overview of the unit costs associated with the BESS. This summary includes key cost components such as CAPEX, OPEX, and other technical metrics relevant to the implementation and maintenance of the BESS.

Table 10. Unit Cost of the BESS System (BEDS Sisteminin Birim Maliyeti)

Technology	Lifetime	CAPEX(TL/kWh)	OPEX(TL/year)	Efficiency
Li-ion BESS	20 years	300960000.00	188100	0.90

The discount rate used in the NPV calculation is based on [27], with the value r taken as an average of 9.8%.

$$NPV = \sum_{t=1}^{n} \frac{Rt-Ct}{(1+r)^t} - CAPEX \quad (6)$$

Here R_t is the revenue in year t, C_t is the operating cost in year t, r is the discount rate, n is the project lifespan (20 years in this case).

To calculate the Net Present Value (*NPV*) for each year and determine the payback period for a system with a lifespan of 20 years, initial CAPEX of 300960000 TL, annual revenue of 56432954 TL, and given the OPEX of 188100 TL, the following assumptions were made.

-Discount Rate (r): 9.8%
-Revenue (R_t): 56,432,954 TL per year
-Operating Cost (C_t): 188100 TL per year
-Lifespan (n): 20 years
-CAPEX: 300960000TL

Table 11 presents the NPV calculations for each year is shown for 40 MWh BESS. The future value (FV) is calculated as total revenues minus OPEX. The year in which FV minus CAPEX becomes positive indicates the payback period.

Table 11. NPV Calculation (Net Bugünkü Değer Hesaplaması)

Year	BESS Revenue	BESS OPEX	BESS Revenue - BESS OPEX	BESS FV - BESS CAPEX (NPV)	$(1+r)^t$
1	56432954.00	188100.00	51224821.49	-249735178.51	1.10
2	56432955.00	188100.00	46652843.72	-203082334.79	1.21
3	56432956.00	188100.00	42488929.46	-160593405.32	1.32
4	56432957.00	188100.00	38696657.76	-121896747.57	1.45
5	56432958.00	188100.00	35242858.33	-86653889.24	1.60
6	56432959.00	188100.00	32097321.45	-54556567.79	1.75
7	56432960.00	188100.00	29232533.72	-25324034.07	1.92
8	56432961.00	188100.00	26623437.38	1299403.31	2.11
9	56432962.00	188100.00	24247211.16	25546614.47	2.32
10	56432963.00	188100.00	22083070.66	47629685.13	2.55
11	56432964.00	188100.00	20112086.57	67741771.70	2.80
12	56432965.00	188100.00	18317019.06	86058790.76	3.07
13	56432966.00	188100.00	16682167.02	102740957.78	3.37
14	56432967.00	188100.00	15193230.71	117934188.49	3.70
15	56432968.00	188100.00	13837186.68	131771375.17	4.06
16	56432969.00	188100.00	12602173.89	144373549.05	4.46
17	56432970.00	188100.00	11477389.90	155850938.95	4.90
18	56432971.00	188100.00	10452996.45	166303935.41	5.38
19	56432972.00	188100.00	9520033.37	175823968.77	5.91
20	56432973.00	188100.00	8670340.20	184494308.97	6.49

The following calculation in (7) was performed to determine the payback period (PP), where Y represents the years and X represents the FV-CAPEX value. The goal is to find Y (the payback period) when X is 0, which indicates that the investment is fully paid back [28].

$$Y = \frac{Y_2 - Y_1}{X_2 - X_1} * (X - X_1) + Y_1 \quad (7)$$

$$PP = \frac{8 - 7}{(1299403.31) - (-25324034.07)} * \big(0 - (-25324034.07)\big) + 7 = 7.9512 \text{ years}$$

Based on the calculations, it has been determined that the 40 MWh BESS system connected to the PV-wind hybrid system will amortize its cost in approximately 8 years solely through energy arbitrage. This indicates that the investment is economically viable, leveraging price fluctuations in the energy market effectively. The amortization period suggests that significant price volatility exists, allowing the system to profit from buying energy at low prices and selling it during peak periods. It also implies that the BESS system operates with high efficiency and minimal operational costs. An 8-year payback period is considered reasonable for energy investments, highlighting the project's financial attractiveness. One of the main reasons the amortization period is feasible for the investment is that the BESS does not purchase energy from the grid, as it obtains the necessary energy for charging from the solar-wind hybrid system. Additionally, this timeframe reflects favorable market conditions in Türkiye for energy arbitrage for high energy level BESSs.

6. CONCLUSIONS (SONUÇLAR)

In this study, the integration of a Battery Energy Storage System (BESS) with a photovoltaic and wind hybrid power plant in Türkiye for arbitrage purposes is examined, motivated by the Regulation on Storage Activities in the Electricity Market in Türkiye. The time intervals for arbitrage were determined by analyzing past market clearing prices. Estimated revenues were calculated for spring, summer, winter, and autumn using production data from the hybrid power plant within these determined time intervals. The integration of the BESS enhanced the hybrid power plant's profitability, generating a total additional revenue of 5,872,081 TL over nearly a year, with a positive revenue impact of 1.81%. Specifically, the BESS contributed 1,745,374 TL in summer (2.11% impact), 1,420,917 TL in autumn (1.54% impact), 1,814,786 TL in winter (2.15% impact), and 891,004 TL in spring for 2 months (1.38% impact). Additionally, for a 40 MWh battery with a 20-year lifespan, the Net Present Value (NPV) calculation indicates an amortization period of 8 years. BESS can be used for various applications, including grid frequency ancillary services, stabilizing fluctuating energy production, meeting additional energy demands, and utilizing dispatchable capacities. For effective arbitrage, management should focus on exploiting price differentials between daytime peaks and nighttime lows, storing energy during low-price periods, and selling energy during high-price periods.

This paper provides insights into the benefits of BESS arbitrage within Türkiye's specific conditions and regulatory framework. It represents one of the initial studies on energy arbitrage in Türkiye using solar, wind, and BESS technologies, offering practical insights into leveraging the country's energy market regulations. The study delivers a comprehensive analysis of integrating solar and wind energy with BESS, highlighting economic benefits. It is beneficial for stakeholders by enhancing revenue for energy producers, informing regulatory authorities, improving reliability and reducing costs for consumers, and offering investment insights.

Future research could explore the timing of arbitrage for profit maximization using artificial intelligence methods and extend the analysis to include battery degradation costs and optimization methods.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Eren GÜZ*:** Eren GÜZ: Contributed to methodology, performed the calculations, conducted the investigation, curated the data, and wrote the original draft of the manuscript.

Yönteme katkıda bulunmuş, hesaplamaları gerçekleştirmiş, araştırmayı yürütmüş, verileri düzenlemiş ve makalenin ilk taslağını yazmıştır.

Kübra Nur AKPINAR: Contributed to conceptualization and methodology, performed the calculations, and was responsible for writing – review & editing the manuscript.

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CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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