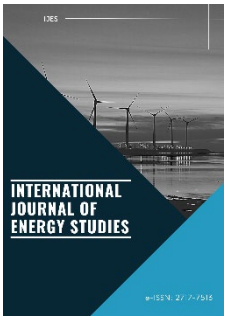
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Evaluating renewable energy investment flexibility under policy transition: A real options approach to YEKDEM reform in Türkiye

Duygu Bıyıklı [a*]

[a]*Kastamonu University, İhsangazi Vocational School, Department of Architecture and Urban Planning, Kastamonu, Turkey, ORCID : 0000-0002-0220-5101*

*(*Corresponding Author: dbiyikli@kastamonu.edu.tr)*

Highlights

- Evaluates the impact of Türkiye's transition from a USD-based to a TRY-based FiT (YEKDEM) on wind power investment timing and value using NPV and real options approaches.
- Shows that increased uncertainty under the TRY-based mechanism significantly shortens optimal deferral periods and accelerates investment timing.
- Demonstrates that the expansion option gains value under uncertainty, with optimal capacity expansion occurring in the early years of operation.
- Reveals that electricity price-based volatility is substantially higher than project-based volatility, indicating that the TRY-based YEKDEM structure embeds higher policy and market uncertainty.
- Provides evidence that real options valuation restores project feasibility under uncertainty and highlights the joint role of FiT design and macroeconomic volatility in shaping investment flexibility and decision thresholds.

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ABSTRACT

This study examines the impact of the transition of the Renewable Energy Resources Support Mechanism (YEKDEM) from a foreign currency-based to a Turkish lira (TRY)-based Feed-in Tariff (FiT) system on the decision-making processes of Wind Power Plants (WPPs) using a real options approach. To assess investment timing and capacity flexibility under uncertainty, Net Present Value (NPV) and option values are analyzed comparatively using Black–Scholes and Binomial models based on financial and operational parameters for 2021 and 2025. The findings indicate that under low volatility conditions in 2021, postponing investment is rational, whereas the higher uncertainty associated with the TRY-based FiT structure in 2025 shortens optimal deferral periods and accelerates investment timing. In addition, expansion option analysis shows that a capacity increase in the early years of operation maximizes option value, highlighting the importance of staged investment strategies. A key contribution of the study is the comparison of alternative volatility measures. The results reveal that electricity price-based volatility is significantly higher than project-based volatility, and that this difference critically affects both optimal timing decisions and model outcomes. While lower volatility leads to convergence between Black–Scholes and Binomial results, higher volatility increases divergence, emphasizing the importance of uncertainty specification in real option valuation. Overall, the findings demonstrate that the TRY-based FiT system increases the value of flexibility in investment decisions under uncertainty. The study contributes to the literature by showing that real options modeling serves not only as a risk analysis tool but also as a decision-support framework for policy design and strategic investment planning. Furthermore, consistent with the Paris Climate Agreement and the United Nations Sustainable Development Goals (SDGs 7, 9, and 13), the results highlight the role of flexible investment strategies in supporting low-carbon energy transitions.

Keywords: Real options, Feed-in tariff (FiT), Investment timing under uncertainty, Renewable energy, Wind power investment

1. INTRODUCTION

Globally increasing environmental concerns, energy supply security issues, and sustainable development goals have radically shifted the direction of energy policies from fossil fuels to renewable energy sources [1, 2]. Within the framework of the low-carbon development vision, renewable energy (RE) systems have become not only an environmental necessity but also a strategic imperative for economic growth and energy security [3]. According to projections by the International Renewable Energy Agency (IRENA), by 2050, more than 80% of global electricity production will come from renewable sources, with wind and solar energy accounting for more than half of this [4]. However, this transformation creates a complex investment environment for investors due to high capital requirements, long payback periods, and market price volatility [5, 6].

Renewable energy investments often depend on publicly supported incentive systems to be financially sustainable. These systems mitigate financial risks and lower the cost of capital by providing investors with predictable cash flows [6, 7]. Support mechanisms generally fall into two main approaches: price-based policies that provide direct income support (e.g., FiT) and market-based quantity-driven systems (e.g., green certificates or quota-based systems). FiT policies provide long-term income stability by guaranteeing investors a fixed price for a specified period; this model originated with the 1978 National Energy Act of the United States and has been widely implemented in countries such as Europe, China, and Korea [8-11]. In contrast, quota and certificate systems expose investors to market price uncertainty but create a more competitive market structure [12, 13]. China, with its benchmark FiT policy implemented since 2009, has achieved record increases in wind and solar installations and gradually phased out subsidies by reaching its grid parity target by 2021 [11, 14]. South Korea implemented a fixed FiT between 2002 and 2012, then transitioned to the Renewable Portfolio Standard (RPS) system and introduced REC (Renewable Energy Certificate) trading; this system also offered strong incentives for energy storage investments after 2020 [15]. While the United States does not have a federal FiT system, the Investment Tax Credit (ITC) and Production Tax Credit (PTC) mechanisms, along with state-level Renewable Portfolio Standards (RPS), have significantly reduced investment costs [6, 10]. Japan, with its FiT Law enacted in 2012, achieved rapid growth in solar PV capacity and transitioned its system to a FiP-based hybrid model by 2022 [9, 16]. Australia, on the other hand, has developed a market-based certificate trading model through state-based FiT systems and the Large-scale Renewable Energy Target (LRET) program [17, 18]. The same policy architecture is

being implemented in Europe with different design details across countries. In Germany, classical FiTs became widespread with the 2000 EEG, and from 2017 onwards, tender-based fixed premium/CfD-like contracts were introduced for large projects [5, 19]. Italy provided high FiTs for PV during the "Conto Energia" period, then shifted its capacity allocation to a hybrid scheme based primarily on tenders and premiums [20].

In addition to these cases, several European countries have followed similar but distinct policy paths. While Spain granted FiT with RD 661 in 2007, it made retroactive corrections after the 2013 reform; today, large power plants are supported through competitive tendering and contracts for difference [13]. In the United Kingdom, the Renewables Obligation mechanism, similar to the Green Certificate, was replaced by Contracts for Difference (CfD) for new investments after 2014; price risk has been significantly reduced [21]. Denmark has achieved high penetration, especially in wind, by using a combination of fixed premium FiT and tendering since the early stages [8]. In the Netherlands, the SDE/SDE+ (now SDE++) system offers a cost-effective support framework with a variable premium awarded above the market price [22]. France applies FiT for small/medium-sized projects and a mix of tendering and premium for large projects; Long-term purchase agreements increase financing availability [23]. Poland, on the other hand, has historically evolved from a green certificate system to auction-based support, with most new wind and PV capacity being allocated this way [24]. Among emerging markets, Türkiye provides a particularly relevant case. In Türkiye, since 2011, YEKDEM has provided revenue stability through a USD-based FiT (10 years) for wind; with the 2021 reform, the incentive structure was made TRY-based and tied to indexation rules [25]. This transformation highlights the value of flexibility (deferral/expansion) in the timing of investment decisions under exchange rate and inflation uncertainty; therefore, the real options approach [26, 27] is preferred in our study. YEKDEM, which entered into force in 2011 to encourage renewable energy investments, has been one of the most important policy tools that accelerated private sector investments in Türkiye's energy transformation process. By offering investors a fixed foreign currency-based purchase guarantee, the mechanism ensured long-term income stability and created a strong investment momentum, particularly in wind and solar energy investments [28, 29]. However, the transition from a foreign currency-based to a TRY-based support system with the regulation enacted in 2021 directly affected investor behavior and financial feasibility [25, 30]. The elimination of foreign currency-based income guarantees made investors' income streams more vulnerable to exchange rate risk and high inflation conditions. In this context, the structural transformation of YEKDEM

has reshaped the risk-return balance of renewable energy investments in Türkiye. Unlike the previous fixed-price structure, the new mechanism introduces a dynamic pricing formula indexed to macroeconomic variables such as CPI, PPI, and exchange rates, shifting a significant portion of financial risk from the public sector to private investors [31-33]**.** This transition has shown that it significantly alters the risk-return profile of renewable energy investments, particularly where exchange rate volatility and inflation dynamics directly affect project feasibility and payback periods [34, 35]**.** Studies also show that under the TRY-based YEKDEM, project profitability has become highly sensitive to macroeconomic fluctuations, and significant differences in annual returns have been observed [33]**.** Furthermore, the TRY-based support mechanism has been associated with increased financing constraints due to increased uncertainty in revenue streams, especially in an environment of high inflation and currency depreciation [36, 37]**.** Studies highlight that dependence on imported capital goods and equipment in renewable energy projects exacerbates the negative effects of Turkish Lira depreciation, thereby increasing investment costs and weakening financial sustainability [38, 39]**.**

Traditional investment valuation methods fail to internalize policy changes, price volatility, and uncertainties in technology costs that frequently occur in energy markets. The Net Present Value (NPV) method is limited in accurately reflecting investment timing and scale decisions, particularly in renewable energy projects, because it does not account for irreversibility and policy risk [26, 27]. Therefore, the Real Options Approach (ROA) is increasingly preferred in the analysis of investment decisions under uncertainty and flexibility. Real options add a dynamic dimension to static NPV analysis by measuring the financial value of strategic options such as postponing, expanding, or abandoning the investment [40, 41]. Energy policy uncertainty has emerged as a critical determinant of investment behavior in renewable energy systems, especially under conditions of high irreversibility and long payback periods. Recent evidence shows that fluctuations in energy-related uncertainty significantly affect investment dynamics, market volatility, and strategic decision-making processes in the energy sector [42, 43]. In this context, ROA offers a powerful analytical framework for evaluating investment decisions under uncertainty by combining the value of managerial flexibility, irreversibility, and waiting options [44]. Furthermore, systematic reviews confirm that ROA has become an increasingly adopted tool in renewable energy investment analysis, particularly for hybrid systems, due to its ability to capture multiple sources of uncertainty, including policy, market, and technological risks [45]. Energy transition policies and diversification strategies implemented in the European Union

highlight the need for stable and predictable policy environments to reduce uncertainty and accelerate the adoption of renewable energy [46-48]. Conversely, policy instability increases financing constraints and weakens investor confidence, leading to delays or reductions in investments. Furthermore, it demonstrates that renewable energy investments are inherently characterized by market conditions, regulatory frameworks, and uncertainties regarding future energy production, and are therefore particularly suitable for evaluation based on real options [49-50].

In energy investment studies, the choice between Black-Scholes and Binomial models reflects a trade-off between analytical simplicity and modeling flexibility within the framework of real options. The Black-Scholes model is widely used due to its closed-form solution and computational efficiency; however, its restrictive assumptions, such as constant volatility and continuous price dynamics, limit its applicability in energy markets characterized by policy changes and structural uncertainty [51-53].

In contrast, Binomial models offer greater flexibility by incorporating discrete-time dynamics and time-varying parameters, enabling explicit modeling of managerial decisions such as deferral, expansion, and abandonment. This makes them particularly suitable for capital-intensive energy investments exposed to regulatory and market uncertainty [54-55]. Finally, recent studies are increasingly adopting a comparative approach using both models to assess the sensitivity of option values and optimal investment timing to model assumptions [56-57]. Such comparisons provide valuable information about the soundness of investment decisions and highlight the critical role of model selection in actual option-based energy valuation [58, 59].

In renewable energy projects, ROA has emerged as a powerful tool for assessing the impact of policy mechanisms, particularly FiT and FiP. Global studies show that the income stability provided by FiT systems to investors increases real option value and accelerates investment decisions. For example, Boomsma et al. [5] analyzed the effects of different support systems on real option value in European energy markets and found that FiT systems encourage early investment decisions, while green certificate mechanisms trigger larger-scale investments with a delay. Similarly, Adkins and Paxson [60] examined the impact of policy uncertainty on investment timing in the US wind market and showed that fixed support systems like FiTs lower the investment waiting threshold. ROA has also become increasingly prevalent in the Asian literature.

Zhang et al. [61] examined the evolution of FiT policies in China's wind and solar power plants from "benchmark" prices to "grid parity," showing that during this period, investors optimized their waiting and capacity expansion decisions to preserve option value. Wesseh and Lin [21], by evaluating FiT and carbon pricing mechanisms together in China, showed that support design significantly affects investment return and option value. Furthermore, studies such as Arefen et al. [62] and Wang et al. [16] have indicated that exchange rate volatility and policy changes shape investor behavior, especially in emerging Asian economies, and that ROA models provide high accuracy in capturing these effects. In Europe, Kitzing et al. [8] analyzed the investment risk profiles of different support mechanisms using the examples of Denmark and Germany, emphasizing that while FiT systems provide income stability, FiP and auction-based systems transfer risk to investors. Hodt and Hodt [23], using a real option model for offshore wind farms in the Baltic Sea, showed that investment timing differs significantly as the type of support mechanism changes. Tellez et al. [63] analyzed how FiT systems shape investor behavior in Spain and Portugal, demonstrating that the tendency to postpone investment decisions based on option value increases during periods of high volatility. Boomsma and Linnerud [22], by modeling the impact of policy uncertainty on real option value, showed that discontinuities in support mechanisms can lead to significant delays in investment timing. Consequently, global and European literature demonstrates that the real option approach not only makes investment valuation under uncertainty more realistic but also serves as a powerful tool for assessing the effectiveness of policy design [27, 64, 65]. Drawing on these studies, the real option model also provides a suitable methodological framework for analyzing the impact of the transformation of the YEKDEM (Republic of Türkiye) from a foreign currency-based system to a TRY-based system on investment decisions.

Wind energy investments are often systematically undervalued when analyzed with traditional investment valuation methods due to their high capital requirements and the exposure of revenue streams to long-term uncertainties [26, 66]. Therefore, the ROA offers a more realistic analysis framework for wind energy investments by considering timing, scale, and policy risk under uncertainty [64, 67]. Early studies in the United States have shown that periodic interruptions in the Production Tax Credit (PTC) system significantly affect investor behavior, and that ROA is successful in modeling these uncertainties [60, 68]. Boomsma et al. [5] compared wind investments under different support mechanisms (fixed FiT and green certificate systems), showing that investment decisions occur earlier under fixed FiT systems, while larger but delayed

investments emerge under certificate systems. In Europe, the examples of Denmark, Germany, and Spain clearly demonstrate the effectiveness of FiT systems in accelerating wind investment. Haas et al. [69] and Butler and Neuhoff [70] show that the German FiT mechanism achieved significantly higher capacity additions than the UK Renewables Obligation Certificate system. Kitzing et al. [8] and Hodt and Hodt [23] emphasized that the transition from FiT to auction-based or premium models in Europe increased the real options effect on investment timing, and investors increasingly used deferral options. Additionally, Ritzenhofen and Spinler [71] showed that FiT regime changes in Germany created "policy switching risk" in wind power plant investments, leading investors to reassess their flexibility to defer and expand using ROA-based models. In Asia, wind energy policies in Japan, China, and South Korea were examined through support mechanisms that began with FiT implementations and later evolved into FiP or RPS systems. Zhang et al. [61] analyzed FiT reforms in China, finding that the government-set benchmark tariff level for wind projects increased option value and that investors tended to postpone investments as they approached grid parity. Kim et al. [72] used a compound option model on wind power R&D investments in South Korea, finding that FiT support accelerated the timing of investment, but market price volatility in the post-FiT period revalued the option to postpone. Similarly, Wesseh and Lin [21] show that the FiT levels implemented for solar and wind in China remain suboptimal, considering fossil fuel price volatility and learning effects, and that investment options remain unexercised. Kumbaroğlu et al. [73] proposed a real options model that takes into account the learning curve and price uncertainty for wind energy investments in Türkiye, demonstrating that the continuity and predictability of the support mechanism are determinants of investment value. Consequently, the literature emphasizes that FiT support for wind energy investments, both globally and regionally, shapes investor behavior and that real options are a powerful tool in determining the optimal investment timing under uncertainty [27, 64, 74].

The primary objective of this study is to demonstrate the effects of currency conversion in the YEKDEM incentive system on investor behavior, project value, and investment flexibility using a financial modeling approach under uncertainty. In other words, "Does NPV decrease when the TRY is adopted?" In addition to the question, we seek to answer the question, "How does the real economic value of an investment change if investors make different strategic decisions (wait, expand) in this new system?" Numerous studies in the literature examine the impact of "FiT" policies, but the impact of the incentive system's transition from a foreign currency-based to a TRY-based system on investment flexibility has not been quantitatively analyzed before. This is a

modeling study that measures the impact of the structural transformation of Türkiye's energy incentive system on investor behavior using a real options approach for the first time, providing both theoretical and practical contributions. The study's results fill a gap in the academic literature, providing investors with the ability to make rational decisions under uncertainty, and demonstrating to policymakers how incentives can be optimized in line with sustainability goals.

2. MATERIALS AND METHODS

2.1. Data Set and Model Inputs

This study used both the classical NPV method and the ROA, which incorporates decision flexibility under uncertainty, to determine the economic value of a WPP in Türkiye. Traditional NPV calculations were performed within the scope of the analysis, taking into account the project's cash flows, investment costs, operating revenues, purchase prices applied under the YEKDEM (Renewable Energy Market Regulatory Authority), and the investment's economic life. The basic model parameters used in the NPV analysis are presented in Tables 1 and 2.

In this study, the economic lifetime of the wind power plant is assumed to be 15 years, in line with Section 45 of General Communiqué No. 333 issued under the Turkish Tax Procedure Law and commonly applied financial evaluation practices. However, it is important to distinguish between accounting-based economic life and technical lifetime. While the technical operating life of wind turbines is generally considered to be around 20–25 years, the present analysis focuses on a financially relevant evaluation horizon to ensure consistency with cash flow projections and investment appraisal conditions. The selected time frame, therefore, represents a conservative and practice-oriented approach, and extending the analysis to a full technical lifetime could lead to higher project valuations. For NPV analysis, a risk-adjusted discount rate was used instead of the risk-free interest rate. This rate was determined using simplified Weighted Average Cost of Capital (WACC) based logic, where the risk-free interest rate forms the base component and an additional premium is included to reflect country risk, macroeconomic uncertainty, financing conditions, and project-specific risks. The risk-free interest rate used in the real option valuation is represented by the yields on long-term Turkish Lira-denominated government loans for the relevant analysis period. Accordingly, the risk-free interest rate was taken as approximately 17.5% for June 2021 and 25% for March 2025. Therefore, the discount rate was determined as 26% for 2021 and 34% for 2025. Practically, this corresponds to adding a risk premium of approximately 8.5 percentage points in 2021 and approximately 9 percentage points in 2025 on top of the respective risk-free

interest rates. The higher discount rate in 2025 reflects the deterioration in inflation, borrowing conditions, and macroeconomic performance compared to 2021. While the NPV framework reflects risk through the discount rate, real options reflect risk by including it in the volatility parameter (σ), which reflects uncertainty. Therefore, the use of a higher discount rate in the NPV framework and a lower risk-free rate in the real options model does not represent a contradiction but reflects two distinct valuation approaches.

An important methodological consideration concerns currency denomination. Although the 2021 FiT mechanism is denominated in USD, the analysis is conducted in nominal TRY terms to ensure consistency across scenarios and to reflect local financing conditions, cost structures, and investment decision-making processes. In practice, renewable energy investments in Türkiye are largely financed and evaluated in local currency, and therefore, the use of a TRY-based discount rate is considered appropriate for capturing the actual investment environment.

In addition to currency considerations, using a USD-based discount rate for 2021 would create inconsistency in the comparative analysis, as the 2025 scenario is entirely TRY-based. The inflation rate was incorporated into the model using the 12-month average CPI values for the relevant year and month published by TurkStat. Since investment costs and operating expenses are in USD, they were converted to TRY using the average exchange rates for the relevant periods. In this context, an average exchange rate of 8.60 TRY/USD was used for June 2021, and 36.07 TRY/USD for March 2025. Operating expenses (OPEX) are assumed to be approximately 2% of capital expenditures (CAPEX) annually, consistent with typical assumptions in the evaluation of wind energy projects. Electricity generation is assumed to remain constant throughout the project life, based on a constant capacity factor. The increase in capital expenditures in the 2025 scenario reflects nominal TRY-based valuation effects resulting from inflation and exchange rate movements, rather than an increase in underlying technology costs.

Finally, several technical assumptions are incorporated into the model. Furthermore, the initial investment cost was determined based on reference project costs included in the WPP feasibility and valuation reports for the relevant periods; a 35% wind capacity factor was assumed in production estimates, consistent with industry practices. This value is based on regional wind resource assessments reported in the Renewable Energy Potential Atlas (REPA) for Türkiye. The capacity factor is a key parameter directly affecting electricity generation, revenue, and

consequently the project value. Higher capacity factors lead to increased cash flows and higher NPV and option values, while lower values may significantly reduce project feasibility. Therefore, the results of this study should be interpreted within the context of the assumed 35% capacity factor. Variations in this parameter may lead to different investment timing and valuation outcomes. The main reason for calculating values in TRY is the transition of the YEKDEM incentive mechanism to a TRY-based structure as of 2025, and the purpose of examining the impact of this change on investment feasibility. Unless otherwise stated, all monetary values reported in this study are expressed in nominal TRY in order to ensure consistency and comparability across the 2021 and 2025 scenarios.

Table 1. Project Parameters for NPV Analysis (June 2021)

Project Cost / Capital Expenditures (CAPEX)	75,250,000 TRY
Annual Revenue	9,492,336 TRY
Economic Lifetime	15 years
Installed Capacity	5 MW
Discount Rate	26%
Operational Expenditure (OPEX)	1,505,000 TRY
Depreciation Amount	5,016,666.67 TRY
Corporate Tax Rate	25%=0.25
Inflation Rate	17.53%=0.1753
Unit Electricity Price / FiT (TRY/kWh)	0.073USD*8.60 TRY/USD=0.6278 TRY

Table 2. Project Parameters for NPV Analysis (March 2025)

Project Cost / Capital Expenditures (CAPEX)	378,735,000 TRY
Annual Revenue	30,176,496 TRY
Economic Lifetime	15 years
Installed Capacity	5 MW
Discount Rate	34%
Operational Expenditure (OPEX)	7,214,000 TRY
Depreciation Amount	25,249,000 TRY
Corporate Tax Rate	25%=0.25
Inflation Rate	38.10%=0.3810
Unit Electricity Price / FiT (TRY/kWh)	1.9958 TRY

2.2 FiT Scenarios: USD vs. TRY

In Türkiye, the feed-in tariff (FiT) mechanism is implemented through the YEKDEM framework. YEKDEM is a national incentive system that aims to reduce investment risk, limit market volatility, and increase renewable energy capacity by providing producers with a purchase guarantee and fixed price support for a specified period. The FiT design significantly affects volatility (σ) through revenue uncertainty.

USD-based FiT (2011–2020): During this period, the purchase price is set fixed in foreign currency, and investor returns are protected from exchange rate risk. Because exchange rate fluctuations are borne by the public, the revenue stream remains largely predictable. This is represented in the model by assuming lower volatility (σ) and negligible opportunity cost (q≃0) in most scenarios.

TRY-based FiT (2021+): The purchase price is in TRY and is updated monthly using the PPI/CPI + foreign exchange indices. Effective σ increases as exchange rate and inflation shocks are retained by the investor. If necessary, different σ and price level assumptions are defined for the free market period (remaining life) after the FiT period. This design aims to partially offset inflationary pressures while maintaining investment incentives. The transition from USD-based to TRY-based FiT constitutes a structural shift in risk allocation, which is explicitly incorporated into the model through changes in volatility and revenue dynamics.

2.3. Real Option Formulation

2.3.1. Deferral option

The right to wait t years instead of starting the investment immediately is valued as a European-style call option [27, 40].

Black–Scholes:

$$C_0 = S_0 N(d_1) - K e^{-r_f t} N(d_2) \quad (1)$$

$$d_{1=} \frac{\ln\left({S_0}/{K}\right) + \left(r_f + {\sigma^2}/{2}\right)T}{\sigma\sqrt{T}} \quad (2)$$

$$d_2 = d_1 - \sigma\sqrt{T} \quad (3)$$

Here, S_0 is the risk-neutral present value that would arise if it were started today; K is the investment cost, i.e., CAPEX. The waiting period $t^{\backslash *}$ that resets the NPV is approximately found from the division $|NPV_0| \simeq C(t^{\backslash *})$.

Within the scope of discrete-time evaluation, a Binomial tree structure representing potential upward and downward movements in project value is constructed, and the option value (C_0) is calculated at each node using the backward induction method for the investment value. This concretizes the "wait/apply" choice at annual decision points.

$$\Delta t = {}^{T}/_{N}, u = e^{r_f\sqrt{\Delta t}}, d = {}^{1}/_{u}, r = e^{r_f \Delta t}, p = {}^{r-d}/_{u-d} \quad (4)$$

Here, p represents the risk-neutral probability; thanks to this structure, the project value can be calculated backwards under possible price movements in each period.

2.3.2. Expansion option

The present value of the capacity increase, S_Δ, is priced as a call with the additional investment cost K_Δ;

$$C_{exp}(t_e) = Call(S_{\Delta,} K_\Delta, t_e, r, q, \sigma) \quad (5)$$

The expansion value (SΔ) represents the incremental project value generated by the capacity increase [6]. This value is modeled as a function of both the scale of the expansion and the timing of the decision. The formula SΔ = S0 × 30% × (15 − T)/T reflects two key economic effects. First, the 30% term represents the proportional increase in capacity. Second, the (15 − T)/T ratio captures the timing effect, showing that earlier expansion allows the investor to benefit from the additional capacity over the remaining project life. As T increases, the remaining life decreases, leading to a decrease in incremental value. Therefore, the formula captures the diminishing economic benefit of delayed expansion. The expansion CAPEX (KΔ) is assumed to be approximately 30% of the base investment cost, consistent with the proportional increase in installed capacity. This assumption is based on a simplified linear scaling approach, which is commonly adopted in preliminary investment analyses where detailed engineering cost breakdowns are not available. The expansion year is calculated using the formula;

$$S\Delta = S_0 \times \%30 \times (15 - T)/T \quad (6)$$

In the Black-Scholes model, the opportunity cost q, which arises during the waiting period, is included in the model, and the relevant equations are shown below [75].

$$C_0 = S_0 e^{-qT} N(d_1) - K e^{-r_f T} N(d_2) \quad (7)$$

$$d_1 = \frac{\ln\left(S_0/K\right) + \left(r_f - q + \sigma^2/2\right)T}{\sigma\sqrt{T}} \quad (8)$$

$$d_2 = d_1 - \sigma\sqrt{T} \quad (9)$$

In the Binomial model, opportunity cost is included in the model by simply adding it to the risk-free interest rate r_f in the risk-neutral valuation structure.

$$r = e^{(r_f - q)}\Delta t \quad (10)$$

2.4. Data and Parameter Calibration

The project's present value (S_0) represents the risk-neutral present value of the cash flows that would be generated if the investment were initiated immediately. In this study, S_0 was calculated by carrying forward to the present the cash flow projections generated using the project's annual operating revenues, operational expenses, depreciation, tax effects, and YEKDEM unit electricity price using the risk-neutral discounting approach. In other words, it is the sum of the annual discounted present values in the NPV calculation. Thus, S_0 directly constitutes the project's economic value, namely the underlying asset for the expansion or deferral option.

In real options literature, the asset's strike price, K, directly represents the investment cost required at the project inception. In this study, the K value was obtained by converting the investment's USD-based CAPEX items (e.g., turbine costs, site preparation, infrastructure, and connection costs) into TRY using the average exchange rate for the relevant periods. The exchange rate used was 8.60 TRY/USD for 2021 and 36.07 TRY/USD for 2025. The main reason for converting the investment cost to TRY is that YEKDEM has transitioned to a fully TRY-based incentive mechanism as of 2025, and the study aims to examine the impact of this transition on investment feasibility.

The risk-free interest rate (r_f), used as the discount rate in real option models, is derived from the yields on long-term TRY-denominated government bonds corresponding to each analysis period. Based on market data published by the Ministry of Treasury and Finance of the Republic of Türkiye, the compound interest rate on a 10-year TRY-denominated government bond was approximately 17.5% for June 2021, and the yield on a similar-term bond was approximately 25% for March 2025. Therefore, r_f was included in the model as the period-specific average risk-free return based on market data for each year. Thus, (r_f), used in real option valuation, was determined both in line with the literature and consistent with market realities. The volatility (σ) parameter represents the level of investment uncertainty and is a key determinant in real options analysis. In renewable energy investments, volatility is influenced by multiple sources, including electricity prices, exchange rates, inflation, and regulatory conditions. In this study, volatility is primarily derived from electricity price dynamics to capture the impact of the YEKDEM regime transition between the 2021 (USD-based) and 2025 (TRY-based) systems. The electricity price series is based on publicly available data from TEİAŞ and EPİAŞ, and volatility is calculated as the standard deviation of annual proportional changes in unit electricity prices. The results show that price-based volatility is significantly higher in 2025, reflecting increased uncertainty under the TRY-based pricing structure. Specifically, volatility is estimated as 0.6897 for 2021 and 1.2414 for 2025. As a robustness check, an alternative volatility measure is calculated using the logarithmic returns of annual net cash flows. This approach captures project-level financial variability, incorporating not only revenues but also operating costs, taxes, and depreciation. The resulting cash flow-based volatility values are substantially lower, at 0.0072 for 2021 and 0.0231 for 2025. The divergence between these two measures indicates that electricity price dynamics constitute the primary source of uncertainty under the YEKDEM mechanism, while project-level cash flows partially dampen these fluctuations. Therefore, electricity price-based volatility is adopted as the main reference parameter, as it more effectively reflects the impact of policy and market conditions on investment risk. The calculated volatility values for both 2021 and 2025, based on price and cash flow approaches, are presented in Table 3.

Table 3. Project parameters (Real options - June 2021)

Volatility (σ)	2021	2025
Price-based	0.6897	1.2414
Cash-flow	0.0072	0.0231

The deferral option was available for both years, while the expansion option was only exercised in 2025 after the deferral option. Under the expansion option, it was assumed that the existing project could achieve a capacity increase of approximately 30% with an additional turbine investment at the same site. This rate is consistent with the 20–40% range predicted for similar renewable energy investments in the literature [26, 75, 76]. Therefore, a 30% increase in asset value (S_0) represents this potential capacity expansion. The additional investment cost for the capacity increase is assumed to be 3 million USD. This amount corresponds to approximately 29% of the total project cost and is based on the assumption that the cost per unit of capacity will remain constant due to economies of scale. The parameters were calibrated for two reference dates (Table 4, Table 5).

Table 4. Real Option Parameters (June 2021)

Annual Risk-Free Interest Rate	r_f	17.5%=0.1750
Present Value of the Asset	S_0	50,496,176.52 TRY
Exercise Price (Investment Cost)	K	75,250,000 TRY
Economic Life of the Option	T	15 years
Annual Standard Deviation (Volatility)	σ	0.6897
Annual Time Fraction	Δt	3.1/15

Table 5. Real Option Parameters (March 2025)

Annual Risk-Free Interest Rate	r_f	25%=0.25
Present Value of the Asset	S_0	258,404,886.20 TRY
Exercise Price (Investment Cost)	K	378,735,000 TRY
Economic Life of the Option	T	15 years
Annual Standard Deviation (Volatility)	σ	1.2414
Annual Time Fraction	Δt	1.2/15
Opportunity Cost Rate	q	1/15

3. RESULTS

In this section, numerical findings from real option and NPV analyses are presented comparatively for the 2021 (USD-based FiT) and 2025 (TRY-based FiT) periods. The analyses focus on the

option values and optimal decision points obtained under investment deferral and expansion scenarios.

3.1. Discounted Cash Flow (NPV) Results

Evaluations using the DCF method indicate that the project's NPV is -24,753,823.48 TRY in 2021 and -120,330,113.80 TRY in 2025. The negative NPV values in both periods indicate that the project would be deemed financially infeasible under conventional discounted cash flow criteria. The discount rate (26%) and inflation (17.53%) are relatively low in 2021. Because the price is held constant at 0.073 USD/kWh under the USD-based FiT regime, revenue streams are not affected by exchange rate volatility. Furthermore, low operational expenses contribute to limiting the negative value. In the 2025 period, the transition to the TRY-based FiT regime resulted in a significant deterioration in financial parameters. The discount rate increased to 34%, inflation rose to 38.10%, investment costs reached 378.73 million TRY, and OPEX increased approximately fivefold. However, the indexed sales price remained insufficient in real terms to offset rising costs and macroeconomic pressures. Therefore, in the TRY-based FiT environment, high inflation and the discount effect significantly eroded the real value of cash flows, causing the NPV to be significantly more negative compared to 2021.

3.2. Real Options: Analysis of Deferral and Expansion Values Based on the FiT Structure

Real options analysis clearly demonstrates the impact of the two FiT regimes on the strategic flexibility of investment.

For the deferral option, the option value is limited in the 2021 period due to low volatility, and the optimal deferral period is found to be 3.1 years in the Black–Scholes model and 3.2 years in the Binomial model. The low-income volatility, thanks to the USD-based fixed price structure, creates a limited but positive deferral value that encourages investors to wait longer. The transition to the TRY-based FiT structure in 2025 significantly increased volatility. Although increased uncertainty raises option value, the present value of cash flows declines more rapidly due to elevated discount rates and inflation. Therefore, the optimal deferral period decreases to approximately 1.2 years in both models, demonstrating that early investment decisions create greater value in a high volatility and high discount environment. The following applications illustrate the numerical values of the optimal deferral periods and post-delay investment expansion.

• Deferral Option Valuation and Optimal Investment Timing (June 2021)

The optimum waiting period satisfying the condition $C_t \approx |NPV_0|$ was calculated as approximately 3.1 years.

$$d_1 = \frac{\ln\left({}^{50,496,176.52}/_{75,250,000}\right) + \left(0.175 + {}^{(0.6897)^2}/_{2}\right)3.1}{0.6897\sqrt{3.1}} \quad (11)$$

$$d_1 = 0.7254 \quad N(d_1) = 0.7659 \quad (12)$$

$$d_2 = 0.7254 - 0.6897\sqrt{3.1} \quad (13)$$

$$d_2 = -0.4889 \quad N(d_2) = 0.3114 \quad (14)$$

In this case, the option value is as follows;

$$C_0 = (50,496,176.52 \times 0.7659) - \left(75,250,000 \times e^{(-0.175 \times 3.1)} \times 0.3125\right) \quad (15)$$

$$C_0 = 25,005,548.66\ TRY \quad (16)$$

$$ENPV = -24,753,823.48 + 25,005,548.66 \quad (17)$$

$$ENPV = 251,725.18\ TRY \quad (18)$$

The parameter values calculated for the Binomial model are as shown below.

$$u = 1.375110231$$
$$d = 0.7272144278$$
$$r = 1.038032921 \quad (19)$$
$$p = 0.4797353085$$
$$1 - p = 0.5202646915$$

The option value obtained after constructing the Binomial and option trees using the above values is C_0= 24,724,389.40 TRY. When the deferral period is increased to 3.3 years, the option value is 25,275,874.50 TRY. Although this value completely overcomes the negative effect of NPV and moves the project into positive territory, it deviates from both the equilibrium and the threshold proximity sought for the optimum point. Therefore, the model results indicate that the optimal deferral period is approximately 3.2 years. While the Black–Scholes model yields an optimal deferral period of approximately 3.1 years under the continuous time assumption, the optimal period is found to be 3.2 years due to the time decomposition used in the Binomial model. The small difference between the two models is consistent with the known property (convergence) that

the Binomial model will converge to the Black–Scholes value as the number of steps increases ($\Delta t \to 0$). Therefore, the deviation is due to the discrete-time structure and does not indicate a methodological inconsistency.

- **Deferral Option Valuation and Optimal Investment Timing (March 2025)**

The optimal deferral period satisfying the condition $C_t \approx |NPV_0|$ was found to be approximately 1.2 years for both models. The option value calculated with the Black–Scholes model was found to be 124,840,430.50 TRY, and the value obtained with the Binomial model was found to be 121,309,727.47 TRY. Both values exceed the absolute value of the negative NPV calculated for the same year, which was -120,330,113.80 TRY.

- **Valuation of the Expansion Option and Optimal Expansion Timing (March 2025)**

In the expansion option, in the first five-year analysis conducted for 2025, the option value increases until the third year in the Black-Scholes model, reaching a peak at which point it begins to decrease. This dynamic demonstrates that while indexation-related price volatility creates an attractive value for capacity expansion in the early years, expansion opportunities lose value as uncertainty costs and discount effects become more dominant over time. In the Binomial model, this period is analyzed as four years. The Binomial structure's discrete-time decision points allow investors to dynamically evaluate the "apply-deferral-expand" decision by periodically monitoring FiT updates, price movements, and volatility changes. This feature increases the practical importance of decision flexibility, especially in the new FiT regime, which is TRY-based, frequently updated, and subject to high uncertainty. Overall, the findings reveal that option values remain limited in the USD-based low-risk period, while in a TRY-based high-volatility environment, both deferral-and-expand options become more decisive in investment decisions. The table 6 below shows the 5-year expansion option values for both models. These values represent the optional return that can be added after the investment begins, not to cover the negative NPV gap. In other words, the expansion option is added as an additional value to the investment.

Table 6. Expansion option values

Year (T)	$S\Delta(T)(TRY)$	$K\Delta(TRY)$	Black-Scholes (C_0)	Binomial (C_0)
1	72,353,368.14	108,210,000	27,526,788.32	28,063,663.38
2	67,185,270.41	108,210,000	35,210,743.75	39,204,779.46

3	62,017,172.69	108,210,000	36,388,714.75	43,516,202.14
4	56,849,074.96	108,210,000	34,619,467.44	44,324,008.54
5	51,680,977.24	108,210,000	31,443,317.27	43,072,551.78

3.3. Sensitivity Analysis: Deferral Option under Alternative Volatility Measures

When volatility is recalculated based on project cash flows, the optimal deferral periods increase significantly compared to the price-based results. For the 2021 scenario, the optimal waiting time rises to approximately 6.1 years, while for the 2025 scenario it increases to around 4.0 years in both the Black–Scholes and Binomial models. In addition, the results obtained from the two models converge more closely under lower volatility levels. This finding is consistent with theoretical expectations, as reduced uncertainty diminishes the value of flexibility and limits the divergence between continuous-time and discrete-time valuation approaches. Overall, these results indicate that lower volatility reduces the value of flexibility but leads to longer optimal waiting periods, resulting in more stable and convergent investment timing across models. Table 7 shows the deferral periods according to volatility values. Figure 1 shows the results obtained in the table graphically.

Table 7. Sensitivity of Optimal Deferral Period to Alternative Volatility Measures

Scenario	Volatility Source	σ	Black–Scholes (Years)	Binomial (Years)
2021	Price-based	0.6897	3.1	3.2
2021	Cash-flow-based	0.0072	6.1	6.1
2025	Price-based	1.2414	1.2	1.2
2025	Cash-flow-based	0.0231	4.0	4.0

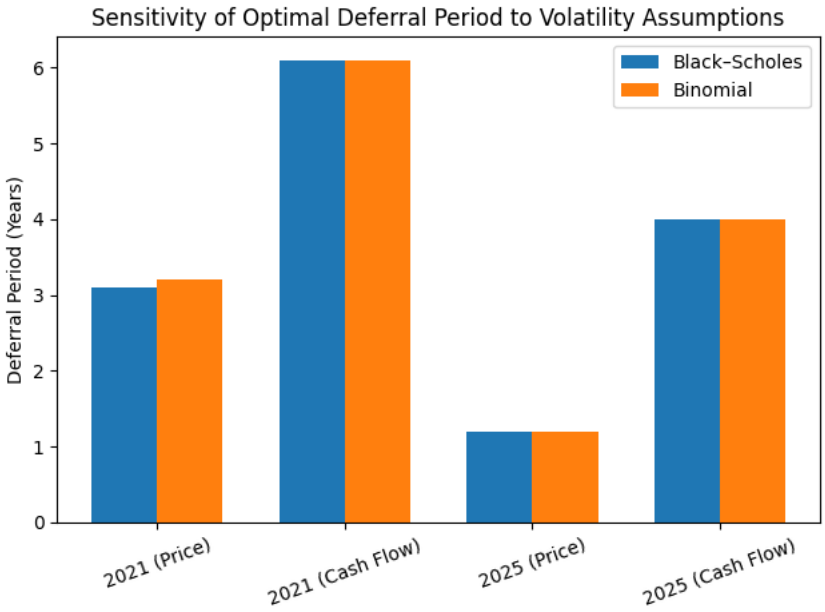


Figure 1. Sensitivity of Optimal Deferral Period to Alternative Volatility Measures

3.4. Sensitivity Analysis of Expansion Option (2025 Scenario)

To further assess the robustness of the expansion option results, a sensitivity analysis is conducted for different capacity increase ratios. Alongside the baseline 30% expansion scenario, alternative cases of 20% and 40% are evaluated. The sensitivity analysis results of the expansion option for different capacity increase scenarios under the Black–Scholes and Binomial models are presented in Tables 8 and 9.

Table 8. Sensitivity Analysis of Expansion Option (Black–Scholes, 2025)

Year (T)	SΔ(T) – 20% (TRY)	C_0 – 20% (TRY)	SΔ(T) – 30% (TRY)	C_0 – 30% (TRY)	SΔ(T) – 40% (TRY)	C_0 – 40% (TRY)
1	48,235,578.76	13,672,659.07	72,353,368.14	27,532,984.38	96,471,157.52	43,636,353.53
2	44,790,180.27	20,318,270.93	67,185,270.41	35,211,655.02	89,580,360.55	51,203,872.17
3	41,344,781.79	22,223,775.72	62,017,172.69	36,391,796.72	82,689,563.59	51,169,367.78
4	37,899,383.31	21,773,087.68	56,849,074.96	34,617,164.36	75,798,766.61	47,817,254.56
5	34,453,984.83	20,127,888.75	51,680,977.24	31,442,191.30	68,907,969.65	42,970,085.13
6	31,008,586.35	17,911,273.43	46,512,879.52	27,663,510.84	62,017,172.69	37,545,832.98
7	27,563,187.86	15,472,328.38	41,344,781.79	23,714,099.39	55,126,375.72	32,035,728.85
8	24,117,789.38	13,009,240.06	36,176,684.07	19,832,930.18	48,235,578.76	26,705,781.02
9	20,672,390.89	10,633,286.22	31,008,586.34	16,149,543.76	41,344,781.79	21,696,006.63

Year (T)	SΔ(T) – 20% (TRY)	C₀ – 20% (TRY)	SΔ(T) – 30% (TRY)	C₀ – 30% (TRY)	SΔ(T) – 40% (TRY)	C₀ – 40% (TRY)
10	17,226,992.41	8,404,414.39	25,840,488.62	12,729,875.85	34,453,984.83	17,073,762.65

Table 9. Sensitivity Analysis of Expansion Option (Binomial, 2025)

Year (T)	SΔ(T) – 20% (TRY)	C₀ – 20% (TRY)	SΔ(T) – 30% (TRY)	C₀ – 30% (TRY)	SΔ(T) – 40% (TRY)	C₀ – 40% (TRY)
1	48,235,578.76	16,237,712.24	72,353,368.14	31,794,400.33	96,471,157.52	50,365,549.70
2	44,790,180.27	25,771,016.50	67,185,270.41	42,996,405.26	89,580,360.55	62,850,350.04
3	41,344,781.79	29,631,942.53	62,017,172.69	47,093,865.67	82,689,563.59	66,471,868.91
4	37,899,383.31	30,570,453.55	56,849,074.96	47,507,788.92	75,798,766.61	65,723,710.54
5	34,453,984.83	29,830,769.01	51,680,977.24	45,794,360.79	68,907,969.65	62,551,883.76
6	31,008,586.35	28,081,128.49	46,512,879.52	42,794,746.81	62,017,172.69	57,961,963.19
7	27,563,187.86	25,708,053.40	41,344,781.79	38,998,388.10	55,126,375.72	52,516,228.97
8	24,117,789.38	22,944,196.21	36,176,684.07	34,701,384.95	48,235,578.76	46,543,314.26
9	20,672,390.89	19,932,998.91	31,008,586.34	30,087,054.58	41,344,781.79	40,241,110.25
10	17,226,992.41	16,764,285.51	25,840,488.62	25,270,558.82	34,453,984.83	33,776,832.13

The sensitivity analysis reveals two important insights. First, expansion option values increase proportionally with the scale of capacity expansion, indicating that larger expansion decisions generate higher economic value. Second, and more importantly, the optimal timing of expansion remains relatively stable across all scenarios. In the Black–Scholes framework, the third year consistently emerges as the optimal expansion timing, regardless of whether the expansion ratio is 20%, 30%, or 40%. This finding suggests that the timing of expansion is primarily driven by the trade-off between uncertainty resolution and the remaining project lifetime, rather than the scale of expansion itself. From an investment perspective, this implies that while investors may adjust the size of capacity expansion according to financial constraints or strategic preferences, the optimal timing decision is more robust and should be prioritized around the early operational years of the project. The Binomial model produces a similar pattern, with a slight shift in the peak value due to its discrete-time structure, further confirming the robustness of the results. Figure 2 presents the sensitivity of expansion option values to different capacity increase ratios (20%, 30%, and 40%) under the Black–Scholes and binomial models for the 2025 scenario.

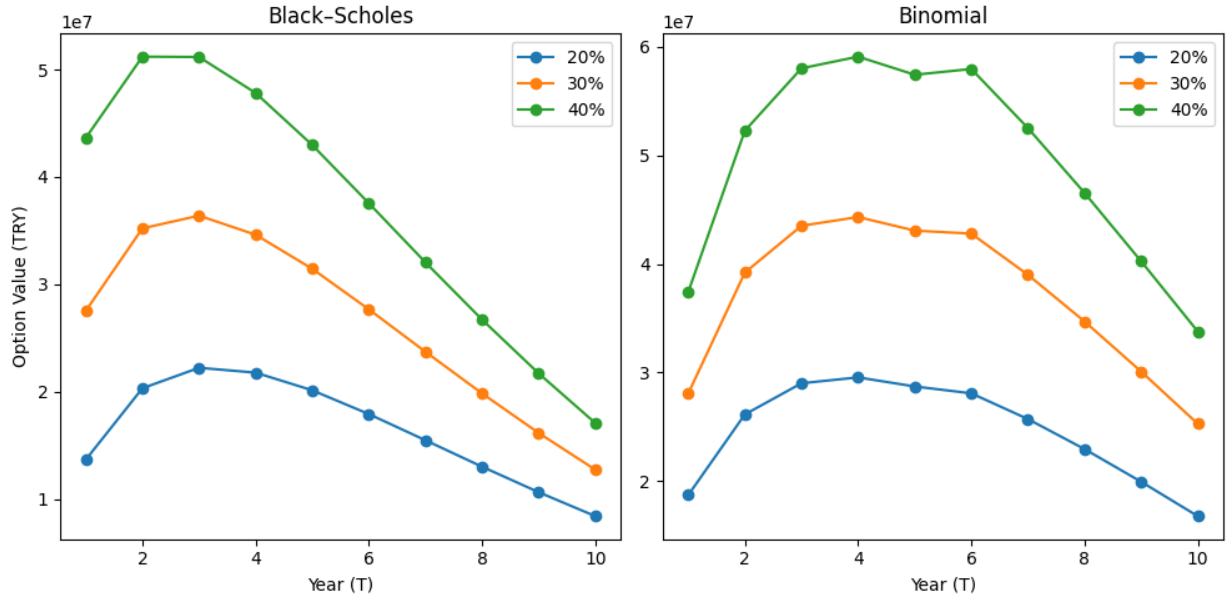


Figure 2. Sensitivity of expansion option values to alternative capacity increase ratios (20%, 30%, and 40%) under the Black–Scholes and Binomial models for the 2025 scenario.

The observed differences between the Black–Scholes and Binomial results are due to the continuous-time nature of the Black–Scholes model and the discrete-time structure of the Binomial model. While the Binomial approach evaluates decision points at discrete intervals, the Black–Scholes model assumes a continuous evolution of uncertainty. This leads to slight differences in the timing of peak option values. However, both models provide consistent economic insights regarding the pattern of expansion value over time.

4. DISCUSSION

This study contributes to the literature by providing an integrated evaluation of policy transition and investment flexibility under macroeconomic instability. The findings demonstrate that while high inflation and volatility, in particular, reduce the present value of an investment, decision flexibility creates critical value for investors. These results are broadly consistent with trends in the international energy economics and real options literature.

4.1. Comparison of Findings with Literature

Existing literature identifies volatility, price uncertainty, carbon markets, investment costs, and FiT structures as key determinants of investment timing in renewable energy projects. Recent studies further demonstrate that support mechanisms directly shape investor behavior [77–79]. The

findings of this study are consistent with this literature, showing that the deferral option becomes more valuable in 2025, while the optimal deferral period shortens due to heightened volatility in electricity prices and macroeconomic variables. This aligns with prior evidence that higher volatility increases option value, whereas higher discount rates accelerate option exercise [80, 81].

Moreover, studies focusing on Türkiye indicate that TRY-based incentive structures expose investors to increased risks on both the revenue and cost sides, particularly under inflationary conditions [55, 33]. The results of this study support these findings, as reflected in the significant decline in NPV for 2025 (−120 million TRY), suggesting that the current mechanism is insufficient to compensate for rising macroeconomic risks.

In the real options literature, particularly in wind and solar investments, increasing uncertainty has been shown to enhance the value of flexibility and make deferral strategies more critical [83–85]. Consistent with this, the results indicate that uncertainty under the TRY-based FiT regime increases real option value and strengthens investors' ability to adapt their decisions. In addition, the higher value generated by the expansion option—especially in 2025—aligns with empirical findings that staged or expansion-based investment strategies create value under uncertain conditions [86–88].

A key contribution of this study lies in the comparison of alternative volatility measures. The results show that volatility derived from electricity prices is significantly higher than that calculated from project cash flows, leading to important differences in investment outcomes. Sensitivity analysis reveals that when lower, cash flow-based volatility is used, optimal deferral periods become longer and the results of the Black–Scholes and Binomial models converge. In contrast, higher price-based volatility leads to shorter deferral periods and greater divergence between model outcomes.

This finding is consistent with recent studies emphasizing that different sources of uncertainty—such as market prices, policy changes, and macroeconomic factors—affect real option values through distinct transmission channels [44, 77, 81, 85]. Recent evidence also shows that high volatility tends to increase option value while accelerating investment timing, whereas lower uncertainty reduces flexibility value and leads to more stable and convergent model results [52, 54, 79, 88].

Overall, this study contributes to the literature by demonstrating that not only the level of uncertainty but also its measurement significantly influences real option valuation outcomes. In doing so, it provides new evidence on the interaction between policy uncertainty, macroeconomic instability, and investment flexibility in renewable energy projects, particularly in emerging market contexts such as Türkiye.

In addition to these findings, recent literature has highlighted the increasing importance of hybrid energy systems and resource complementarity. Renewable energy research is increasingly focusing on hybrid energy systems as a way to improve reliability and economic performance under conditions of uncertainty. In particular, hybrid configurations such as wind-solar and solar-hydro systems have been shown to reduce interruptions and increase overall system efficiency by stabilizing production profiles over time [89, 90]. In the context of Turkey, recent case studies highlight that hybrid renewable systems can significantly improve energy supply stability and mitigate investment risk by reducing reliance on a single energy source [91–94]. Furthermore, simulation-based analyses show that the integration of multiple renewable sources leads to better capacity utilization and more stable output patterns, which are crucial for long-term financial feasibility [95, 96].

Another important dimension in renewable energy investments is the concept of complementary generation profiles, which refers to the temporal balancing of different renewable resources. Studies show that wind and solar energy often exhibit inverse or weakly correlated production patterns, allowing one resource to compensate for the variability of another [97, 98]. This complementarity reduces output volatility and enhances predictability, which in turn improves revenue stability and investment attractiveness. In emerging markets such as Türkiye, where macroeconomic uncertainty and price volatility are significant, the use of complementary renewable profiles can play a critical role in reducing financial risk and strengthening the robustness of investment decisions [99, 100].

4.2. Economic and Political Impacts of the YEKDEM Mechanism

Türkiye's transition from a USD-based fixed FiT regime to a TRY-based indexed structure in 2021 is a critical turning point for the financial sustainability of energy investments. Our findings reveal three key policy impacts:

4.2.1. Increased uncertainty and ınvestment

Although the TRY-based system partially offsets exchange rate and inflation effects through monthly indexation, it fails to fully protect real revenues during periods of high inflation, leading to an increase in investor risk premiums. This finding is consistent with international studies highlighting the strong relationship between incentive mechanism design and investment uncertainty [5, 8, 71].

The transition to the TRY-based YEKDEM structure has not only altered the nominal pricing framework but also fundamentally reshaped the nature of investment risk by linking project revenues more directly to domestic macroeconomic conditions. Recent studies on Türkiye and other emerging economies show that exchange rate pass-through, persistent inflation, and policy design jointly influence renewable energy investment behavior, particularly in contexts where imported equipment and foreign currency-linked cost structures remain dominant [1, 16, 33, 82]. In this regard, the findings of this study confirm that the TRY-based incentive regime increases exposure to revenue-side uncertainty while weakening the protection previously provided by the USD-based structure.

Furthermore, the volatility analysis indicates that uncertainty is significantly higher when measured using electricity price dynamics compared to project-based cash flows. This suggests that the primary source of risk under the TRY-based YEKDEM regime stems not only from project-level financial variability but also from the instability embedded in the pricing mechanism itself. This result aligns with recent literature emphasizing that market-driven and policy-induced uncertainties can substantially influence investor expectations and lead to more cautious or delayed investment decisions in renewable energy projects [77, 81, 85].

4.2.2. The ımportance of decision flexibility

Under the TRY-based YEKDEM structure, increased exposure to macroeconomic uncertainty significantly alters investor behavior by making decision flexibility more critical. In particular, the deferral option allows investors to postpone irreversible investment decisions in response to uncertainty in inflation, exchange rates, and electricity prices. The findings suggest that, in such an environment, waiting becomes a rational strategy, as investors seek to reduce downside risks before committing capital. In addition, the expansion option enables a more gradual and adaptive investment approach. Rather than committing to full capacity at the outset, investors may prefer

staged investment strategies that allow them to adjust capacity in line with evolving market conditions. This reflects a shift from static investment planning toward more flexible and sequential decision-making under uncertainty.

Overall, the results indicate that under the TRY-based support mechanism, flexibility is no longer merely an optional feature but a necessary component of investment strategy. This finding is consistent with recent studies highlighting that real options-based flexibility plays a key role in managing policy and market uncertainty in renewable energy investments [79, 85].

4.2.3. Long-Term energy transition and policy coordination

Global literature on energy transition emphasizes that sustainable energy investments are highly sensitive to financial incentive design, and that FiT mechanisms, in particular, are critical to achieving carbon neutrality targets [36, 80, 101, 102]. In this context, Türkiye's transition to a TRY-based FiT design highlights important aspects that need to be reassessed in terms of its capacity to attract and sustain long-term investments.

The findings of this study indicate that, while the TRY-based structure introduces a degree of adaptability through indexation, it simultaneously increases exposure to macroeconomic risks, particularly under conditions of high inflation and exchange rate volatility. This weakens revenue predictability and may reduce overall investment attractiveness. Accordingly, effective policy design should aim to balance adaptability with stability in order to sustain long-term renewable energy investments.

From a policy perspective, the results suggest that the current TRY-based YEKDEM structure could be enhanced through more targeted design adjustments. One potential approach is the adoption of hybrid pricing mechanisms that combine foreign currency anchoring with domestic indexation, thereby limiting excessive exposure to exchange rate fluctuations while preserving flexibility. In addition, revising indexation formulas to include smoothing mechanisms or caps on inflation and exchange rate adjustments may help stabilize revenue streams. The introduction of partial hedging instruments or floor price guarantees could further mitigate downside risks for investors. Such refinements would improve investment predictability without eliminating the adaptive features of the current system.

Furthermore, this relationship between incentive design and investment behavior is also reflected in the evolution of installed wind capacity in Türkiye. Periods characterized by more predictable support mechanisms are associated with more stable and accelerated capacity growth, whereas increased uncertainty under the TRY-based structure corresponds to more cautious and fluctuating investment dynamics. This observation provides empirical support for the argument that feed-in tariff design influences not only financial valuation outcomes but also the pace and stability of renewable energy deployment.

4.3. Assessment in the Context of the UN Sustainable Development Goals

These findings demonstrate that Türkiye's energy transition goals are not only economic but also linked to global climate policies. The effects of the YEKDEM incentive structure on investment behavior are directly aligned with the carbon reduction commitments of the Paris Climate Agreement and the United Nations Sustainable Development Goals (specifically SDG 7 – Affordable and Clean Energy, SDG 9 – Industry, Innovation, and Infrastructure, and SDG 13 – Climate Action). The real option approach's more realistic modeling of decisions under uncertainty demonstrates its utility as a strategic tool in long-term planning for sustainable energy investments. In this context, the results not only provide an assessment of the national incentive mechanism but also provide an analytical framework that will contribute to policy design in Türkiye's low-carbon economic transformation process.

4.4. Methodological Comparison of Real Option Models

The findings of this study suggest that the relationship between Black–Scholes and Binomial model outcomes is strongly influenced by both the structure of the option and the specification of volatility. In line with existing literature, the results show that for deferral options—characterized by a single optimal exercise decision—the two models tend to converge, particularly under relatively stable conditions [65, 78, 81, 103, 104]. This convergence becomes more evident when volatility is derived from project cash flows, where lower uncertainty leads to nearly identical optimal deferral periods. However, the results also indicate that this consistency weakens when volatility is measured based on electricity prices. Under higher and more volatile conditions, the difference between model outputs becomes more pronounced, suggesting that model sensitivity increases with the level and source of uncertainty. This observation aligns with recent studies emphasizing that real option valuation outcomes are highly dependent on how uncertainty is modeled, particularly in energy investments exposed to market and policy risks [44, 77, 81].

A clearer distinction emerges in the case of the expansion option, where multiple decision points and time-varying payoffs introduce additional complexity. In this study, the variation in SΔ(T) across years, combined with a constant expansion cost, creates a dynamic structure that resembles American-style decision-making. In such settings, the Binomial model appears to capture the flexibility embedded in sequential investment decisions more effectively. This is consistent with recent literature highlighting the advantages of discrete-time models in representing staged investments and policy-driven uncertainty in renewable energy projects [79, 85, 88].Within this context, the difference observed between the two models—where the Black–Scholes model suggests Year 3, and the Binomial model suggests Year 4 as the optimal expansion timing—can be interpreted as a reflection of their underlying structural assumptions. Rather than indicating a contradiction, this difference highlights how discrete-time modeling captures additional layers of flexibility that may slightly shift optimal decisions.

Overall, these findings suggest that model selection becomes increasingly important in environments characterized by higher uncertainty and multi-stage decision structures. While Black–Scholes provides a useful benchmark under simplified conditions, Binomial approaches offer a more flexible framework for capturing the dynamic nature of investment decisions in renewable energy projects.

4.5. Limitations and Generalizability

This study is based on a stylized single-project framework, which may limit the generalizability of the results. Similar to many real options applications in the energy literature, the analysis relies on a representative project structure to capture investment dynamics under uncertainty [63, 88]. First, the findings are sensitive to key input parameters such as capacity factor, volatility, discount rate, and investment costs. Variations in these parameters may lead to different optimal investment timings and option values. Second, the model assumes a representative wind power project with a fixed capacity and financing structure; therefore, the results may not directly apply to projects with different scales, resource conditions, or capital structures. This limitation is consistent with previous Türkiye-focused real options studies, which also emphasize the project-specific nature of investment valuation [104, 105]. Third, while the findings provide important insights into the effects of the TRY-based YEKDEM mechanism, they should not be interpreted as fully representative of the entire Turkish renewable energy sector, but rather as indicative results for similar project configurations. Finally, future research could extend this framework by

incorporating multiple project types, stochastic policy scenarios, and alternative financing structures.

5. CONCLUSIONS AND RECOMMENDATIONS

This study examines the economic feasibility of renewable energy investments in Türkiye within the context of changing market conditions following the transition from a fixed foreign exchange-based price structure to a TRY-based indexation system under the YEKDEM incentive mechanism. Analyses based on both the Net Present Value (NPV) method and the real options approach (ROA) demonstrate that, in environments characterized by macroeconomic volatility, traditional valuation methods provide a limited perspective, whereas real options models offer a more comprehensive framework by incorporating risk, flexibility, and investment timing.

The findings reveal that the transformation of the incentive mechanism has a decisive impact on investment feasibility. The predictable cash flows provided under the foreign exchange-based system are replaced by a more volatile income structure that is highly sensitive to inflation, exchange rate fluctuations, and policy-driven risk. As a result, NPV declines to negative values—particularly in the 2025 scenario—suggesting that investments appear unfeasible under conventional methods. However, increased volatility under the TRY-based structure enhances the value of managerial flexibility, particularly through deferral and expansion options. When evaluated using real options, the total investment value returns to positive levels. This finding confirms that ROA is not only complementary but also an essential analytical tool in environments characterized by high volatility and policy-driven risk.

A key contribution of this study lies in the comparison of alternative volatility specifications. The results show that volatility derived from electricity prices is significantly higher than volatility calculated based on project cash flows, indicating that risk is primarily driven by market and policy dynamics rather than project-level variability. Sensitivity analysis further reveals that lower, cash flow-based volatility leads to longer optimal deferral periods and convergence between Black–Scholes and Binomial model outcomes, whereas higher price-based volatility shortens investment timing and increases divergence between model results. This highlights the critical importance of volatility specification in real options valuation.

The study also highlights the importance of decision flexibility in shaping investor behavior under the TRY-based YEKDEM regime. Investors increasingly rely on deferral and staged expansion

strategies to manage macroeconomic volatility, reflecting a shift from static investment decisions toward more adaptive and sequential approaches. This is reflected in the shorter optimal deferral periods and higher expansion option values observed under the 2025 scenario. Furthermore, electricity price volatility and the discount rate emerge as the most influential determinants of investment value, while financing conditions and broader macroeconomic risks further reinforce investment uncertainty.

From a policy perspective, the results suggest that the effectiveness of incentive mechanisms depends not only on their structural design but also on their ability to provide revenue stability under macroeconomic volatility. While the TRY-based structure introduces adaptability through indexation, it may weaken investment attractiveness by increasing exposure to inflation and exchange rate risks. Therefore, a balanced policy framework that combines adaptability with predictability is essential for sustaining long-term renewable energy investments in Türkiye. This suggests that policy design plays a central role not only in investment feasibility but also in shaping the pace of energy transition.

Based on these findings, the widespread adoption of real option-based valuation approaches at the institutional level in the Turkish energy market emerges as a critical need. Integrating ROA into investment planning, incentive design, and policy evaluation processes will enable more realistic and resilient decision-making in uncertain environments. The development of real option-based guidelines by public institutions and regulatory authorities would further strengthen both investor strategies and policy effectiveness.

The high option values identified in this study demonstrate that renewable energy investments remain a rational and sustainable choice even under conditions of significant uncertainty. By enabling more flexible and informed decision-making, the real options approach supports the continuation of investments rather than their postponement, thereby contributing to the expansion of renewable energy capacity in Türkiye and the reduction of greenhouse gas emissions. In this context, the study highlights that ROA not only enhances financial feasibility but also supports policy objectives aligned with the Paris Climate Agreement and the United Nations Sustainable Development Goals (SDG 7: Affordable and Clean Energy, SDG 9: Industry, Innovation, and Infrastructure, and SDG 13: Climate Action).

Taken together, these findings provide both methodological and policy-relevant insights for renewable energy investment under uncertainty. Overall, the study demonstrates that in markets characterized by high volatility, investment decisions should not rely solely on deterministic cash flow-based methods. Instead, dynamic valuation approaches that incorporate flexibility, timing, and strategic options are essential for improving the quality and sustainability of long-term renewable energy investments.

USE of AI TOOLS

The authors used AI-based language tools solely for grammar checking, language editing, and improving readability. No AI tools were used for data analysis, model development, or generation of scientific content. All results, interpretations, and conclusions are the sole responsibility of the authors.

DECLARATION OF ETHICAL STANDARDS

The author of the study submitted declares that nothing which is necessary for achieving the study requires ethical committee and/or legal-special permissions

CONTRIBUTION OF THE AUTHORS

Duygu Bıyıklı: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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