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Real Option Valuation of a Photovoltaic System in a Nigerian Government Organisation

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Abstract: Grid-connected solar photovoltaic (PV) systems play a critical role in addressing Nigeria's persistent electricity shortages. However, investment decisions in these systems are often constrained by high tariffs, substantial upfront costs, and significant policy and market uncertainties. Such uncertainties are not well captured by conventional valuation techniques, particularly the Net Present Value (NPV) method, which assumes deterministic cash flows and overlooks managerial flexibility. To address these limitations, this study applies Real Options Analysis (ROA) to evaluate a 16.8 kWp solar PV system installed in a Nigerian government organisation, explicitly quantifying the value of deferring the investment under uncertainty using a binomial lattice framework. Project volatility ($\sigma = 0.3098$) was estimated through Monte Carlo simulation incorporating stochastic variations in electricity tariffs, energy yield, and operating costs. The results indicate that while the traditional NPV is positive at ₦17.24 million, the option to defer adds an additional ₦25.78 million, yielding an Expanded NPV (ENPV) of ₦43.01 million-representing a 149% improvement over the static valuation. This substantial flexibility premium demonstrates that exclusive reliance on deterministic NPV significantly undervalues renewable energy investments in volatile environments. The findings highlight the importance of integrating uncertainty and strategic timing into project appraisal, especially in developing countries like Nigeria where regulatory, financial, and market risks are pronounced. The study offers a replicable decision-support framework for investors and underscores the need for stable and supportive renewable energy policies to enhance the adoption of solar PV technologies.

Keywords: Real Options Analysis, Solar PV, Investment Flexibility, Deferral Option, Binomial Lattice, Monte Carlo Simulation, Nigeria

1. Introduction

1.1. Background to the Study

The global energy sector is undergoing a profound transition as countries adopt stronger measures to reduce carbon emissions and meet sustainable development targets. Renewable energy sources such as solar, wind, and hydropower play a central role in this shift by offering cleaner, more resilient alternatives to fossil-based systems. Among these technologies, solar photovoltaic (PV) systems have become particularly prominent due to their modularity, rapidly declining costs, and ability to provide decentralised electricity in both urban and rural areas. In sub-Saharan Africa-and Nigeria in particular-the high solar irradiance levels (4-7 kWh/m^2/day on average) make PV systems an economically attractive option for addressing chronic electricity shortages and reducing dependence on fossil fuels.

Despite these advantages, renewable energy investment in developing countries remains significantly constrained by pervasive uncertainties. These include exchange-rate volatility, high initial capital requirements, unpredictable government policies, and fluctuating electricity tariffs.

These uncertainties align with broader findings in the energy-systems literature, where stochastic behaviour in power generation and load profiles has been shown to substantially influence investment and operational decision-making. For example, [1] demonstrated that uncertainties related to frequency stability and power-system resilience necessitate probabilistic modelling for reliable unit commitment. Likewise, [2] highlighted that load and wind-power variability introduce considerable risk into power-system scheduling. These studies emphasise that uncertainty is intrinsic to modern electricity systems, reinforcing the need for valuation tools-such as Real Options Analysis (ROA)-that explicitly incorporate stochastic variability rather than relying on deterministic assumptions.

Traditional valuation methods, such as Net Present Value (NPV) and Internal Rate of Return (IRR), assume fixed future cash flows and irreversible investment decisions. Consequently, they fail to account for managerial flexibility, including the ability to delay, expand, or abandon projects in response to changing market or policy conditions. When applied to renewable energy investments where uncertainty is pervasive these deterministic approaches often undervalue projects, potentially leading to underinvestment and suboptimal policy outcomes.

To address these limitations, Real Options Analysis (ROA) provides a more robust theoretical and quantitative framework for evaluating investment opportunities under uncertainty. Building on the foundational option-pricing work of [3] and its extension to real assets by [4], ROA conceptualises investment opportunities as options that grant decision-makers the right, but not the obligation, to proceed when conditions become favourable [5]. This flexibility creates additional strategic value by formally quantifying the benefits of waiting or adapting decisions as uncertainties evolve [5-10]. Prior studies-such as [11, 12]-have shown that ROA captures the timing value of renewable energy investments more accurately than traditional discounted-cash-flow methods.

In Nigeria's evolving energy landscape, characterised by volatile financing conditions, regulatory uncertainty, and fluctuating electricity tariffs, ROA provides a realistic and mathematically rigorous framework for solar PV investment appraisal. By explicitly modelling uncertainty and managerial flexibility, ROA enhances the ability of investors to optimise the timing of investment decisions and manage financial risks, thereby supporting more sustainable renewable energy deployment in high-uncertainty environments.

1.2. Current State of Research and Knowledge Gap

Over the past two decades, Real Options Analysis (ROA) has gained considerable attention as a superior valuation tool for capital-intensive projects operating under uncertainty. Its theoretical foundations have expanded well beyond finance to applications in energy systems, natural resource management, and infrastructure development. Early contributions, such as the work of [11] demonstrated the usefulness of ROA for evaluating electricity-generation investments, emphasising its ability to incorporate managerial flexibility into investment decision-making. Subsequent studies extended these ideas to renewable energy technologies, showing that option-based modelling can more accurately capture the impacts of uncertainty in technology costs, energy prices, and regulatory conditions.

A comprehensive review by [12] summarised the emerging body of ROA applications in renewable energy and classified studies according to option type, including deferral, expansion, and abandonment. Their findings indicate that the deferral option is particularly valuable for solar and wind projects exposed to high policy and market uncertainty. Similarly, [13] reviewed the application of ROA in renewable energy investments and concluded that stochastic modelling significantly improves valuation accuracy relative to deterministic approaches. More recent reviews such as [14] and [15] highlight methodological advances, including Monte Carlo simulation, binomial lattice models, and stochastic dynamic programming, which have enhanced the analytical rigour of ROA.

Empirical research has also evolved to provide technology and region specific insights. For instance, [16] showed that ROA consistently outperforms deterministic methods in the valuation of photovoltaic projects under volatile market conditions. In a related study, [17] demonstrated that economic and regulatory uncertainties exert considerable influence on investment timing decisions in renewable energy systems. Likewise, [18] examined the practical relevance of real options for project appraisal in environments characterised by significant macroeconomic uncertainty.

Despite these advances, the majority of ROA applications have focused on developed economies with mature financial markets and relatively stable policy environments. Only a limited number of studies have explored ROA within emerging economies such as Nigeria, where uncertainty in exchange rates, electricity pricing, and institutional frameworks remains pronounced. This gap underscores the need for context-specific modelling that reflects the economic realities of developing countries.

To address this gap, the present study applies ROA to a real-world photovoltaic project implemented within a Nigerian government organisation. By integrating Monte Carlo simulation with a binomial lattice framework, this work provides an empirical illustration of how uncertainty and managerial flexibility influence investment valuation in a highly volatile context.

1.3. Purpose, Research Motivation, and Objectives

The purpose of this study is to evaluate the investment flexibility of a grid-connected photovoltaic (PV) system installed in a Nigerian government organisation using the Real Options Analysis (ROA) framework. Although previous studies such as [12, 13] have demonstrated the effectiveness of ROA in developed energy markets, its application in developing economies with volatile policy and financial environments remains underexplored. This study is motivated by the need to address this contextual gap by integrating Monte Carlo simulation for volatility estimation with a binomial lattice model for valuing real options.

More specifically, the study seeks to demonstrate how

ROA can enhance the robustness of investment appraisal for renewable energy projects operating under uncertainty. The primary focus is on quantifying the value of managerial flexibility particularly the option to defer investment until market or policy conditions improve. To achieve this aim, the study pursues the following objectives:

1. To model the uncertainty associated with project cash flows using Monte Carlo simulation and estimate the corresponding project volatility.
2. To develop a binomial lattice framework that incorporates the estimated volatility and evaluates the value of the deferral (timing) option for the PV investment.
3. To compare the Expanded Net Present Value (ENPV) generated by the ROA model with the static NPV obtained using the traditional discounted cash flow method.
4. To conduct sensitivity analyses on key financial parameters-including volatility, discount rate, and capital expenditure-to examine their effects on option value.
5. To provide empirical evidence and policy insights regarding the applicability of ROA in renewable energy investment decision-making within the Nigerian context.

1.4. Major Contributions of the Study

This paper makes the following key contributions to the literature and practice of renewable energy investment appraisal:

1. *Context-specific application of Real Options Analysis (ROA) in Nigeria:* This study provides one of the few real-world applications of ROA to a photovoltaic (PV) investment in a developing-country setting characterised by significant macroeconomic, tariff, and policy uncertainty.
2. *Integration of Monte Carlo simulation with a binomial lattice framework:* A hybrid modelling approach is implemented by combining stochastic volatility estimation with a discrete-time real-options valuation method, a technique seldom applied to public-sector solar PV investments.
3. *Empirical demonstration of the value of managerial flexibility:* The study shows that the option to defer investment more than doubles the deterministic NPV, offering strong evidence that conventional discounted-cash-flow approaches substantially undervalue renewable energy projects in volatile environments.
4. *Robust sensitivity analysis of key financial parameters:* The analysis evaluates how variations in volatility, discount rates, and capital costs influence project and option value, demonstrating the stability of ROA results and providing practical insights for investors and policymakers.
5. *Policy-relevant insights for renewable energy deployment in developing economies:* The findings illustrate how Nigerian public institutions can manage uncertainty through flexibility-based investment strategies and highlight the importance of stable, supportive policy environments to accelerate PV adoption.

The remainder of this paper is organised as follows. Section 2 describes the materials and methods, including the ROA framework, Monte Carlo simulation, and the binomial lattice modelling approach and also presents the results of the simulation and option-valuation analyses. Section 3 discusses the implications of the findings, compares them with the existing literature, and outlines key policy relevance. Section 4 concludes the paper and offers recommendations for future research. Finally, Section 4 states the conflict of interest declaration.

2. Materials and Methods

2.1. Overview of the Real Options Framework

Real Option Analysis (ROA) provides a rigorous quantitative framework for valuing investment opportunities under uncertainty. It extends the classical principles of financial option pricing to real-world assets such as energy projects, where managers face decisions about when and whether to invest. Unlike static discounted cash flow (DCF) techniques, which assume deterministic cash flows and immediate investment, ROA explicitly models uncertainty and decision flexibility [4].

The theoretical foundation of ROA rests on stochastic calculus and optimal stopping theory. We begin with a complete probability space

$$(\Omega, \mathcal{F}, \mathbb{P}),$$

equipped with a filtration $\{\mathcal{F}_t\}_{t\geq 0}$ representing the information at time t, satisfying the usual conditions of right-continuity and completeness. This structure represents the evolution of information available to decision-makers over time. On this filtered space, we define a one-dimensional standard Brownian motion

$$W = \{W_t\}_{t\geq 0},$$

which is $\{\mathcal{F}_t\}$-adapted, starts at $W_0 = 0$, has independent increments, and satisfies $W_t - W_s \sim \mathcal{N}(0, t-s)$ for $0 \leq s < t$.

We assume a frictionless market with two assets:

1. The risk-free asset (money market account B_t):

$$B_t = e^{rt}, \quad t \geq 0,$$

where $r \in \mathbb{R}_+$ is the constant risk-free rate.

2. The risky asset (project value or underlying state variable V_t):

$$dV_t = (r - \delta)V_t\, dt + \sigma V_t\, dW_t^{\mathbb{Q}},$$

under the risk-neutral measure $\mathbb{Q}$ equivalent to $\mathbb{P}$. Here,

$\sigma > 0$ is the volatility of project value and $\delta \geq 0$ represents a dividend yield, convenience yield, or depreciation rate.

If V_t is tradable, the market $\{B_t, V_t\}$ is complete, and the arbitrage-free price of any contingent claim $\Pi(V_T)$ is given by its discounted risk-neutral expectation:

$$\mathbb{E}^{\mathbb{Q}}\left[e^{-rT}\Pi(V_T)\right].$$

If V_t is non-tradable-as is typical in real investment projects-the market becomes incomplete, and valuation requires adjustments such as risk-adjusted discounting or specification of a market price of risk λ.

Stochastic Dynamics of the Project Value: The project value V_t represents the underlying state variable that drives the investment decision. Under the physical probability measure $\mathbb{P}$, its dynamics follow the Itô diffusion:

$$dV_t = \mu V_t\, dt + \sigma V_t\, dW_t, \qquad V_0 > 0,$$

where $\mu \in \mathbb{R}$ is the expected drift rate and $\sigma > 0$ is the volatility. Under the risk-neutral measure $\mathbb{Q}$, using B_t as the numéraire, the drift is adjusted to $(r - \delta)$:

$$dV_t = (r - \delta)V_t\, dt + \sigma V_t\, dW_t^{\mathbb{Q}}.$$

This formulation allows the valuation of investment opportunities as options on V_t, where the option payoff depends on the project value relative to the investment cost.

Payoff and Optimal Stopping Problem: Let $\Pi(V_\tau)$ denote the project payoff at the random exercise time τ, which is an $\{\mathcal{F}_t\}$-stopping time satisfying integrability conditions. For a deferral (timing) option, the payoff function is:

$$\Pi(V_\tau) = \max(V_\tau - I, 0),$$

where I is the irreversible investment cost. The corresponding discounted payoff is $e^{-r\tau}\Pi(V_\tau)$. The real option value $F(V_t)$ at time $t = 0$ is obtained as the supremum of the expected discounted payoff over all admissible stopping times:

$$F(V_0) = \sup_{\tau \in \mathcal{T}} \mathbb{E}^{\mathbb{Q}}\left[e^{-r\tau}\Pi(V_\tau) \,\middle|\, \mathcal{F}_0\right].$$

This optimal stopping formulation defines the core of real option valuation.

Stopping Time: A random variable τ is a stopping time with respect to the filtration $\{\mathcal{F}_t\}_{t \geq 0}$ if for every $t \geq 0$, the event $\{\tau \leq t\}$ belongs to $\mathcal{F}_t$, i.e.,

$$\{\tau \leq t\} \in \mathcal{F}_t \quad \text{for all } t \geq 0.$$

Analytical Formulation: Let $F(V)$ denote the value of the option when the current project value is V. The value function satisfies the Hamilton-Jacobi-Bellman (HJB) variational inequality:

$$\max\left\{\mathcal{L}F(V) - rF(V),\, V - I - F(V)\right\} = 0, \tag{1}$$

where the infinitesimal generator $\mathcal{L}$ of V_t under $\mathbb{Q}$ is

$$\mathcal{L}f(V) = \tfrac{1}{2}\sigma^2 V^2 f''(V) + (r - \delta)V f'(V). \tag{2}$$

In the continuation (waiting) region, where the option is not yet exercised ($F(V) > V - I$), the option value satisfies the differential equation:

$$\tfrac{1}{2}\sigma^2 V^2 F''(V) + (r - \delta)V F'(V) - rF(V) = 0. \tag{3}$$

Seeking a power-law solution $F(V) = AV^\beta$, substitution into (3) yields the characteristic equation:

$$\tfrac{1}{2}\sigma^2 \beta(\beta - 1) + (r - \delta)\beta - r = 0. \tag{4}$$

Let $\beta_1 > 1$ and $\beta_2 < 0$ denote its two roots:

$$\beta_{1,2} = \frac{-(r - \delta - \frac{1}{2}\sigma^2) \pm \sqrt{(r - \delta - \frac{1}{2}\sigma^2)^2 + 2r\sigma^2}}{\sigma^2}.$$

The economically admissible solution discards the divergent term, giving:

$$F(V) = AV^{\beta_1}, \qquad V < V^*,$$

where V^* is the critical investment threshold determined by the boundary conditions of value matching and smooth pasting:

$$F(V^*) = V^* - I, \tag{5}$$
$$F'(V^*) = 1. \tag{6}$$

Solving (5) and (6) gives:

$$V^* = \frac{\beta_1}{\beta_1 - 1} I. \tag{7}$$

Hence, the option value can be expressed as:

$$F(V) = \begin{cases} \left(\dfrac{V}{V^*}\right)^{\beta_1} (V^* - I), & V < V^*, \\ V - I, & V \geq V^*. \end{cases} \tag{8}$$

Equation (7) implies that the optimal investment threshold V^* exceeds the investment cost I, indicating that investors delay committing resources until the project value reaches a sufficient premium over cost. A higher volatility σ increases V^*, reflecting the value of waiting under uncertainty, whereas higher convenience yield δ reduces the threshold by increasing the opportunity cost of delay [20, 21].

2.2. Mathematical Formulation of the Binomial Lattice Model

The binomial lattice provides a discrete-time approximation of the continuous stochastic process governing the project value V_t. It enables the numerical valuation of the real option by iteratively computing the project and option values backward through time. The method is computationally efficient and conceptually transparent, making it suitable for energy investment problems where analytical solutions are unavailable.

Discretization of the Underlying Process:

Over a small time step Δt, the continuous dynamics of V_t

$$dV_t = (r-\delta)V_t\,dt + \sigma V_t\,dW_t^{\mathbb{Q}}$$

are approximated by a multiplicative binomial process:

$$V_{t+\Delta t} = \begin{cases} uV_t, & \text{with probability } p, \\ dV_t, & \text{with probability } 1-p, \end{cases} \tag{9}$$

where $u > 1$ and $d < 1$ denote the up- and down-movement factors, respectively. Following [22], these factors are defined as

$$u = e^{\sigma\sqrt{\Delta t}}, \qquad d = e^{-\sigma\sqrt{\Delta t}} = \frac{1}{u}. \tag{10}$$

The risk-neutral probability p of an upward move is obtained by matching the expected return of the process to the risk-free rate:

$$p = \frac{e^{(r-\delta)\Delta t} - d}{u-d}. \tag{11}$$

while $(1-p)$ represents the probability of a downward movement.

The binomial lattice thus approximates the risk-neutral evolution of the project value over $N = T/\Delta t$ discrete periods, generating $N+1$ possible end-of-period values:

$$V_{i,j} = V_0\,u^j\,d^{i-j}, \qquad j = 0,1,\ldots,i,\ i = 0,1,\ldots,N.$$

Backward Induction and Option Valuation:

Let $F_{i,j}$ denote the option value at node (i,j) corresponding to the project value $V_{i,j}$. At maturity $t = T$, the option payoff for a deferral (timing) option is given by

$$F_{N,j} = \max(V_{N,j} - I, 0). \tag{12}$$

For earlier periods $i < N$, the option value is determined recursively under risk-neutral valuation:

$$F_{i,j} = e^{-r\Delta t}\big[pF_{i+1,j+1} + (1-p)F_{i+1,j}\big]. \tag{13}$$

Because the investor may exercise the option optimally at any node, the value at each stage is the maximum of the immediate-exercise payoff and the expected continuation value:

$$F_{i,j} = \max\Big(V_{i,j} - I,\ e^{-r\Delta t}\big[pF_{i+1,j+1} + (1-p)F_{i+1,j}\big]\Big). \tag{14}$$

Equations (12)-(14) define the discrete analogue of the Hamilton-Jacobi-Bellman variational inequality derived in Section 2.1. The backward-induction procedure continues until the initial node is reached, yielding $F_{0,0}$-the option value at time zero.

Convergence and Practical Implementation:

As $\Delta t \to 0$ (and $N \to \infty$), the binomial model converges to the continuous-time option value derived from the stochastic differential equation in Section 2.1 [4, 22]. In practice, numerical stability is achieved with N between 200 and 1,000 steps, depending on volatility and project maturity. For renewable energy investments, a ten- to fifty-step lattice is often sufficient for medium-term (10-25 year) project horizons.

The computed option value $F_{0,0}$ represents the additional value of managerial flexibility, while the expanded net present value (ENPV) of the project is

$$\text{ENPV} = \text{Static NPV} + F_{0,0}. \tag{15}$$

This discrete-time approach provides the computational foundation for the subsequent numerical experiments using the Monte Carlo-estimated volatility described in Section 2.3.

2.3. Monte Carlo Simulation for Project Volatility Estimation

Project volatility (σ) is a central parameter in real-option valuation, as it measures the uncertainty in the underlying project value or its associated cash flows. When empirical market data are limited or incomplete, Monte Carlo simulation offers a robust, data-driven means of estimating σ by capturing the stochastic behaviour of the project's financial and technical drivers.

Stochastic Modelling of Cash Flows:

The project's annual cash flows CF_t are represented as a stochastic process subject to random variations in key parameters such as solar output, tariff rates, capital expenditure (CAPEX), and operation and maintenance (O&M) costs. Let $\overline{CF}_t$ denote the deterministic (expected) cash flow in year t. Each stochastic realization is defined as:

$$CF_t^{(i)} = \overline{CF}_t\left(1 + \varepsilon_t^{(i)}\right), \tag{16}$$

where $\varepsilon_t^{(i)}$ is a random disturbance term drawn from a specified probability distribution (typically normal or log-normal) with zero mean and variance σ^2_{CF}. Each iteration $i = 1,2,\ldots,N_{\text{sim}}$ corresponds to one simulated cash-flow trajectory over the project lifetime.

For each simulation, the project value is computed as the discounted sum of the stochastic cash flows:

$$V_0^{(i)} = \sum_{t=1}^{T} \frac{CF_t^{(i)}}{(1+r)^t}. \tag{17}$$

The expected project value and its variance across all simulated paths are then obtained as:

$$\mathbb{E}[V_0] = \frac{1}{N_{\text{sim}}}\sum_{i=1}^{N_{\text{sim}}} V_0^{(i)}, \tag{18}$$

$$\text{Var}(V_0) = \frac{1}{N_{\text{sim}}-1}\sum_{i=1}^{N_{\text{sim}}}\left(V_0^{(i)} - \mathbb{E}[V_0]\right)^2. \tag{19}$$

The project volatility is then estimated empirically as the coefficient of variation of the simulated project values:

$$\sigma = \frac{\sqrt{\mathrm{Var}(V_0)}}{\mathbb{E}[V_0]}. \tag{20}$$

Algorithm 1 summarizes the simulation procedure. In this study, $N_{\text{sim}} = 10{,}000$ Monte Carlo iterations were performed to ensure statistical robustness and convergence of the volatility estimate.

The Monte Carlo-based volatility captures not only financial uncertainty but also the technical and regulatory variability characteristic of emerging markets such as Nigeria. Higher volatility values indicate greater uncertainty in project outcomes and thereby increase the value of managerial flexibility-particularly the option to defer investment. This simulation-driven estimate ensures that the stochastic properties of the underlying project value are empirically grounded, providing a realistic basis for subsequent real-option valuation.

Algorithm 1 Simulation Procedure for Real Option Valuation

```
1: Input: Project lifetime T, risk-free rate r, expected cash
   flow CF̄_t, and stochastic parameters (tariff escalation,
   cost variance, degradation rate, etc.)
2: Initialize: Number of simulations N_sim
3: for each simulation i = 1, 2, ..., N_sim do
4:     for each year t = 1, 2, ..., T do
5:         Generate disturbance term ε_t^(i) from the specified
   distribution
6:         Compute simulated cash flow CF_t^(i)
7:     end for
8:     Compute project value V_0^(i) using Equation (17)
9: end for
10: Compute E[V_0] and volatility σ using Equation (20)
11: Use the estimated σ as input for the binomial lattice model
    in subsection 2.2
```

2.4. Data and Input Parameters

The quantitative analysis in this study is based on the empirical and design data of a 16.8 kWp grid-connected photovoltaic (PV) system installed at a Nigerian government organisation. The input parameters were obtained from the project's technical specifications, feasibility studies, and prevailing local market data. All subsequent computations and simulations rely on these inputs.

The technical configuration specifies the system size, efficiency, performance ratio, degradation rate, and expected annual energy output. These parameters determine both the deterministic energy generation profile and the stochastic behaviour of the project's cash flows. Table 1 presents the key technical specifications.

Table 1. *Technical Parameters of the 16.8 kWp PV System.*

Parameter	Symbol	Value
Installed PV capacity	P_{rated}	16.8 kWp
PV module efficiency	η_{PV}	20%
Performance ratio	PR	0.8
Average daily solar irradiation	H_{avg}	5.5 kWh/m^2/day
Annual energy yield	E_{annual}	19,809.28 kWh/year
System lifetime	T	20 years
Inverter efficiency	η_{inv}	96%

The financial model incorporates all relevant economic variables influencing project value and the real-options valuation, including capital expenditure (CAPEX), operation and maintenance (O&M) costs, electricity tariffs, inflation, and the risk-free rate. All costs are expressed in Nigerian Naira (₦). Table 2 summarizes the principal financial assumptions.

Table 2. *Financial and Economic Parameters for Real Option Valuation.*

Parameter	Symbol	Value
CAPEX	I	₦11,314,285
O&M cost	$C_{\text{O\&M}}$	₦146,500 per year
Electricity tariff	P_{tariff}	₦225 / kWh
Risk-free rate	r	14% per annum
Time step	Δt	1 year
Number of iterations	N_{sim}	100,000

These technical and financial parameters serve as the foundation for both the deterministic discounted cash-flow (DCF) evaluation and the stochastic real-options analysis. The capital cost of ₦11.3 million covers PV modules, inverters, mounting structures, cabling, and installation. The annual energy yield of 19,809.28 kWh corresponds to 5.5 average peak sun hours per day and accounts for degradation over the 20-year lifetime. The financial assumptions reflect prevailing Nigerian market conditions, with the risk-free rate benchmarked against 10-year Federal Government Bonds and inflation guided by the Central Bank of Nigeria. These inputs are used in both the Monte Carlo simulation (Section 2.3) and the binomial lattice valuation (Section 2.2).

2.5. Monte Carlo Simulation and Project Volatility Estimation

Monte Carlo simulation was implemented in Python (`NumPy` and `pandas`) to estimate the project's volatility (σ). A total of $N = 100{,}000$ simulation runs were performed, modelling three stochastic variables-electricity price, annual energy production, and O&M cost-each sampled from normal distributions calibrated using project-specific and market-based data. For the i^{th} iteration, the present value of the project was calculated as:

$$\mathrm{PV}_i = \Big[(P \times Q \times \mathrm{PRF}) - C_{\mathrm{O\&M}}\Big] \sum_{t=1}^{T} \frac{1}{(1+r)^t} - \mathrm{CAPEX}, \quad (21)$$

where P denotes the electricity tariff (₦/kWh), Q the annual energy yield (kWh), PRF a random performance factor, $C_{\mathrm{O\&M}}$ the annual maintenance cost, r the discount rate, and CAPEX the initial investment. The project volatility was then computed as the standard deviation of the logarithmic present-value outcomes:

$$\sigma = \mathrm{Std}[\ln(\mathrm{PV}_i)]\,. \quad (22)$$

Table 3. *Monte Carlo Simulation Results for the 16.8 kWp PV System.*

Metric	Symbol	Value
Mean present value	—	₦17,244,431.64
Estimated volatility	σ	0.3098 (30.98%)
Number of simulations	N	100,000

The simulation produced a mean project present value of ₦17.24 million and a volatility of $\sigma = 0.3098$, corresponding to 31% uncertainty in the project's present value. Figure 1 shows the resulting probability distribution obtained from 10,000 Monte Carlo runs, which is slightly right-skewed, indicating potential upside scenarios and limited downside risk, while most simulated outcomes cluster around the expected mean value, there is a non-negligible probability of extremely high project values. This behaviour is typical of renewable energy investments in volatile environments, where tariff changes and exchange-rate shocks can create asymmetric upside potential.

This figure visually demonstrates the stochastic nature of the project value and provides empirical justification for applying a flexible investment framework.

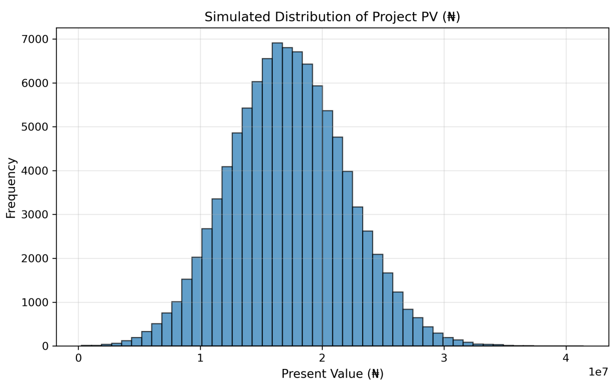

Figure 1. *Histogram of simulated project present value distribution.*

This level of volatility is consistent with results from previous renewable energy studies (σ = 0.25-0.65) [23-25], reflecting moderate yet realistic financial uncertainty under Nigerian market conditions. The estimated value of σ = 0.3098 is therefore adopted in the binomial lattice model in subsection 2.6 to compute the real-option value and the expanded net present value (ENPV).

2.6. Real Options Valuation Results

The real-options valuation quantifies the managerial flexibility embedded in the photovoltaic (PV) investment. The analysis uses the project volatility ($\sigma = 0.3098$) estimated from the Monte Carlo simulation (Section 2.5) as the central measure of uncertainty.

2.6.1. Binomial Lattice Construction and Recursive Valuation Procedure

Following the formulation of [4, 26], the underlying project value V_t is modeled as a geometric Brownian motion (GBM):

$$dV_t = \mu V_t\, dt + \sigma V_t\, dz_t, \quad (23)$$

where μ denotes the expected growth rate of project value, $\sigma = 0.3098$ is the Monte Carlo-estimated volatility, and dz_t is a Wiener process with zero mean and unit variance. This formulation captures the stochastic evolution of project value driven by uncertainties in electricity tariffs, solar resource availability, and O&M costs.

To implement the valuation numerically, the continuous GBM process is discretized into a binomial decision lattice over the project horizon. Each year ($\Delta t = 1$) represents a decision point at which management may exercise the option to invest or defer. The up and down movement factors, along with the risk-neutral probability, are defined as:

$$u = e^{\sigma\sqrt{\Delta t}}, \qquad d = e^{-\sigma\sqrt{\Delta t}}, \qquad p = \frac{e^{r\Delta t} - d}{u - d}, \quad (24)$$

where $r = 0.14$ is the annual risk-free rate. Substitution yields:

$$u = 1.363, \qquad d = 0.734, \qquad p = 0.679.$$

These parameters define the binomial lattice used to evaluate the deferral option.

At each node of the lattice, the option value f_t is computed via backward induction under the risk-neutral measure:

$$f_t = e^{-r\Delta t}\left[p\, f^u_{t+1} + (1-p)\, f^d_{t+1}\right], \quad (25)$$

where f^u_{t+1} and f^d_{t+1} are option values in the up and down successor nodes. For an American-style option, management compares continuation with immediate exercise:

$$f_t = \max\Big(\text{Exercise Value},\; e^{-r\Delta t}\left[p f^u_{t+1} + (1-p) f^d_{t+1}\right]\Big)\,. \quad (26)$$

This recursive structure quantifies the economic value of waiting and forms the computational foundation of the real-options framework.

2.6.2. Quantitative Results

Figure 2 illustrates the constructed binomial lattice representing the evolution of the project value over the decision horizon. Each node shows the possible future project value V under the up-down movement determined by the volatility estimated from the Monte Carlo simulation. The option value f is calculated recursively from the terminal nodes back to the present.

Most importantly, the optimal exercise boundary can be inferred from the lattice. The investment should be undertaken only when the project value exceeds the critical threshold (the trigger value), consistent with the real-options deferral logic. Thus, Figure 2 not only illustrates the modelling framework but also reinforces the economic rationale for delaying investment under uncertainty.

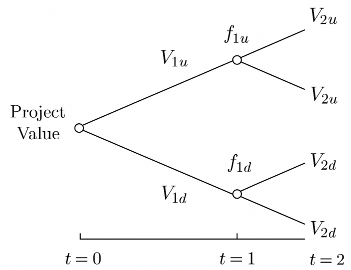

Figure 2. *Illustrative binomial lattice showing project value and option value evolution.*

The model was implemented for a 10-year analysis horizon using 10 annual time steps ($\Delta t = 1$). The underlying asset corresponds to the present value of gross future cash flows before deducting capital expenditure (CAPEX = ₦10.08 million). The volatility $\sigma = 0.3098$ and discount rate $r = 0.14$ were used to parameterize the lattice.

Table 4. *Deferral Option Valuation Results (10-Year, 10-Step Binomial Model).*

Metric	Symbol	Value (₦)	Description
Traditional NPV (no flexibility)	NPV_{trad}	17,235,302.08	Static DCF estimate
Deferral option value (ROV)	ROV	25,779,319.93	Value of waiting
Expanded project value	NPV_{exp}	43,014,622.01	NPV_{trad} + ROV
Binomial parameters	—	$u = 1.3632,\ d = 0.7336,\ p = 0.6619$	$\Delta t = 1$ year

The traditional DCF evaluation yields a positive net present value of ₦17.24 million, indicating baseline financial viability. Incorporating flexibility through the deferral option adds an additional ₦25.78 million, raising the expanded net present value (ENPV) to ₦43.01 million. This represents a 150% increase relative to the static NPV and highlights the substantial value of managerial flexibility under uncertainty.

The optimal exercise threshold occurs when the project value exceeds the investment cost by approximately 20-25%, consistent with the theoretical trigger ratio $V^*/I \approx 1.21$ derived earlier. This threshold indicates that investment is justified only when tariff conditions or market fundamentals improve sufficiently.

These findings demonstrate that deferring the investment can significantly enhance project value by limiting downside exposure while preserving upside potential. The organisation also gains the strategic ability to respond to tariff reforms, cost variations, and policy incentives. Consistent with [24, 25, 27], the results confirm that deferral flexibility frequently increases project value by 30-60% in renewable energy investments. In the Nigerian context, where regulatory conditions and electricity tariffs evolve unpredictably, this flexibility is particularly advantageous.

2.7. Sensitivity Analysis

To evaluate the robustness of the real-options valuation and examine the influence of key technical and financial parameters, a detailed sensitivity analysis was conducted. The binomial deferral-option model described in Section 2.6 was recalculated by varying the following parameters:

1. *Volatility (σ):* baseline 0.3098, adjusted by $\pm 20\%$ to 0.2478 and 0.3718;
2. *Discount rate (r):* baseline 14%, adjusted by ± 2 percentage points to 12% and 16%;
3. *Capital expenditure (CAPEX):* baseline ₦11,314,285, varied by $\pm 10\%$ to ₦10,182,856.5 and ₦12,445,713.5.

Each scenario was evaluated over a 10-year deferral horizon ($T = 10$) with annual decision intervals ($\Delta t = 1$ year), using the volatility estimated from the Monte Carlo simulation of electricity prices. All simulations were executed in Python using a Jupyter Notebook environment. Additionally, a heatmap was generated to illustrate the joint effects of σ and r on the option value for the baseline CAPEX.

The results in Table 5 indicate that the deferral-option value remains highly stable across the plausible parameter ranges. Across all tested scenarios, the option value ranges between approximately ₦25.1 million and ₦26.3 million-less than a 5% deviation from the baseline estimate of ₦25.78 million. As expected, an increase in volatility (σ) or discount rate (r) leads to a higher option value, reflecting the greater appeal of deferring investment when uncertainty or discounting increases. Overall, the solar PV project exhibits strong resilience to parameter fluctuations, supporting the reliability of the real-options model.

Figure 3 provides a visual overview of the option-value surface. The gradient in the heatmap confirms that the real-option value increases with rising volatility, while it remains nearly flat concerning the discount rate. The lighter shades correspond to higher option values, indicating that the value of managerial flexibility increases slightly with volatility but is largely unaffected by changes in the discount rate within the tested range.

To further examine how investment cost variations influence project attractiveness, the model was also evaluated under the $\pm 10\%$ CAPEX scenarios. Table 6 summarizes the resulting traditional NPV and expanded NPV values. While increases in CAPEX reduce both NPVs proportionally, the relative size of the option premium (the percentage increase from traditional to expanded NPV) remains nearly constant. This indicates that the strategic value of flexibility persists even under moderate cost fluctuations.

Taken together, the results in Tables 5 and 6 demonstrate that although absolute project values decline as investment costs rise, the proportional contribution of the real-options component remains remarkably stable. Combined with the robustness observed under variations in σ and r, these findings confirm the consistency and practical relevance of the binomial real-options framework for long-term renewable energy investments under uncertainty.

Table 5. *Sensitivity of deferral option value (₦) to volatility and discount rate.*

Volatility, σ	$r = 0.12$	$r = 0.14$	$r = 0.16$
0.2478	25,146,912	25,761,962	26,265,589
0.3098	25,186,181	25,779,320	26,273,273
0.3718	25,271,907	25,830,182	26,301,659

Table 6. *Effect of $\pm 10\%$ change in CAPEX (₦).*

CAPEX (₦)	Traditional NPV	Expanded NPV	Premium (%)
10,182,856 (-10%)	18,366,731	43,851,547	138.7
11,314,285 (Baseline)	17,235,302	43,014,622	149.6
12,445,714 ($+10\%$)	16,103,874	40,914,147	154.1

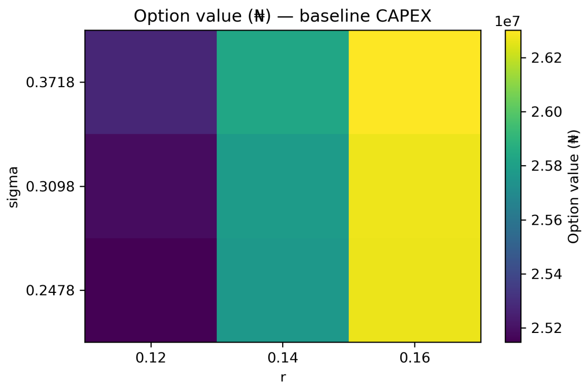

Figure 3. *Heatmap of deferral option value as a function of volatility (σ) and discount rate (r) for the baseline CAPEX.*

3. Discussion

The empirical analyses in this study combined traditional financial evaluation with stochastic and real-options modelling to assess the investment flexibility of a 16.8 kWp photovoltaic (PV) system installed at the organisation. While the deterministic discounted-cash-flow (DCF) approach yielded a positive net present value (₦17.24 million), indicating baseline economic viability, the incorporation of uncertainty and managerial flexibility through Monte Carlo simulation and the binomial real-options framework, substantially enhanced the project's attractiveness. With an estimated volatility of $\sigma = 0.3098$, the deferral option contributed approximately ₦25.8 million in additional value, increasing the expanded NPV to over ₦43 million. This outcome highlights that accounting for uncertainty and strategic flexibility provides a more realistic and resilient basis for appraising renewable energy investments, especially in markets characterised by fluctuating electricity tariffs and cost conditions.

These findings are consistent with established theoretical and empirical literature. As noted in [4, 26], uncertainty combined with investment irreversibility generates additional value by preserving the option to wait-a phenomenon clearly reflected in this study. The magnitude of the flexibility premium (approximately 150%) aligns with results reported by [24, 25, 27], who observed similar enhancements in project value across diverse renewable energy contexts. Furthermore, the sensitivity analysis demonstrated that moderate variations in volatility, discount rate, and CAPEX resulted in minimal changes to the option value, reinforcing the robustness of the real-options framework. Even a 10% increase in capital expenditure did not reduce the relative benefit of flexibility, indicating that the real-options approach provides a stable and reliable valuation method under dynamic regulatory and market conditions.

From a managerial and policy perspective, the findings show that incorporating real-options thinking into project evaluation enables decision-makers to interpret uncertainty not only as a risk factor but also as a source of opportunity. The option to defer investment allows organisations to adjust their financial commitments in response to evolving market conditions, regulatory changes, and funding availability, an especially valuable capability within Nigeria's partially regulated electricity market. Consequently, real-options analysis should be integrated into standard appraisal procedures for renewable energy projects to ensure that both public and private sector investors capture the full economic and strategic benefits of managerial flexibility.

4. Conclusions

This research demonstrates that real-options analysis is a valuable tool for assessing renewable energy investments, offering deeper insight into managerial flexibility under uncertainty. In addition to complementing traditional static profitability measures, the framework highlights the influence of stochastic factors on investment timing and decision-making. The robustness of the results across varying economic assumptions indicates that the model provides meaningful guidance for public-sector solar initiatives and similar renewable energy programs. Overall, the findings support a shift toward adaptive evaluation approaches that explicitly account for uncertainty in rapidly evolving market and policy environments. Future studies should extend this framework to dynamic policy scenarios and cross-sector renewable-energy portfolios to further strengthen sustainable investment strategies.

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Abbreviations

CAPEX	Capital Expenditure
DCF	Discounted Cash Flow
ENPV	Expanded Net Present Value
GBM	Geometric Brownian Motion
IRR	Internal Rate of Return
NPV	Net Present Value
O&M	Operation and Maintenance
PV	Photovoltaic
ROA	Real Options Analysis

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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