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A Real Options-Based Methodology for Evaluating Photovoltaic Investments in Healthcare Facilities under Uncertainty: Application in Colombia

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ABSTRACT

This study proposes a financial evaluation methodology based on real options to assess photovoltaic energy projects in health-care institutions under uncertainty. Applied to a hospital in Barranquilla, Colombia, a solar system generating 16,761 kilowatt-hours (kWh) per year—covering 50% of electricity demand in critical areas—reduced operating costs and improved energy security. The traditional valuation yielded a net present value of US$10,316, while real options analysis produced a value of US$5,334. Scenario analysis showed outcomes ranging from US$5,168 to US$15,467. The expansion strategy could increase the project value to US$72,901, and a put option of US$2,559 offers a safeguard under adverse conditions. The probability of achieving positive returns was 50.1%, with electricity price and solar irradiation as the most influential variables. Beyond its practical findings, the study introduces a novel application of real options tailored to the health-care sector, offering a robust framework for sustainable energy investment planning.

KEYWORDS

Healthcare institutions, Photovoltaic systems, Project feasibility, Real options method, Sustainability, Energy transition.

INTRODUCTION

Colombia's electricity system is heavily dependent on hydropower, accounting for approximately 64% of national generation [1]. While this has historically ensured low-carbon electricity, it also exposes the country to significant risks associated with climate variability, particularly the El Niño–Southern Oscillation (ENSO) phenomenon [2]. ENSO events have triggered severe droughts, reservoir depletion, and electricity shortages, such as the blackouts

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of 1992–1993 and price surges in subsequent years. In response to these vulnerabilities and recent increases in electricity tariffs—averaging 15.3% annually between 2021 and 2024—the Colombian government has implemented policies to diversify the energy matrix, promote decentralised generation, and accelerate investment in renewable technologies, especially photovoltaic (PV) systems [3].

Healthcare institutions represent one of the most critical and energy-intensive sectors affected by these challenges. Hospitals operate 24/7 and require uninterrupted power supply for life-support equipment, surgical facilities, and emergency care units [4]. Interruptions or fluctuations in energy quality can compromise patient safety and system reliability [5]. Despite these high stakes, electricity consumption in the healthcare sector remains reliant on the national grid, with limited integration of renewable energy systems. In recent years, Colombia has experienced a sharp increase in electricity tariffs, averaging 15.3% annually between 2021 and 2024, with a peak of 28.5% in 2022 [6]. This scenario, combined with the country's high photovoltaic generation potential and updated energy policies, has driven remarkable growth in installed PV capacity—from just 6 GWh in 2000 to 964 GWh in 2023, a more than 160-fold increase [7]. According to the Mining-Energy Planning Unit (UPME), the healthcare sector belongs to the tertiary segment, which accounts for approximately 26% of national electricity consumption. In Bogotá, this sector represents 15.1% of tertiary consumption, while in Medellín and Barranquilla it reaches 33.7% and 32.8%, respectively [8]. These conditions highlight a strategic opportunity to deploy PV projects in hospitals to reduce costs, improve energy resilience, and support national sustainability goals.

Recent studies have analysed the economic feasibility of PV systems in buildings and institutions using traditional evaluation methods. For instance, Karanam and Chang [9] assessed solar PV installations in higher education institutions in Connecticut and projected annual revenues across multiple U.S. states based on normalised inputs. Al-Zoubi et al. [10] evaluated an on-grid PV system for a hotel in Jordan, reporting favourable energy yields and a 4.1-year payback period. Imam and Al-Turki [11] examined a residential PV system in Saudi Arabia, using techno-economic indicators and sensitivity analysis to evaluate feasibility. Dalton et al. [12] explored renewable energy supply options for a large hotel, but without considering uncertainty or investment flexibility. In residential contexts, Shabbir et al. [13] optimised battery storage for PV systems using linear programming, while Zhao et al. [14] applied simulation and multi-objective optimisation to evaluate PV integration into hospital buildings in Inner Mongolia. Jafarian et al. [15] analysed multigeneration systems with PV in hospitals and other buildings, focusing on energy, economic, and environmental indicators.

Although some studies focus on the health sector, they typically assess technical or economic feasibility without considering uncertainty. Kowsar et al. [16] evaluated rooftop PV potential in public hospitals in Bangladesh, estimating coverage and emissions reduction, but without modelling decision-making under uncertainty. In contrast, other studies have applied real options theory to PV investment in different contexts. Mintah [17] analysed perceptions of real options in residential property development in Australia, identifying barriers to adoption despite recognition of flexibility. Penizzotto et al. [18] proposed a real options framework for rooftop PV in public buildings, emphasising deferral under uncertain market conditions. Morano et al. [19] demonstrated how real options capture volatility more effectively than traditional net present value analysis in urban redevelopment projects. In the residential sector, Martinez-Cesena et al. [20] modelled deferral options for PV investments in the UK, showing how flexibility can encourage technology adoption. Zeng and Chen [21] applied real options and game theory to optimise concession periods for PV projects in China under policy incentives. Balibrea-Iniesta [22] analysed large-scale PV projects in France, identifying administrative put and call options linked to subsidies. Vargas and Chesney [23] used real options to optimise timing and location of solar panel recycling infrastructure in the U.S.

While these studies contribute valuable insights, few have addressed the application of real options to the healthcare sector, where electricity continuity and quality are paramount.

Moreover, most real options models focus on residential, commercial, or utility-scale contexts and overlook the specific operational and regulatory requirements of healthcare institutions. In contrast to traditional evaluation methods such as net present value or internal rate of return—which assume static cash flows and fail to capture managerial flexibility—real options provide a dynamic framework that incorporates volatility, uncertainty, and the strategic value of decision-making rights [24]. This gap underscores the need for tailored methodologies that evaluate PV investments in hospitals under uncertainty, incorporating strategic tools and power quality requirements in critical areas.

This study addresses this gap by proposing a financial evaluation methodology based on real options, specifically designed for healthcare institutions in Colombia. Unlike traditional methods, this approach incorporates strategic flexibility—such as expansion, deferral, and abandonment—while also addressing the operational reliability required in medical facilities. Although real options have been applied to residential, commercial, and utility-scale photovoltaic projects, they have not been tailored to the critical constraints and planning dynamics of healthcare systems. The novelty of this study lies in the integration of financial flexibility with hospital-specific energy requirements, offering a conceptual and practical advancement over conventional ROM applications. The proposed methodology is tested through a real-world case study in a level 2 hospital in Barranquilla, Colombia, offering a robust framework for sustainable and resilient energy planning in the health sector.

MATERIALS AND METHODS

This section outlines the methodological framework developed to evaluate the financial viability of PV systems in HSPs under uncertainty, using the ROM. The methodology integrates a combination of data collection techniques, analytical tools, and modelling approaches to enhance the reliability and replicability of the results. While the procedure was applied to a specific hospital in Barranquilla, Colombia, the structure is designed to be general and adaptable across different healthcare contexts and geographic locations.

The proposed methodology comprises five sequential stages:

1. Energy consumption characterisation.
2. Sizing of the PV system.
3. Project evaluation using the ROM.
4. Sensitivity and scenario analysis.
5. Definition of the best option.

Each stage comprises a sequence of steps involving procedures, analytical tools, and decision criteria that ensure methodological rigor and allow for appropriate contextual abstraction. Figure 1 presents the flowchart of the methodology, detailing the procedures associated with each stage.

To ensure replicability, the methodology adheres to international standards (e.g., ISO 50001 [25], IEEE Std 1159-2019 [26], employs open-access simulation tools (e.g., HOMER Pro [27], RETScreen [28], or PV*SOL [29]), and integrates both deterministic (NPV) and stochastic (ROM) financial evaluation methods. The approach aims to generalise critical parameters (such as demand profiles, power quality, investment volatility, and real option valuation) and formalize them through equations and decision algorithms that can be adapted to various institutional and regulatory environments.

By treating investment decisions as real options rather than static projections, the methodology captures the value of flexibility in scenarios of fluctuating electricity prices, solar irradiation, and policy uncertainty. This contributes to more resilient and informed planning of PV systems in energy-intensive service sectors such as healthcare. Each stage of the methodology is described in detail below.

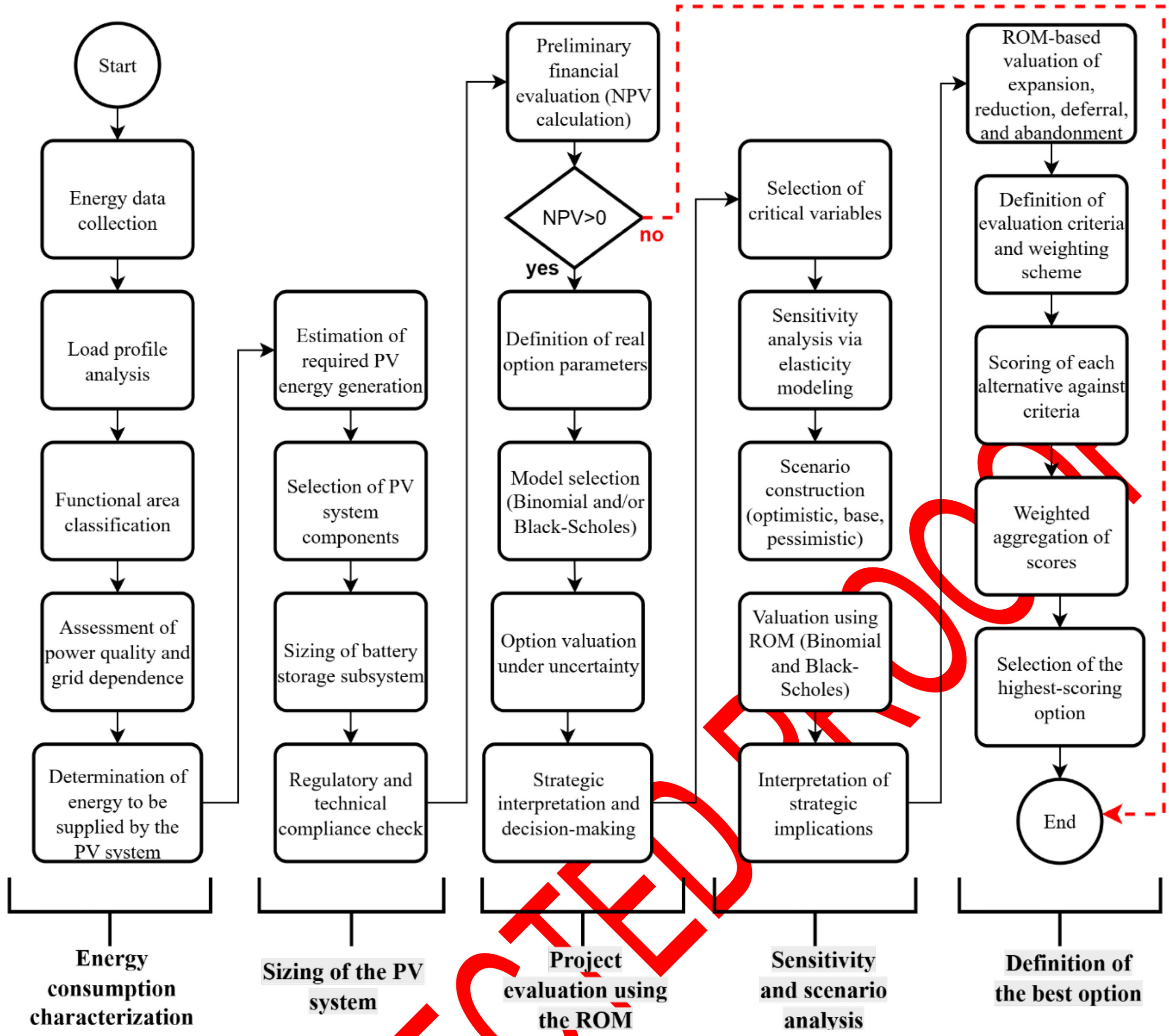


Figure 1. Flowchart of the ROM-based financial evaluation methodology for PV projects in HSPs

Stage 1. Energy consumption characterisation

The accurate characterisation of electricity consumption in HSPs is a fundamental stage in assessing the technical feasibility and economic viability of PV systems. This stage aims to identify the actual demand for electrical energy, define critical consumption patterns, and establish parameters for optimal system sizing. The process involves five structured sub-stages applicable across healthcare settings.

Energy data collection

The first sub-stage involves gathering quantitative and qualitative data on electricity usage through a combination of primary and secondary sources. This ensures a robust foundation for load assessment and PV design. The data collection process typically includes the components shown in Table 1. This stage may be supported by national energy audits, asset management systems, or building energy management systems (BEMS), depending on the institution's technological maturity.

Load profile analysis

Once consumption data is collected, a temporal analysis is conducted to construct the daily, weekly, and seasonal load profiles of the facility. This analysis enables the identification of operational patterns, peak load intervals, and base load requirements. Key analytical considerations are shown in Table 2. Load profiling may be conducted using statistical or data-driven methods, such as clustering algorithms or Fourier series for cyclic behaviour approximation.

Table 1. Standard sources for collecting electricity consumption data in healthcare facilities

Aspect	Description
Electricity billing	Compilation and review of historical monthly and annual energy consumption (kWh) from utility invoices over at least one year.
On-site measurements	Power grid analysers are used to monitor demand in real-time and obtain load profiles.
Maximum demand history	Analysis of energy consumption peaks and maximum power demand during critical periods.
Inventory of electrical equipment	The devices used in the HSPs are catalogued, including medical equipment, air conditioning systems, lighting, and energy backup.

Table 2. Parameters for constructing healthcare facility load profiles

Aspect	Description
Time variability	Disaggregation of load across hours of the day to distinguish between daytime, night-time, and shift-specific consumption patterns.
Impact of critical equipment	Isolation of high-dependency areas such as intensive care units, operating theatres, and emergency services with continuous load profiles.
Seasonal effects	Detection of seasonal variations driven by climate factors (e.g., air conditioning load in tropical climates or heating load in temperate regions).

Functional area classification

Segmenting electricity consumption by functional areas within HSPs is a critical methodological component in the optimal design and economic evaluation of PV systems. This classification provides a structured understanding of how energy is distributed across hospital subsystems, allowing for prioritisation in PV system integration based on criticality, consumption intensity, and operational continuity requirements.

From a theoretical perspective, the principle of energy use stratification supports this approach, wherein energy consumption is analysed not as a homogeneous aggregate but as a differentiated set of loads with distinct functions, temporal behaviours, and sensitivities to power quality. According to energy systems theory and building performance modelling, this stratification enables improved system targeting, load matching, and resilience planning.

Methodologically, this stage aligns with energy audit protocols and demand-side management strategies proposed in international standards such as ISO 50001 [25] and the ASHRAE Energy Audit Levels (Level 2 and 3) [30]. It also reflects recommendations from the RETIE [31], which mandates the identification and segregation of electrical circuits for critical services in medical facilities. Table 3 presents the functional classification of electrical energy consumption across different areas within HSPs.

This classification supports key methodological decisions such as:

- Defining PV supply boundaries: total vs partial load coverage based on area typology.
- Battery storage dimensioning: storage prioritised for critical areas requiring autonomy.
- Economic scenario modelling: differentiating cost savings and risk exposure by area.

Moreover, functional classification enhances replicability and benchmarking, enabling comparisons across different healthcare institutions and supporting the development of typological energy models in HSPs (e.g., base-case hospitals or energy archetypes).

Table 3. Functional classification of energy consumption in HSPs

Functional Area	Typical Components	Key Characteristics
Critical areas	ICUs, operating theatres, emergency rooms, sterilisation centres.	24/7 demand; high reliability and power quality (IEEE Std 1159 [26]); redundancy required (RETIE Art. 14) [31].
Air conditioning and ventilation systems	Central/decentralised HVAC, mechanical ventilation units.	Variable demand; aligns with daytime PV generation; efficiency potential via control/modulation.
Lighting and administrative equipment	General/emergency lighting, computers, printers, outpatient workstations	Low criticality; flexible PV integration; enables load shifting and cost optimisation.

<u>Assessment of power quality and grid dependence</u>

Beyond total consumption, it is essential to evaluate power quality parameters—such as voltage stability, harmonic distortion, and supply continuity—due to the sensitivity of medical devices. Common disturbances (e.g., short interruptions, voltage sags) can compromise equipment operation and patient safety. The assessment of power quality must be performed in accordance with IEEE Std 1159-2019 [26] and relevant sections of RETIE [31] related to hospital environments and electromedical applications. This diagnostic enables the evaluation of potential benefits of PV systems not only in terms of cost reduction but also in improving electrical service resilience.

<u>Determining the energy to be supplied by the photovoltaic system</u>

Based on the results of the previous sub-stages, the proportion of the load to be offset by PV generation is determined. This fraction depends on space availability, economic constraints, and continuity requirements. Table 4 summarises the guiding criteria.

Table 4. Decision criteria for PV system energy coverage definition

Criterion	Description
Load coverage strategy	Define full or partial replacement of conventional supply based on technical and financial trade-offs.
Economic self-consumption optimisation	Maximise PV usage to reduce energy procurement and demand charges.
Resilience for critical loads	Ensure supply continuity in critical areas via storage systems, complying with RETIE backup standards [31].

When applicable, simulations can be performed using tools such as HOMER Pro [27], RETScreen [28], or PV*SOL [29], incorporating real solar irradiation datasets (e.g., NASA POWER [32], Meteonorm [33]). These tools allow modelling of generation profiles, self-consumption rates, and battery autonomy under different sizing strategies and climatic conditions.

Stage 2. Sizing of the photovoltaic system

The sizing of the PV system is a crucial stage that defines its generation capacity in relation to the healthcare facility's electricity demand, the local solar resource availability, and technical and regulatory constraints specific to HSPs. Proper sizing ensures that the PV system operates efficiently, meets energy reliability requirements, and optimises economic performance. This phase involves two key sub-stages: determining the required PV generation and selecting system components, including the storage subsystem. The sizing of the PV system in HSPs follows a structured methodology composed of four sequential stages.

Estimation of required photovoltaic energy generation

The first task is to quantify the amount of electricity the PV system must supply to meet a defined portion of the HSP's energy demand. This is calculated using the following equation [34].

$$Np = \frac{E_c}{HSP \times P_r} \tag{1}$$

A correction factor of 15% is applied to account for common PV system losses, including those due to high temperatures, module ageing, and dust accumulation. This factor is in line with international practices in system design [35] and should be adapted based on site-specific degradation data when available.

Selection of photovoltaic system components

Once the generation capacity has been determined, the main components of the system must be selected based on performance, durability, and compatibility with hospital infrastructure. Table 5 summarises the primary components considered in PV system design for HSPs.

Table 5. Main components of the PV system in HSPs

Component	Description
Solar panels	High-efficiency PV modules (>15%) with a service life exceeding 25 years are selected.
Inverters	Convert direct current (DC) to alternating current (AC); must provide pure sine wave output and comply with hospital-grade electrical standards.
Batteries	Lithium-ion batteries with sufficient backup capacity to ensure autonomy in critical load areas.
Charge regulators	Manage power flow between PV modules and storage units, protecting the system from overvoltage or deep discharge.
Monitoring system	Enables real-time system performance tracking, fault detection, and operational optimisation.

The choice of components should consider factors such as operating temperature range, manufacturer warranties, certifications (e.g., IEC 61215 [36], UL 1741 [37]), and compliance with medical facility standards.

Sizing of the battery storage subsystem

Energy storage plays a vital role in ensuring uninterrupted supply to critical hospital functions such as intensive care units (ICUs), operating rooms, and emergency systems. The required battery bank capacity is calculated as [38]:

$$C_b = \frac{E_b}{DOD \times V_s} \tag{2}$$

Depth of discharge (DOD) is typically set at 80% for lithium-ion technologies [39], balancing usable capacity and battery lifespan. The storage system must be dimensioned to support the full load of critical areas for a predefined autonomy period, often ranging from 2 to 8 hours, depending on hospital category and redundancy requirements.

Regulatory and technical compliance

To ensure safe and reliable integration into healthcare infrastructure, PV systems for HSPs must comply with the following standards and technical guidelines:

- Technical Regulations for Electrical Installations (RETIE) [31], which define the legal and safety framework for electrical systems in Colombia, including healthcare environments.
- Colombian Technical Standards (NTC 2050) [40], which align with the National Electrical Code and set detailed installation requirements for PV components.
- IEEE Std 1159-2019 [26], which outlines procedures for power quality monitoring and establishes thresholds for voltage fluctuations, harmonics, and transient events—especially relevant for electromedical devices.

Prior to commissioning, system compatibility with the existing electrical infrastructure must be verified. This includes ensuring that the PV system:

- Does not introduce voltage or frequency fluctuations beyond allowable limits.
- Provides adequate isolation and fail-safe mechanisms in critical branches.
- Is protected by appropriate grounding, lightning protection, and selective coordination of protective devices.

Additionally, systems must be evaluated for electromagnetic compatibility (EMC) to avoid interference with diagnostic and therapeutic equipment, in accordance with international medical equipment standards such as IEC 60601 [41].

For replicability, designers should follow a structured decision-making process that begins with energy audits, proceeds through simulation-assisted sizing, and culminates in site-specific engineering design. Software tools such as HOMER Pro [27], RETScreen [28], and PV*SOL [29] are widely used to simulate generation profiles and match them against load curves. These tools enable the assessment of multiple configurations considering climate data, performance ratios, storage scenarios, and economic indicators.

The sizing strategy must be context-sensitive. In urban tertiary hospitals, space constraints may limit the installed capacity, requiring hybrid or grid-tied models. In contrast, rural or isolated facilities may prioritise energy autonomy, justifying larger storage investments and higher PV penetration ratios.

Stage 3. Project evaluation using the real options method

Evaluating the economic feasibility of PV systems in HSPs under uncertainty requires a methodology that goes beyond deterministic cash flow analysis. The ROM addresses this challenge by incorporating flexibility into the investment decision process. Under this framework, the investment is treated as a real option—analogous to a financial derivative—where the investor holds the right, but not the obligation, to undertake the project depending on how future conditions evolve [42].

ROM allows for a dynamic assessment of the project's value by considering not only the static net benefit but also the managerial flexibility to expand, defer, reduce, or abandon the project in response to changing variables such as electricity prices, solar resource availability, or regulatory signals. The ROM-based evaluation follows a structured process consisting of five stages.

<u>Preliminary financial assessment using net present value</u>

The first stage involves calculating the NPV of the project, which serves as the underlying asset in ROM analysis. This is done using traditional financial evaluation, incorporating all relevant investment and operating costs:

- Cost of acquiring PV panels, inverters, batteries, and charge controllers.
- Installation, assembly, and integration with the hospital's electrical infrastructure.
- Preventive and corrective maintenance over the system's lifespan.
- Operating costs related to system monitoring and management.

The NPV is calculated as follows [43]:

$$NPV = -K + \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{3}$$

The benefit is calculated as:

$$B_t = Energy\ generated\ by\ PV \times Energy\ price\ (Colombia) \tag{4}$$

The operating and maintenance costs are assumed to be 2% of the total system cost [44]:

$$C_t = System\ cost \times 0.02 \tag{5}$$

A positive NPV indicates that the project is financially viable under deterministic assumptions. This value is then used as a basis for further evaluation under uncertainty using ROM.

<u>Parameters for the real options method implementation</u>

To apply the ROM, a set of key parameters must be defined, as shown in Table 6 [45].

Table 6. Parameters for the implementation of ROM

Parameter	Description
Value of the risky asset	NPV or cash flow generated by the PV system
Strike price	Total investment cost of the project (K)
Option validity period	Project time horizon (n)
Volatility (σ)	Variation in project value due to changes in electricity prices, demand, etc.
Risk-free interest rate (r_f)	Benchmark for discounting future cash flows

These parameters are incorporated into both the Binomial model and the Black-Scholes model, which allow for the valuation of flexibility under uncertainty.

<u>Binomial model</u>

The Binomial model is a discrete-time framework that models the possible future values of the underlying asset using a decision tree. The asset may increase or decrease in value in each period based on up (u) or down (d) factors [46]:

$$V_u = NPV \times u \tag{6}$$

$$V_d = NPV \times d \tag{7}$$

$$p = \frac{e^{rf \times \Delta t} - d}{u - d} \tag{8}$$

$$u = e^{\sigma\sqrt{\Delta t}} \tag{9}$$

$$d = \frac{1}{u} \tag{10}$$

$$\Delta t = \frac{n}{S} \tag{11}$$

The Binomial tree allows for dynamic evaluation of investment decisions at each node, including the possibility to expand, defer, or abandon the project depending on future outcomes.

Black-Scholes model

The Black-Scholes model is a continuous-time approach based on stochastic differential equations. The value of a call option (i.e., the right to invest) is calculated as follows [47]:

$$C = S_0 \times N(d_1) - K \times e^{-rf \times t} \times N(d_2) \tag{12}$$

For a put option (i.e., the right to abandon):

$$P = K \times e^{-rf \times t} N(-d_2) - S_0 \times N(-d_1) \tag{13}$$

The terms d_1 and d_2 are given by:

$$d_1 = \frac{ln(S_0/K) + (rf + \sigma^2/2) \times t}{\sigma\sqrt{t}} \tag{14}$$

$$d_2 = d_{1\_}\sigma\sqrt{t} \tag{15}$$

This model quantifies the value of managerial flexibility in financial terms, helping decision-makers assess the timing and magnitude of investments.

Types of real options in photovoltaic projects

In the context of HSPs, several real options may apply based on demand evolution, regulatory context, and technological change [48]:

- Expansion Option: Increase PV capacity if energy demand rises; evaluated using Binomial or Black-Scholes considering NPV volatility.
- Downsizing Option: Reduce project scope if costs exceed expectations or incentives change; evaluated through lower investment scenarios in the Binomial model.
- Deferral Option: Postpone the investment until market or regulatory conditions improve; analysed using the Present Real Option Index (PRI).
- Abandonment Option: Exit the project if returns are negative; assessed via the residual value under a put option using the Black-Scholes model.
- These options enable flexible responses to market uncertainties, making ROM a powerful enhancement over traditional NPV-based evaluations.

Stage 4. Sensitivity and scenario analysis

Understanding the robustness of PV investments in HSPs requires evaluating how uncertainty in key variables affects financial outcomes and managerial flexibility. This stage integrates sensitivity analysis and scenario modelling within the ROM framework to assess how fluctuations in external conditions influence the project's value and the optimal investment strategy. The analysis follows a two-pronged approach.

Selection of critical variables

To ensure accurate valuation of real options, only variables with direct influence on investment decisions are included. These factors, showed in Table 7, represent key sources of market and technical uncertainty, and their behaviour determines the feasibility of exercising options such as expansion, deferral, or abandonment.

Table 7. Critical variables considered in the ROM

Variable	Unit of Measurement	Impact on the Project
Price of electricity	USD/kWh	Affects revenue stream and incentives to expand or defer investment
Solar irradiation	kWh/m²/day	Drives energy generation, influencing both NPV and reliability
Initial investment	USD	Determines upfront cost and conditions for scaling or delaying the project
O&M costs	USD/year	Influences long-term viability and breakeven thresholds
Cash flow volatility	%	Quantifies project uncertainty; affects ROM valuation sensitivity

These variables are drawn from technical literature and past empirical studies of PV project risk profiles in emerging markets [49].

Sensitivity analysis using the real options method

Sensitivity analysis quantifies the individual influence of each variable by measuring how changes affect the NPV and, consequently, the real option value. This is achieved by computing elasticity, which relates the proportional change in NPV to the proportional change in the variable [50]:

$$\varepsilon_x = \frac{\Delta NPV/NPV}{\Delta X/X} \tag{16}$$

The results can be visualised using a Tornado diagram, which displays the relative weight of each variable on project flexibility and value [51].

This approach enables hospital administrators and energy planners to identify priority risk drivers and focus mitigation efforts accordingly.

Scenario analysis in the real options method

While sensitivity analysis varies one variable at a time, scenario analysis evaluates the combined impact of multiple variables under predefined conditions. This method captures interdependencies and systemic effects. As shown in Table 8, three representative scenarios are modelled.

Table 8. Scenarios considered in the ROM

Variable	Optimistic (+20%)	Base (0%)	Pessimistic (-20%)
Price of electricity	+20%	Reference	-20%
Solar irradiation	+20%	Reference	-20%
Initial investment	-20%	Reference	+20%
O&M costs	-20%	Reference	+20%

These scenarios simulate realistic changes in tariffs, climate conditions, capital expenditures, and operation and maintenance (O&M) costs. They are aligned with historical variability patterns observed in electricity markets and PV supply chains in Latin America [52], [53].

Valuation under uncertainty

For each scenario, the Real Option Value is recalculated using both the Binomial model and the Black-Scholes model, incorporating adjusted values of S_0, σ, K, t, and r_f.

This dual-model approach strengthens the robustness of the analysis and enables comparative interpretation between discrete (Binomial) and continuous (Black-Scholes) methods. The results provide critical input for investment timing, system scaling, and risk management strategies in HSPs operating under volatile financial and energy conditions.

The integration of sensitivity and scenario analysis within the ROM framework transforms the financial evaluation of PV systems from a static projection into a strategic tool. By quantifying how uncertainty affects option value and decision timing, this stage helps stakeholders navigate risks while preserving operational and economic resilience.

Stage 5. Definition of the best option

This final stage in the financial evaluation process for PV projects in HSPs involves selecting the most viable investment alternative. The selection is based on the results generated by the ROM, particularly the valuation of expansion, reduction, deferral, and abandonment options using both the Binomial and Black-Scholes models.

The ROM framework supports not only the quantification of investment value under uncertainty but also the strategic selection of the most advantageous course of action. To facilitate this decision-making process, a multi-criteria analysis (MCA) is used. This method integrates both financial metrics and strategic considerations, ensuring a balanced assessment of options under varying scenarios and risk profiles.

<u>Evaluation criteria and weighting scheme</u>

The MCA employs four weighted criteria, each addressing a different dimension of investment viability and strategic relevance. The weights reflect their relative importance within the decision-making framework:

- Adjusted Real Option Value (40%) - This criterion captures the enhanced financial value created through strategic flexibility. It reflects the ability of the project to generate additional returns by adapting to evolving energy prices and investment conditions. It is the most heavily weighted due to its direct influence on economic feasibility [45].
- Strategic Flexibility Level (25%) - This assesses the adaptability of the project to external changes, including technological shifts, regulatory developments, and demand variation. While crucial for medium- to long-term positioning, it is considered secondary to direct value creation [54].
- Risk and Uncertainty Management (20%) - This measures the project's resilience under volatility in key variables such as tariffs, solar resource availability, and policy incentives. While ROM inherently incorporates risk modelling, this criterion highlights the qualitative interpretation of model sensitivity [55].
- Impact on Future Profitability (15%) - This evaluates the capacity of the project to maintain stable revenues over time under the modelled conditions. Although essential, it is weighted lowest, as long-term cash flow sustainability is often subject to broader market and policy dynamics [56].

<u>Scoring and decision rule</u>

Each investment alternative (expansion, reduction, deferral, or abandonment) is evaluated across the four criteria using a qualitative scale from 1 to 5, where [57]:

- 1 = Very Low Performance
- 2 = Low Performance
- 3 = Moderate Performance
- 4 = Good Performance
- 5 = Excellent Performance

Once scores are assigned, the weighted score for each alternative is calculated using the formula:

$$Final\ Score\ = \sum(Criterion\ Score\ \times\ Criterion\ Weight) \quad (17)$$

The option with the highest total score is selected as the optimal strategic choice, as it maximises value under uncertainty while maintaining flexibility and resilience.

This multi-criteria approach ensures that the selection of the best investment option is not driven solely by financial projections but also by strategic adaptability and risk considerations. It aligns with the core philosophy of ROM (treating investment as an iterative and contingent process rather than a one-time, all-or-nothing decision).

Validation of the proposed methodology

The proposed methodology was validated through its application in a real-world setting: a level 2 healthcare service provider (HSP) located in Barranquilla, Colombia. Validation included:

- Empirical implementation: The methodology was applied using actual energy consumption data and local economic parameters, ensuring contextual realism.
- Benchmarking against traditional methods: Financial results obtained through the ROM were compared with those from the NPV approach, showing improved flexibility and strategic value.
- Scenario and sensitivity analysis: The methodology was stress-tested against variations in electricity prices, solar irradiation, and investment costs. Elasticity values were calculated to evaluate model responsiveness.
- Multi-criteria evaluation: A structured decision-making framework was applied to rank investment options (expansion, reduction, deferral, abandonment), incorporating technical, financial, and strategic dimensions.

These steps confirmed the method's robustness, adaptability to uncertainty, and practical applicability in healthcare settings. Although this validation is based on a single case, the structured nature of the framework facilitates replication in other institutions and sectors.

RESULTS AND DISCUSSION

The following section presents the application of the proposed methodology in a real-world healthcare setting. Results are structured according to the five stages defined in the ROM-based evaluation framework, encompassing consumption characterisation, system sizing, financial assessment, sensitivity analysis, and strategic decision-making. A comparative analysis with traditional methods is also included, along with a discussion of the methodology's strengths and limitations.

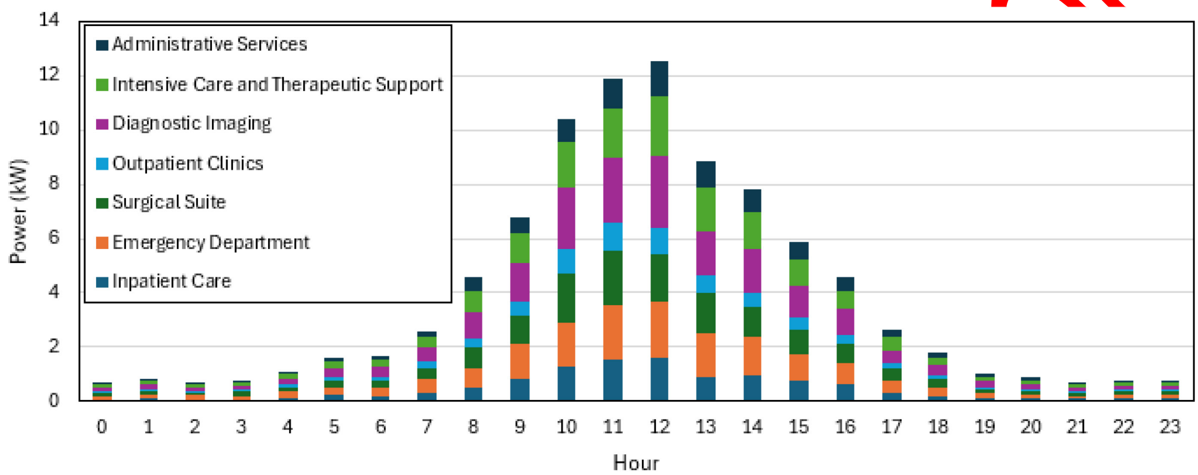
Stage 1. Characterisation of energy consumption

The methodology for the financial evaluation of photovoltaic projects using the ROM was applied in a hospital in Barranquilla, Colombia, classified as level 2 [58]. This Health Service Provider (HSP) offers inpatient, emergency, surgery, outpatient, diagnostic, and therapeutic support services, including intensive care, nursing, and medical specialties. Solar radiation in the area varies between 5.25 and 6.8 kWh/m² annually, with an average Peak Sun Hours (PSH) of 5.3 hours per day [45].

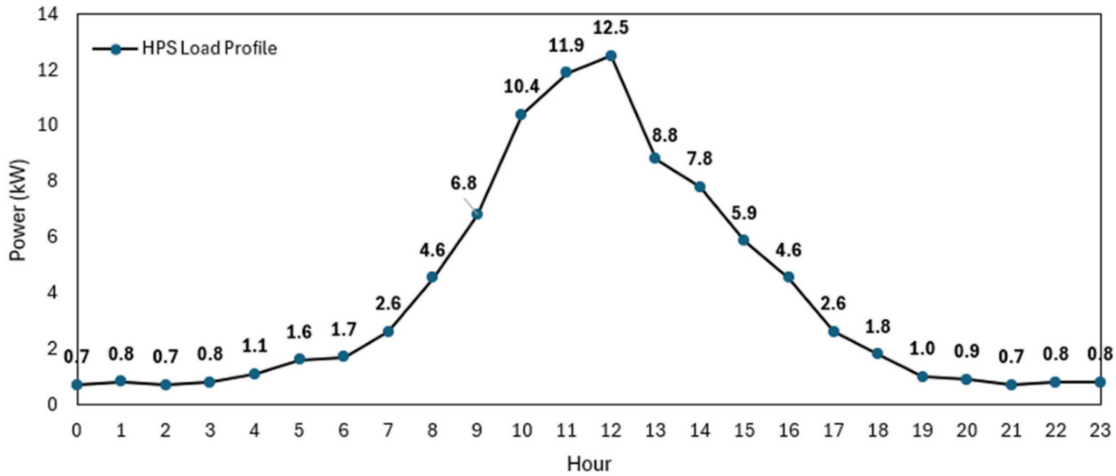
For the study, several areas of the HSP were selected, including the emergency department, intensive care, inpatient care, operating rooms, diagnostic imaging, clinical laboratories, outpatient clinics, and administration. These spaces use monitoring and life support equipment, emergency and general lighting, and air conditioning systems. They also have CT scanners, MRI scanners, X-ray equipment, and sterilisation systems. Additionally, they have computer and ventilation equipment, all of which require high energy consumption and service continuity. Based on the results of the ROM in the selected areas, a decision will be made as to whether the project to install photovoltaic systems at the HSP under study will be expanded, reduced, postponed, or abandoned.

The first step in the financial evaluation was to characterise the energy consumption of the selected areas. This stage allows for identifying electricity demand, analysing consumption patterns, assessing power quality, and determining the energy a solar generation system can supply.

Energy data for 2023 was collected from billing records, on-site measurements with power grid analysers, peak demand analysis, and an electrical equipment inventory. Figure 2 shows the hourly load profile of the HSP, including the disaggregated consumption by department and the total daily demand.



(a)



(b)

Figure 2. Load profile in the HSP under study: (a) hourly electricity consumption distribution by functional area; (b) total consumption

Figure 2(a) shows the hourly electricity demand disaggregated by hospital departments. The largest contributions during peak hours come from the Surgical Suite, Outpatient Clinics, and Inpatient Care, reflecting the concentration of clinical services between 08 h and 14 h. This detailed breakdown helps to identify consumption hotspots and underlines the importance of matching PV generation with daytime load.

Figure 2(b) depicts the load profile of the monitored hospital areas, averaging 91.8 kWh/ day (33 522 kWh/ year) with a peak demand of 12.5 kW. The early-morning valley (00:00–06:00 h) ranges between 0.7 kW and 1.7 kW, consistent with the operation of only emergency lighting, patient-monitoring devices, and life-support equipment. From 06:00 h the load rises steadily, reaching 4.6 kW at 09:00 h as clinical and administrative activity ramps up, and peaks at 12.5 kW around midday due to the simultaneous operation of diagnostic equipment and HVAC. Demand then declines to 7.8 kW at 14:00 h and 5.9 kW at 15:00 h, before falling below 2 kW after 18:00 h and stabilising near 0.7 kW overnight.

Approximately 60% of daily energy is consumed between 08:00 and 16:00 h, coinciding with the 5.3-hour local peak-sun window. Although Colombia applies a flat electricity tariff, self-consuming solar generation during these hours still reduces the total kilowatt-hours purchased from the grid and thereby improves the project's NPV. The marked intra-day swing in demand (about 35% volatility between valley and peak) also feeds directly into the ROM. By quantifying management's ability to expand photovoltaic capacity if future consumption grows or defer upgrades if clinical schedules change, the ROM assigns a flexibility premium that the static NPV cannot capture. Consequently, the load profile not only supports the positive deterministic NPV but also underpins the strategic options valued through the ROM, strengthening the investment case under uncertain operational and regulatory conditions.

Figure 3 shows the percentage distribution of energy consumption across the functional areas, critical areas, air conditioning and lighting systems, and administrative equipment.

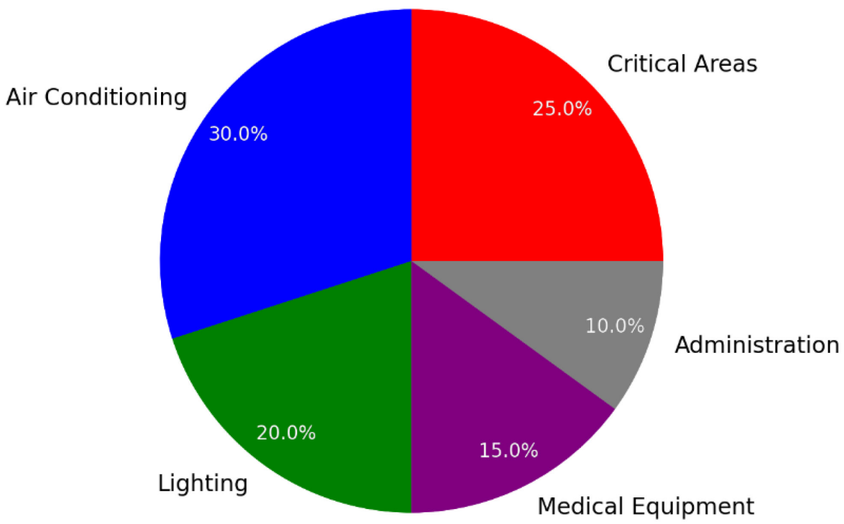


Figure 3. Distribution of energy consumption by functional areas

According to Figure 3, the largest percentage of consumption is attributed to air conditioning systems (30%), which are essential for maintaining thermal comfort for patients and ensuring the proper operation of temperature-sensitive medical equipment. Critical areas, including intensive care units, operating rooms, emergency rooms, and clinical laboratories, account for 25% of total consumption, reflecting their high energy demand. Lighting consumes 20% of the energy, due to its extensive use throughout the hospital, while specialised medical equipment absorbs 15%, primarily due to the operation of monitoring and treatment devices.

Figure 3 indicates that air-conditioning systems account for 30% of the hospital's electricity consumption (they preserve thermal comfort for patients and safeguard temperature-sensitive equipment). Critical medical areas (intensive-care units, operating theatres, emergency rooms and clinical laboratories) contribute an additional 25%, reflecting their continuous high-power demand and strict reliability requirements. Lighting represents 20%, driven by round-the-clock operation in corridors, wards and diagnostic suites, whereas the remaining 15% corresponds to specialised medical devices (mainly monitoring and treatment equipment that operate intermittently at elevated power levels).

This breakdown has two direct implications for the photovoltaic project. First, because HVAC and lighting loads are concentrated during daylight hours, most of the solar generation can be self-consumed, which supports the positive NPV calculated for a system sized to cover about half of the annual demand. Second, the inflexible demand of critical areas establishes the minimum level of security supply and therefore shapes the downside scenarios considered in the ROM (for instance, the decision to defer expansion if additional backup capacity is required). By distinguishing flexibility from non-flexible loads, Figure 3 thus provides the operational rationale for the strategic options valued in the ROM analysis.

Stage 2. Sizing of the photovoltaic system

The size of the photovoltaic system was determined to cover approximately 50% of the energy consumption in the selected areas of the HSP. This system would supply 16,761 kWh/year, thereby reducing grid energy consumption and lowering the cost per unit of energy, ensuring a favourable return on investment. Figure 4 shows the comparison between the HSP's load profile and the estimated generation from the proposed photovoltaic system.

Studies, such as those presented in [58] and [59], recommend sizing photovoltaic systems in HSPs to cover between 50% and 60% of total demand. This recommendation considers several factors. Firstly, the variability of solar irradiation can reduce energy production on cloudy days or during periods of low radiation. Secondly, although rooftop installation is the preferred strategy, the available surface is typically limited due to the presence of technical infrastructure (e.g., HVAC systems, ventilation units, water tanks), safety clearances, and access routes. These constraints reduce the effective area for PV deployment, making it difficult to fully meet energy demand with solar power alone. Finally, the investment costs of a fully self-sufficient system would be high and could exceed the budget of many healthcare institutions.

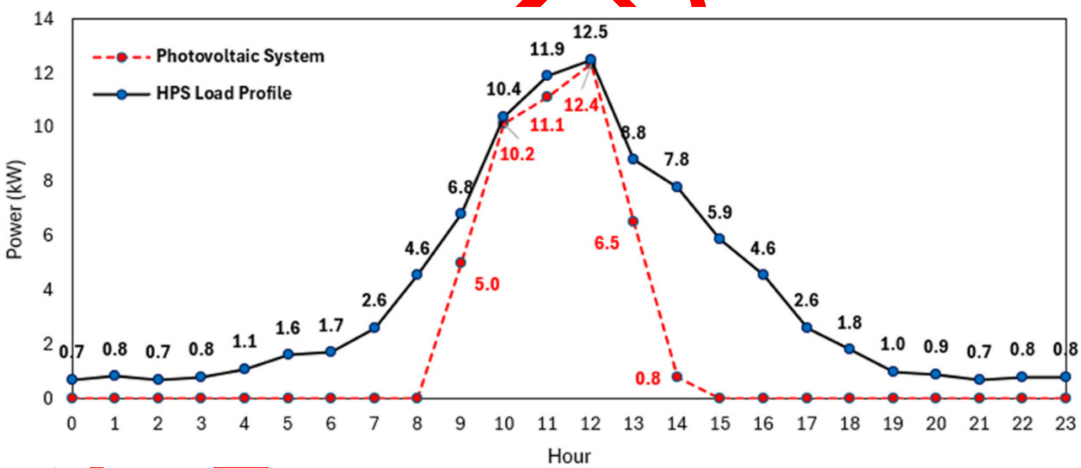


Figure 4. Load profile and projected photovoltaic system for the HSP section under study

Figure 4 confirms that daytime photovoltaic output overlaps well with the hospital load curve, covering a significant share of consumption between 09 h and 13 h. After midday, the load begins to exceed solar generation by as much as 6.5 kW, and during the night production is zero, so the grid remains indispensable. Deterministically, this profile justifies sizing the system at 50% of annual demand because the kilowatt-hours displaced coincide with the hours of highest irradiance (even though the Colombian tariff is flat). Strategically, the midday gap represents an embedded option to add modules or storage later if electricity prices rise, clinical services extend into the evening or carbon-reduction targets tighten; this upside is invisible to the NPV but captured in the ROM.

Maintaining power quality is critical in healthcare applications, therefore a 15 kW medical-grade inverter (pure sine wave, 98% efficiency) was selected. Its modest headroom over the 12.4 kW of installed modules prevents saturation on clear days (and preserves the possibility of connecting an extra string without replacing power electronics, an expansion path valued in the ROM). The array comprises twenty-three monocrystalline panels rated at 540 W each

(21.3% efficiency, 25-year warranty). Although these mid-to-high-end modules increase the upfront cost, they limit degradation and reduce downside risk, which enhances the option value. The complete bill of materials (Table 9) totals USD 13,740 and includes a 5 kWh lithium-ion battery reserved for critical circuits; while this storage has limited influence on the baseline NPV, it provides resilience benefits explicitly monetised in the ROM, reinforcing the hospital's ability to manage grid disturbances and future regulatory changes [60].

Table 9. Proposed components for the photovoltaic installation providing 50% energy coverage at the Barranquilla Hospital

Component	Amount	Main Features	Unit Cost [USD]	Total Cost [USD]
PV panels (540 W)	23	Monocrystalline (21.3% efficiency), 25-year warranty	239.6	5,510
"Standby" inverter (15 kW)	1	Pure sine wave, 98% efficiency, immediate response to faults	1,900	1,900
Support Structure	38 sets of rails	Anodized aluminium, tilt (~15°)	35	1,330
Wiring and Protections	—	DC/AC sizing, overvoltage protections	—	900
Labour and Installation	—	Assembly, connection, start-up tests	—	1,600
Batteries (~5 kWh)	1 bench	Lithium-ion for backup of critical areas	2,500	2,500
Total	—		—	13,740

Stage 3. Project evaluation using the real options method

Table 10 presents the parameters used in the financial evaluation of the photovoltaic project at the HSP under study. The evaluation considers installation, operation, and maintenance costs, as well as the uncertainty associated with key variables such as cash flow volatility and electricity prices.

Table 10. Financial parameters of the photovoltaic system at the Barranquilla Hospital

Parameter	Value
Annual demand for selected areas (kWh)	33,522
Fractions covered by photovoltaic	50%
Energy generated by the system (kWh/year)	16,761
Energy price (USD/kWh)	0.25
Cost of the system with batteries (USD)	13,740
Discount rate	10%
Risk-free rate	6%
Volatility (σ)	35.7%
Project lifespan (years)	10
Period of division into equal steps (years)	3

The values in Table 10 establish the framework for applying the Binomial and Black-Scholes models in project valuation. Discount rates are typically considered to range from 8% to 12% in energy infrastructure in emerging markets [61]. For photovoltaic projects, cash flow volatility in solar investments generally varies between 30% and 40%, depending on electricity price fluctuations and weather conditions [62]. Additionally, the risk-free rate in energy investments is linked to the yield on long-term government bonds (10 years or more), which typically range from 4% to 6% in developing countries [63].

To calculate the NPV, the benefit of the investment in period t, equation (4) was applied:

$$B_t = 16{,}761\,\frac{\text{kWh}}{\text{year}} \times 0.25\,\frac{\text{USD}}{\text{kWh}} = 4{,}190\ \text{USD/year} \tag{18}$$

The cost incurred in period *t* is calculated using equation (5):

$$C_t = 13{,}740\ \text{USD} \times 0.02 = 275\ \text{USD/year} \tag{19}$$

The NPV over the 10 years of the project's life was calculated by applying equation (3):

$$NPV = -13{,}740 + \sum_{t=0}^{n} \frac{4{,}190\frac{\text{USD}}{\text{year}} - 275\frac{\text{USD}}{\text{year}}}{(1+0.1)^t} = 10{,}315.98\ USD \tag{20}$$

This result indicates that the present value of the expected benefits exceeds the initial investment, justifying the project's financial viability under traditional methods.

For the application of the Binomial model, the growth and decrease factors of the value of the underlying asset were determined by applying equations (8), (9), (10) and (11).

$$\Delta t = \frac{10}{3} = 3.33 \tag{21}$$

$$u = e^{0.357\sqrt{3.33}} = 1.919 \tag{22}$$

$$d = \frac{1}{1.919} = 0.521 \tag{23}$$

$$p = \frac{e^{0.06 \cdot 3.33} - 0.521}{1.919 - 0.521} = 0.501 \tag{24}$$

These values indicate that the project has a 50.1% probability of generating positive returns under uncertain scenarios, reinforcing the investment's strategic flexibility.

The Binomial tree is constructed from these values for the project's 10-year life, as shown in Figure 5. The tree is divided into three periods, starting from year 0. The first period evaluates the project at year 3.33, the second period at year 6.66, and the third and final period at year 10.

Figure 5 displays the three-stage binomial lattice used to project the photovoltaic system's value over the ten-year horizon. Starting from the base NPV of USD 10,316 at $t = 0$, the up factor ($u = 1.919$) and down factor ($d = 0.521$) generate a dispersion that ranges from USD 72,901 in the best case to USD 1,459 in the worst. The risk-neutral probability of an up move is 0.501, so the distribution of terminal values is slightly skewed toward favourable outcomes. This spread illustrates how cash-flow volatility of 35.7% magnifies both upside and downside potential, information that a single deterministic NPV cannot convey.

The Black-Scholes model was applied to quantify the real option value of the photovoltaic project.

The parameters d_1 and d_2 were calculated using equations (14) and (15) as follows:

$$d_1 = \frac{ln(10{,}316/13{,}740) + (0.06 + 0.357^2/2) \cdot 10}{0.357 \times \sqrt{10}} = 0.8421 \tag{25}$$

$$d_2 = 0.8421 - 0.357 \times \sqrt{10} = -0.2869 \tag{26}$$

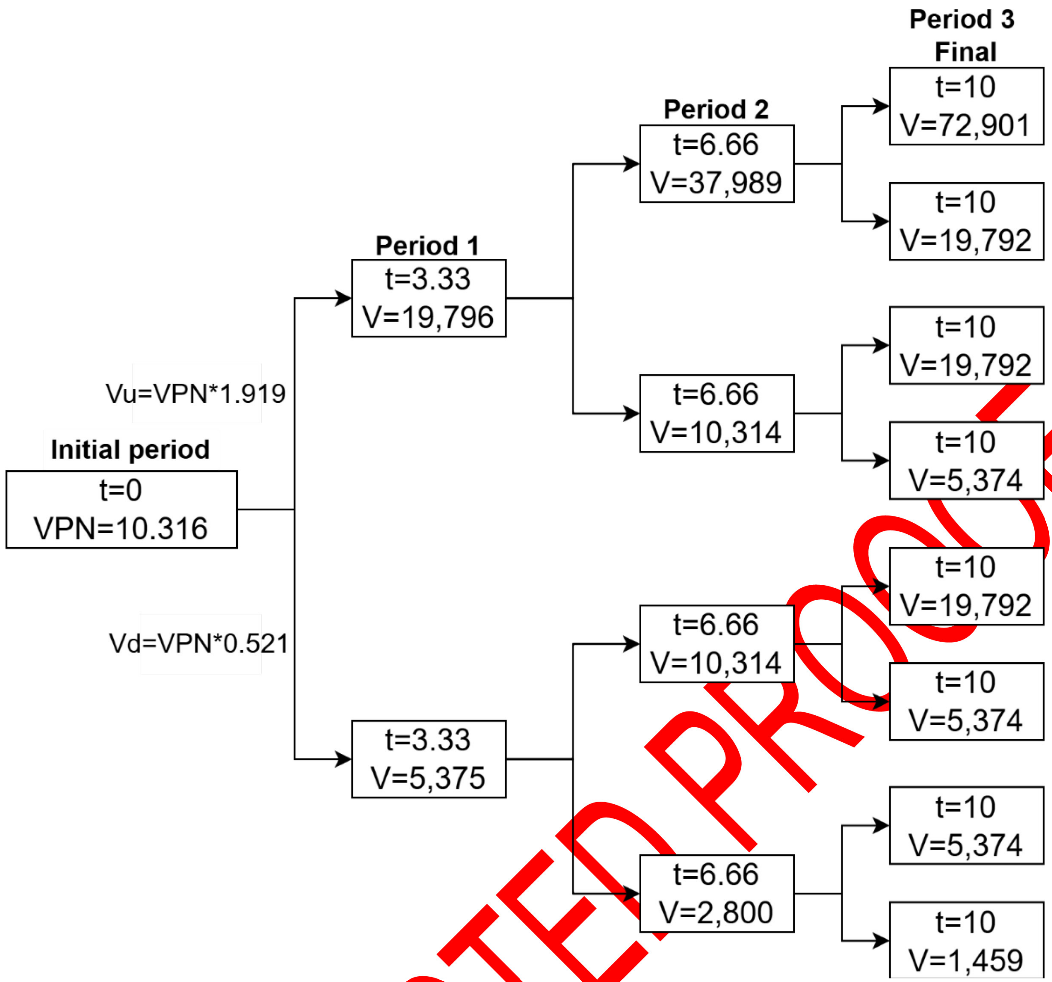


Figure 5. Binomial tree corresponding to the 10 years of the useful life of the project

The value of the "call" option, according to the Black-Scholes model, was calculated using equation (12) as follows:

$$C = 10{,}316 \times N(0.8421) - 13{,}740 \times e^{-0.06\cdot 10} \times N(-0.2869) \tag{27}$$

$$C = 10{,}316 \times 0.8001 - 13{,}740 \times e^{-0.06\cdot 10} \times 0.3871 = 5{,}334.84\ USD \tag{28}$$

For a put option, which grants the right to sell an underlying asset at a strike price, the valuation is calculated using equation (13) as follows:

$$P = 13{,}740 \times e^{-0.06\cdot 10} \times N(0.2869) - 10{,}316 \times N(-0.8421) \tag{29}$$

$$P = 13{,}740 \times e^{-0.06\cdot 10} 0.6129 - 10{,}316 \times 0.1999 = 2{,}559.51\ USD \tag{30}$$

The values of $N(d_1)$ and $N(d_2)$ were obtained using statistical tables of the standard normal distribution [64]. The value of $d_1 = 0.8421$ indicates a high probability that the project will generate benefits when adjusted for market risk. In financial terms, this suggests that the project's future net cash flow is likely to exceed the initial investment, with a cumulative probability of approximately 80%, reinforcing the expectation of profitability. Conversely, $d_2 = -0.2869$ represents the risk that the investment may not achieve the expected returns. Although negative, its absolute value is three times smaller than d_1, indicating a moderate and controlled risk of loss.

Applying backward induction, the ROM assigns an option value of USD 5,335 for expansion (call) and USD 2,560 for abandonment or scale-back (put). Adding the call premium to the base NPV raises the project's risk-adjusted worth to USD 15,651, a 52% improvement. In practical terms, management can commit to the current 12.4 kW array while retaining the right to install additional panels if electricity prices increase or if daytime demand grows beyond the present load curve (for example, through the addition of a new diagnostic wing). Conversely, the put option quantifies the benefit of being able to postpone or cancel further investment should regulatory changes or technology prices evolve unfavourably, thereby limiting downside exposure to roughly one quarter of the initial outlay.

Comparing both metrics clarifies the strategic landscape. The positive NPV confirms economic viability under expected conditions, but the ROM shows that ignoring flexibility undervalues the project by omitting real managerial choices. For hospital administrators who operate under flat tariffs and strict service-continuity constraints, the call option legitimises a phased investment plan (initial installation plus pre-sized inverter, with space for extra modules). Simultaneously, the put option supports a defensive stance if future maintenance costs rise or if new efficiency regulations reduce the price of grid electricity. Therefore, when evaluated through the ROM, the photovoltaic project aligns not only with present cost savings but also with long-term adaptability goals, providing a more robust foundation for capital-budget approval than the NPV alone.

Stage 4. Sensitivity and scenario analysis

A sensitivity analysis was conducted on four critical variables, each subjected to a 20% increase. In each case, the NPV was recalculated using equations (3) and (16), with the results presented in Table 11.

Table 11. Sensitivity analysis results for critical variables

No.	Variable	Initial Value	Modified Value	Initial NPV [USD]	Modified NPV [USD]	ΔNPV [USD]	εx
1	Electricity price	0.25 USD/kWh	0.30 USD/kWh	10,316	15,467	+5,151	+2.50
2	Solar irradiation	16,761 kWh/year	20,113 kWh/year	10,316	15,467	+5,151	+2.50
3	Initial investment	13,740 USD	16,488 USD	10,316	7,920	−2,396	−1.16
4	O&M costs	275 USD/year	330 USD/year	10,316	10,006	−310	−0.16

Table 11 confirms that electricity price and solar irradiance are the two dominant drivers of profitability. A 20% rise in either variable lifts the NPV by USD 5,151 (from USD 10,316 to USD 15,467). The corresponding elasticity of +2.50 means that every 1% increase in tariff or insolation raises project value 2.5%, emphasising how strongly revenue streams depend on external market and climatic conditions. From a ROM standpoint, these variables also enlarge the upside captured by the expansion option, since higher prices or better irradiance improve the payoff of adding extra module strings.

In contrast, a 20% escalation in the initial investment cuts the NPV to USD 7,920 (a loss of USD 2,396). Although the elasticity of −1.16 denotes moderate sensitivity, the indicator remains positive, suggesting that the project can tolerate reasonable cost overruns. Nevertheless, the put option valued in Stage 3 becomes more attractive under this circumstance, as managers could defer or scale back the installation if capital costs rise unexpectedly.

O&M expenses show the smallest influence. A 20% increase trims the NPV by only USD 310, bringing it to USD 10,006. The elasticity of −0.16 demonstrates that routine cost fluctuations have little bearing on viability, largely because O&M outlays account for a small share of total cash flow. This mild response underpins the project's operational resilience and reduces the likelihood that the abandonment option would be exercised purely on the basis of higher maintenance costs.

The Tornado diagram in Figure 6 visualises these effects: electricity price and solar irradiance each add 50% to the NPV for a 20% rise, whereas initial investment subtracts 23% and O&M cost only 3%. The direction and length of the bars confirm that favourable shifts in market tariffs or solar resource enhance profitability, while higher capex and operating costs erode it. These findings support the strategic advantage of low operating costs, which not only enhance project resilience but also open a pathway for potential system expansion. Although the present design targets a 50% coverage due to spatial and budgetary constraints, the ROM captures the value of scaling up generation capacity in future scenarios with favourable economic or regulatory conditions.

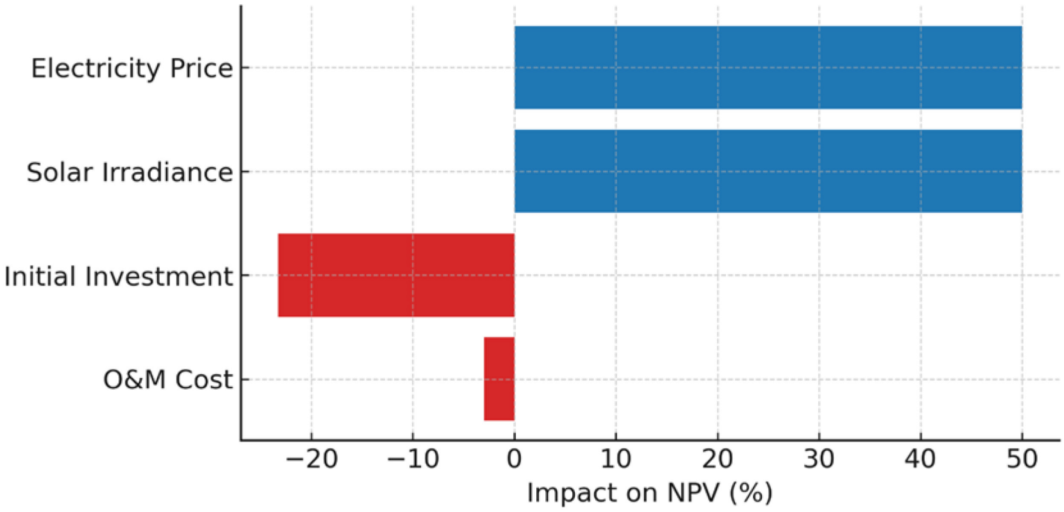


Figure 6. Tornado diagram

To translate single-factor insights into composite outcomes, three scenarios were constructed with the results presented in Table 12.

Table 12. Scenario analysis and its impact on NPV

Variable	Optimistic Scenario (+20%)	Base Scenario (0%)	Pessimistic Scenario (-20%)
Electricity price (USD/kWh)	0.30	0.25	0.20
Solar irradiation (kWh/year)	20,113	16,761	13,409
Initial investment (USD)	10,992	13,740	16,488
O&M cost (USD/year)	220	275	330
Net Present Value (NPV) (USD)	15,467	10,316	5,168

In the optimistic case (+20% on price and irradiance, −20% on capex and O&M) the NPV reaches USD 15,467, strengthening the rationale for exercising the expansion option and increasing system capacity. The baseline case maintains an NPV of USD 10,316, supporting the current design without further adjustments. The pessimistic scenario (−20% on price and irradiance, +20% on capex and O&M) lowers the NPV to USD 5,168, a level that remains positive but narrows the safety margin and underscores the value of the deferral option. Consequently, the combined sensitivity and scenario analysis corroborates the earlier ROM results: upside potential is governed primarily by electricity market conditions and solar availability, while downside risk is cushioned by managerial flexibility rather than small variations in operating costs.

Although the pessimistic scenario still yields a positive NPV, more severe downside conditions, such as a simultaneous and prolonged drop in both electricity prices and solar irradiation, could indeed push the project into a negative NPV territory. For instance, a drop of over 30% in both parameters would significantly reduce revenues while fixed costs remain constant, challenging financial viability. In such a case, mitigation measures become crucial. These may include deploying performance-based O&M contracts to reduce recurring costs, leveraging governmental incentives or carbon credits, incorporating adaptive energy management strategies, or scaling the system incrementally to limit upfront investment. Additionally, the ROM supports managerial flexibility by valuing the deferral or expansion options, which become even more relevant under uncertain or unfavourable conditions.

Stage 5. Definition of the best option

This stage integrates the results obtained in the previous phases to support strategic decision-making. The ROM allows comparing different investment strategies under uncertainty, considering not only their financial performance but also their flexibility and resilience. To this end, a multicriteria analysis was performed to determine the most suitable alternative for the hospital.

Comparative analysis of alternatives based on the ROM

Table 13 combines four decision criteria—adjusted real-option value (40% weight), strategic flexibility (25%), exposure to risk and uncertainty (20%) and impact on long-run profitability (15%). These weights reflect the hospital's dual mandate: achieve immediate savings while preserving the ability to react to uncertain electricity prices and evolving clinical demand. Scores for each alternative were derived from the quantitative results in Stages 3 and 4 and from institutional preferences discussed with facility managers.

Table 13. Multicriteria evaluation of alternatives

Criterion	Weight [%]	Expansion	Reduction	Deferral	Abandonment
Adjusted real option value	40	5	3	4	2
Level of strategic flexibility	25	4	4	5	1
Risk and uncertainty	20	3	4	5	5
Impact on future profitability	15	5	3	2	1
Final Score	100	4.35	3.45	4.15	2.20

The expansion path attains the highest composite score (4.35). Its advantage stems mainly from the call option premium captured in the ROM (criterion one) and from the positive elasticity of NPV to electricity price and irradiance (criterion four). Deferral follows closely at 4.15 because it excels in strategic flexibility and in mitigating risk; the option to wait becomes valuable whenever capital costs or regulatory conditions are uncertain, as illustrated in the pessimistic scenario where the NPV falls to USD 5,168. Reduction ranks third and is preferred only if a moderate downturn persists, while abandonment scores lowest and would be rational solely under extreme deterioration of market conditions or technology obsolescence.

Selection of the final alternative based on the real options method

Given the small margin between expansion and deferral, management is advised to adopt a staged approach. Proceed with the 12 kW array and the fifteen-kilowatt inverter (baseline expansion) while setting explicit triggers for further capacity additions, for example an electricity price above 0.28 USD/kWh or a sustained percentage increase in daytime load. This phased plan aligns with the positive deterministic NPV, captures the USD 5,335 flexibility premium quantified by the ROM and keeps the put option (deferral or scale-back) available should capital costs rise, or policy incentives weaken. In this way the hospital maximises current benefits yet retains the manoeuvrability demanded by a volatile energy and healthcare environment.

Comparative analysis: real options vs. traditional financial methods

Several key factors were analysed to compare traditional financial valuation methods with ROM, including the consideration of uncertainty, flexibility in decision-making, impact on valuation, sensitivity analysis, resilience to market changes, and the possibility of multi-criteria evaluations. Table 14 presents a qualitative and quantitative comparison of both approaches, highlighting the differences in how each method addresses these criteria in the HSP under study

This confirms that the ROM approach enhances decision-making by incorporating market uncertainties and strategic flexibility. It provides a dynamic assessment that considers potential future adjustments, ensuring a more resilient investment strategy for the photovoltaic project

Table 14. Comparison between traditional and ROM methods in the financial evaluation of photovoltaic systems in HSP

Criterion	Traditional Methods	Real Options Method (ROM)
Consideration of uncertainty	Do not incorporate market volatility; rely on static demand projections (e.g., 33,522 kWh/year).	Use stochastic modelling; volatility of 35.7% considered, yielding a real option value of USD 5,334.84.
Flexibility in decision-making	No adjustment possible once investment is made.	Allows strategic decisions such as expansion if electricity prices increase (e.g., >20%).
Impact on valuation	NPV only considers baseline outcome (USD 10,316); ignores future adjustments.	Includes strategic options (expansion, deferral, etc.); Binomial model values project up to USD 72,901.
Sensitivity analysis	Does not assess variation in inputs; risk of over/undervaluation.	Includes elasticities and scenario simulations. A 20% price increase raises NPV by 50%; cost rise lowers it 23%.
Resilience to market changes	Limited adaptability to regulatory or tariff shifts.	Flexible response to changes; deferral option applied to manage investment timing under uncertainty.
Multicriteria evaluation	Project assessed via static financial indicators only.	Uses criteria like option value, flexibility, risk, and long-term returns. Expansion scored highest (4.35/5).

Strengths and limitations

The proposed methodology presents several strengths. First, it integrates real options analysis with operational and regulatory constraints specific to the healthcare sector, offering a novel and replicable framework for evaluating energy projects in critical infrastructure. Second, it provides a probabilistic assessment under uncertainty, incorporating scenario analysis, elasticity estimation, and strategic options such as expansion and abandonment. This allows decision-makers to better capture the value of managerial flexibility and respond to market and environmental variability. Third, the application to a real-world hospital strengthens the practical relevance and transferability of the approach.

However, the study also has limitations. The analysis is based on a single case study, which may limit generalisability to other contexts without proper adaptation. In addition, the simulation assumes constant technical performance of the photovoltaic system over time, without modelling panel degradation or long-term maintenance effects. Finally, while the methodology is compatible with hybrid decision-support systems, this study does not yet integrate artificial intelligence or advanced predictive tools, which could enhance forecasting accuracy and responsiveness in future applications.

CONCLUSIONS

- The application of the Real Options Method (ROM) to the financial evaluation of photovoltaic (PV) systems in healthcare service providers (HSPs) enabled the modelling of investment flexibility and uncertainty. The proposed PV system—covering 50% of the HSP's energy consumption with an annual production of 16,761 kWh—reduces operational costs by approximately USD 1,340/year and enhances energy security. Using the traditional Net Present Value (NPV) method, the project yields a value of USD 10,315.98, while the ROM, implemented through Binomial and Black-Scholes models, assigns a real option value of USD 5,334.84, confirming feasibility and strategic value.
- The ROM allows a more accurate representation of profitability under uncertain market conditions. The analysis revealed high sensitivity to electricity prices and solar irradiation, with elasticities of 2.50, meaning a 20% increase in these variables results in a 50% increase in NPV. Furthermore, Monte Carlo simulations showed that under an optimistic scenario, the NPV increases to USD 15,467, while in the worst-case scenario, it drops to USD 5,168. These results confirm the value of using ROM over traditional methods like NPV and IRR, which do not account for flexibility or risk.
- The evaluation of real options demonstrated the added value of operational adaptability. The call option for system expansion was valued at USD 72,901, reflecting significant potential under favourable conditions. The put option, valued at USD 2,559.51, offers a financial safeguard against cost overruns or underperformance, providing resilience and reducing exposure to risk.
- The ROM also facilitates strategic decision-making by enabling the valuation of options such as deferral, contraction, and staged implementation, which are critical in dynamic and high-risk environments like the healthcare sector.
- Based on the positive results, this methodology is recommended for application in other energy-intensive sectors such as manufacturing, education, and water treatment. In particular, critical infrastructure in developing countries could benefit from flexible investment evaluation tools that incorporate uncertainty and regulatory constraints.
- Future research should explore the integration of the ROM with artificial intelligence and machine learning models, such as supervised learning, time-series forecasting, and reinforcement learning, to enhance predictive capabilities, reduce model subjectivity, and automate scenario analysis. These techniques may improve responsiveness to market volatility and support dynamic decision-making in renewable energy investments. Furthermore, validation in multi-site case studies across diverse climatic and economic regions will help to generalise the findings and improve replicability.
- Beyond its applied contribution, this study offers a methodological advancement by adapting the real options framework to the unique characteristics of healthcare institutions. Unlike prior work focused on residential, commercial, or utility-scale projects, this study incorporates sector-specific needs—such as continuous energy supply and compliance with health regulations—into the financial evaluation process. This adaptation strengthens the practical relevance of ROM-based approaches in energy transition planning for essential public services in emerging economies.

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NOMENCLATURE

Symbols

B_t	benefit obtained in period *t*	[USD]
C	call option value	[USD]
C_b	battery bank capacity	[Ah]
C_t	cost incurred in period *t*	[USD]
DOD	depth of discharge allowed	[%]
E_b	backup energy required	[Wh]
E_c	daily energy consumption of the health service provider	[kWh/day]
K	exercise price of the option (investment required)	[USD]
N(d)	cumulative distribution function of standard normal variable	[–]
N_p	number of photovoltaic panels required	[–]
NPV	net present value	[USD]
P	put option value	[USD]
P_r	rated power of each photovoltaic panel	[W]
PSH	peak sun hours at the system location	[h/day]
r	discount rate or opportunity cost of capital	[–]
r_f	risk-free rate	[–]
s	number of stages into which a project is divided	[–]
S_0	net present value of the underlying asset	[USD]
t	time until the option matures	[years]
u	upward cash flow factor	[–]
V	present value of the project	[USD]
V_d	asset value in downstate	[USD]
V_s	system voltage	[V]
V_u	asset value in upstate	[USD]
X	critical variable in project evaluation	[–]
ΔNPV	change in net present value	[USD]
Δt	time interval in binomial model steps	[years]
ΔX	variation of the analysed variable	[–]
ε_X	elasticity of a variable in project evaluation	[–]

Greek letters

σ	cash flow volatility	[1/year]

Subscripts and superscripts

b	battery
c	consumption
d	down or downstate
f	free (in risk-free rate)
p	panel

r	rated
s	system
t	time
u	up or upstate

Abbreviations

HSP	Health Service Provider
IRR	Internal Rate of Return
RETIE	Technical Regulations for Electrical Installations
ROM	Real Options Method
NTC	Colombian Technical Standard

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