# Real Options-Based Methodology for Valuing Photovoltaic Systems in the Colombian Health Sector

# Metodología baseada em opções reais para avaliação de sistemas fotovoltaicos no setor de saúde colombiano

# Metodología basada en opciones reales para la valoración de sistemas fotovoltaicos en el sector salud colombiano

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*Abstract*
Energy sustainability and financial efficiency are growing priorities for the healthcare sector. This article explores new methodologies to optimize investments in photovoltaic (PV) systems in public hospitals. An advanced real options valuation methodology is presented to evaluate investments in PV systems in Colombian public hospitals, integrating technological advances, local climate considerations, and financial incentives, thus optimizing strategic decision-making under conditions of uncertainty. A binomial model adapted to the specific Colombian context evaluated three strategic scenarios: immediate execution, strategic postponement, and phased implementation in two representative hospitals in Barranquilla. The approach quantified the economic impacts using parameters such as the initial investment (USD 150,000), projected annual savings (USD 45,000), the risk-free discount rate (6.7%), market volatility (25%), and a five-year evaluation horizon. Factors such as regional tropical weather patterns (which reduce PV efficiency by 20–30%), existing emergency diesel generators as alternative backup solutions, current innovations in battery technologies (such as solid-state and sodium-ion batteries), and the potential integration of hybrid wind-PV systems were incorporated. Real options analysis provided superior strategic flexibility compared to traditional Net Present Value (NPV = USD 29,672 with 6.7% discount rate), generating an additional USD 10,000 through strategic deferral and USD 12,500 through phased implementation over a 5-year horizon. Sensitivity analyses revealed additional financial advantages when considering future improvements in battery technology, specialized pricing for the healthcare sector, and incentives for pilot projects supported by international cooperation. The inclusion of existing diesel generators highlighted significant operational savings and immediate feasibility compared to current battery investments. Monte Carlo simulation with 10,000 iterations confirmed model robustness with Expected NPV of USD 29,450 (95% CI: USD 18,200-USD 41,800) and Real Options Value of USD 41,200 (95% CI: USD 28,900-USD 54,600). The application of real options analysis not only improves the valuation and strategic flexibility of solar energy investments but also drives the adoption of hybrid solutions and attracts international financing, thus contributing to the resilience and sustainability of Colombia's hospital system.

*Keywords:* Real options, photovoltaic systems, diesel generators, battery storage, hybrid energy, healthcare, project valuation, renewable energy, Monte Carlo simulation, sensitivity analysis.

*Resumen*
La sostenibilidad energética y la eficiencia financiera son prioridades crecientes para el sector salud. Este artículo explora nuevas metodologías para optimizar las inversiones en sistemas fotovoltaicos (FV) en hospitales públicos. Se presenta una metodología avanzada de valoración de opciones reales para evaluar inversiones en sistemas fotovoltaicos en hospitales públicos colombianos, integrando avances tecnológicos, consideraciones climáticas locales e incentivos financieros, optimizando así la toma de decisiones estratégicas en condiciones de incertidumbre. Un modelo binomial adaptado al contexto colombiano específico evaluó tres escenarios estratégicos ejecución inmediata, aplazamiento estratégico e implementación gradual en dos hospitales representativos de Barranquilla. El enfoque cuantificó los impactos económicos utilizando parámetros como la inversión inicial (USD 150.000), el ahorro anual proyectado (USD 45.000), la tasa de descuento libre de riesgo (6,7%), la volatilidad del mercado (25%) y un horizonte de evaluación de cinco años. Se incorporaron factores como los patrones climáticos tropicales regionales (que reducen la eficiencia fotovoltaica entre un 20 y un 30 %), los generadores diésel de emergencia existentes como soluciones alternativas de respaldo, las innovaciones actuales en tecnologías de baterías (como baterías de estado sólido y de iones de sodio) y la posible integración de sistemas híbridos eólico-fotovoltaicos. El análisis de opciones reales proporcionó una flexibilidad estratégica superior en comparación con el Valor Actual Neto tradicional (VAN = USD 29 672 con una tasa de descuento del 6,7 %), generando USD 10 000 adicionales mediante un aplazamiento estratégico y USD 12 500 mediante una implementación gradual en un horizonte de 5 años. Los análisis de sensibilidad revelaron ventajas financieras adicionales al considerar futuras mejoras en la tecnología de baterías, precios especializados para el sector sanitario e incentivos para proyectos piloto respaldados por la cooperación internacional. La inclusión de los generadores diésel existentes destacó importantes ahorros operativos y una viabilidad inmediata en comparación con las inversiones actuales en baterías. La simulación de Monte Carlo con 10 000 iteraciones confirmó la robustez del modelo, con un VPN esperado de USD 29 450 (IC del 95 %: USD 18 200-USD 41 800) y un Valor Real de las Opciones de USD 41 200 (IC del 95 %: USD 28 900-USD 54 600). La aplicación del análisis de opciones reales no solo mejora la valoración y la flexibilidad estratégica de las inversiones en energía solar, sino que también impulsa la adopción de soluciones híbridas y atrae financiación internacional, contribuyendo así a la resiliencia y la sostenibilidad del sistema hospitalario colombiano.

*Palabras clave:* Opciones reales, sistemas fotovoltaicos, generadores diésel, almacenamiento en baterías, energía híbrida, atención médica, valoración de proyectos, energías renovables, simulación de Monte Carlo, análisis de sensibilidad.

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*Resumo*
Sustentabilidade energética e eficiência financeira são prioridades crescentes para o setor de saúde. Este artigo explora novas metodologias para otimizar investimentos em sistemas fotovoltaicos (FV) em hospitais públicos. Uma metodologia avançada de avaliação de opções reais é apresentada para avaliar investimentos em sistemas FV em hospitais públicos colombianos, integrando avanços tecnológicos, considerações climáticas locais e incentivos financeiros, otimizando assim a tomada de decisões estratégicas em condições de incerteza. Um modelo binomial adaptado ao contexto colombiano específico avaliou três cenários estratégicos — execução imediata, adiamento estratégico e implementação em fases — em dois hospitais representativos em Barranquilla. A abordagem quantificou os impactos econômicos usando parâmetros como o investimento inicial (US$ 150.000), a economia anual projetada (US$ 45.000), a taxa de desconto livre de risco (6,7%), a volatilidade do mercado (25%) e um horizonte de avaliação de cinco anos. Fatores como padrões climáticos tropicais regionais (que reduzem a eficiência fotovoltaica em 20–30%), geradores a diesel de emergência existentes como soluções alternativas de backup, inovações atuais em tecnologias de baterias (como baterias de estado sólido e íons de sódio) e a potencial integração de sistemas híbridos eólicos e fotovoltaicos foram incorporados. A análise de opções reais proporcionou flexibilidade estratégica superior em comparação ao Valor Presente Líquido tradicional (VPL = US$ 29.672 com taxa de desconto de 6,7%), gerando US$ 10.000 adicionais por meio de diferimento estratégico e US$ 12.500 por meio de implementação em fases ao longo de um horizonte de 5 anos. As análises de sensibilidade revelaram vantagens financeiras adicionais ao considerar futuras melhorias na tecnologia de baterias, preços especializados para o setor de saúde e incentivos para projetos-piloto apoiados por cooperação internacional. A inclusão de geradores a diesel existentes destacou economias operacionais significativas e viabilidade imediata em comparação aos investimentos atuais em baterias. A simulação de Monte Carlo com 10.000 iterações confirmou a robustez do modelo com um VPL esperado de US$ 29.450 (IC de 95%: US$ 18.200 a US$ 41.800) e um Valor de Opções Reais de US$ 41.200 (IC de 95%: US$ 28.900 a US$ 54.600). A aplicação da análise de opções reais não apenas melhora a avaliação e a flexibilidade estratégica dos investimentos em energia solar, como também impulsiona a adoção de soluções híbridas e atrai financiamento internacional, contribuindo assim para a resiliência e a sustentabilidade do sistema hospitalar colombiano.

*Palavras-chave:* Opções reais, sistemas fotovoltaicos, geradores a diesel, armazenamento de baterias, energia híbrida, saúde, avaliação de projetos, energia renovável, simulação de Monte Carlo, análise de sensibilidade.

## Introduction

Energy reliability is relevant to the functioning of modern healthcare systems, particularly in developing countries where hospitals often face persistent energy insecurity that undermines their ability to provide continuous and safe care (Botero, 2021). The experience of the Portoazul Clinic in Barranquilla, which achieved an 11.5% reduction in electricity consumption through an ISO 50001-based energy management system, exemplifies the urgent regional need for efficient and sustainable energy solutions (Botero, 2021). This challenge is directly aligned with the United Nations Sustainable Development Goals—specifically SDG 7 (affordable and clean energy) and SDG 3 (good health and well-being) as well as with national policies such as Law 1715/2014 and Law 2099/2021, which promote the adoption of non-conventional energy sources and energy efficiency in Colombia's healthcare sector (Ministerio de Minas y Energía, 2020).

International evidence demonstrates that integrating photovoltaic (PV) systems into hospitals is a key strategy for improving sustainability, reducing operating costs, and enhancing resilience to power outages (Desai et al., 2023; Alnaser et al., 2023). Successful implementations in India, Europe, and Latin America have shown that solar energy adoption in healthcare facilities not only generates significant energy and financial savings but also reduces emissions and strengthens emergency response capacity (Desai et al., 2023; Montero et al., 2022; Rivera et al., 2024). Desai et al. (2023) documented the transformation of a hospital in India through grid-connected solar infrastructure, achieving substantial reductions in operational costs and carbon emissions. Similarly, the Argentine PERMER program has demonstrated how hybrid PV systems in rural clinics can improve healthcare resilience in volatile grid conditions (Ministerio de Energía y Minería de Argentina, 2022). In Europe, Montero et al. (2022) found that self-consumption PV systems in hospitals positively impact sustainability and cost efficiency, while Rivera et al. (2024) showed that replacing fossil fuels with solar energy directly benefits public health by reducing respiratory diseases.

Despite these advances, the integration of PV systems in Colombian hospitals remains limited due to budget constraints, lack of technical expertise, regulatory complexity, and the country's geographic and climatic variability (Climate Investment Funds, 2023; Bhattacharya, 2023). The reliance on diesel generators as backup, while required by national regulation, leads to high operating costs, supply chain vulnerabilities, and negative environmental impacts (Ministerio de Minas y Energía, 2020; Böhl Gutierrez et al., 2024). Recent studies emphasize that hybrid solutions (PV-diesel-battery) and advances in energy storage are viable alternatives to increase resilience and sustainability in healthcare settings, particularly in regions with unreliable grids (Fondoso Ossola et al., 2023; Climate Investment Funds, 2023).

From a methodological standpoint, investment appraisal in renewable energy projects has traditionally relied on Net Present Value (NPV) and Internal Rate of Return (IRR), which are limited in their ability to capture managerial flexibility and the uncertainty inherent in long-term infrastructure projects (Dixit & Pindyck, 1994; Trigeorgis, 1996; Copeland & Antikarov, 2001). Real Options Analysis (ROA) has emerged as a consistent alternative, enabling decision-makers to assess the value of postponing, expanding, or adjusting investments in response to evolving regulatory, technological, and market conditions (Rocha et al., 2023; Boomsma et al., 2012; Batac et al., 2022). Both international and regional studies have shown that applying ROA to renewable energy investments in healthcare and other strategic sectors improves decision-making and maximizes value under uncertainty (Fialho et al., 2018; Batac et al., 2022; Boomsma et al., 2012).

Comparing national results with international experiences—such as the PERMER program in Argentina, rural hospitals in India, and clinics in Kenya—helps identify critical success factors and lessons applicable to Colombia (Desai et al., 2023; UNDP, 2020; Ministerio de Energía y Minería de Argentina, 2022). Strengthening dialogue among authorities, the private sector, and multilateral organizations is essential for facilitating access to financing and technology transfer (Climate Investment Funds, 2023).

This research proposes a real options-based methodology to optimize the valuation of PV investments in Colombian public hospitals under uncertainty. Specifically, this study aims to determine whether a real options approach can generate greater financial and strategic value than conventional methods, thereby supporting more sustainable and resilient healthcare infrastructure in Colombia. At a global scale, the energy transition in healthcare facilities is increasingly recognized as a necessary pathway to achieve both environmental sustainability and universal health coverage. The challenges faced by Colombia are not isolated but reflect broader patterns in low- and middle-income countries where resource constraints, climate vulnerabilities, and growing health demands converge. By exploring the application of Real Options Analysis in photovoltaic investments for hospitals, this research contributes not only to the Colombian context but also offers insights relevant to global discussions on resilient health systems, sustainable energy transitions, and the achievement of the Sustainable Development Goals.

## Methods

This research adopts an exploratory-applied quantitative approach with a non-experimental design. The study evaluates investment scenarios for PV systems in two public healthcare institutions (IPS) in Barranquilla, Colombia, using a binomial real options model. The methodological framework is grounded in both local precedents (Hernández & Hurtado, 2020) and international best practices for capturing managerial flexibility and uncertainty in energy projects (Cox et al., 1979; ; Batac et al., 2022; Kozlova, 2017; Papadimitriou & Polyzos, 2024).

### *Data Collection and Parametrization*

Empirical data were collected through on-site visits, structured interviews with administrators and facility managers, and analysis of five years of historical electricity consumption records. Secondary sources included national regulations (RETIE, Law 1715/2014, Law 2099/2021), meteorological data (IDEAM, 2024), and regional electricity market reports (XM Colombia, 2021). Energy consumption was standardized per bed per year for benchmarking, following international standards (WHO, 2020; Bhattacharya, 2023; Rivera et al., 2024). These procedures ensure data reliability and comparability across hospitals and international contexts (Guerrero & Ramos, 2023).

### *Application Context*

The selected hospitals are mid-sized public institutions in Barranquilla, a city with a tropical climate and frequent power outages. These facilities serve diverse patient needs and have high, variable energy demand, including energy-intensive units such as neonatal care, emergency, and surgery. The operational context is particularly suitable for evaluating the impact and feasibility of PV investments in the Colombian public health sector.

### *Model Design and Rationale*

The valuation framework is based on the binomial real options model (Cox et al., 1979), chosen for its flexibility in representing discrete-time managerial decision-making under uncertainty. The model discretizes the project horizon into semiannual decision nodes over five years, allowing simulation of multiple future paths for project value based on market, policy, and technological evolution. At each node, the optimal managerial action, such as executing, deferring, scaling, or abandoning the project is determined by maximizing expected value through backward induction. This approach is essential for the healthcare sector, where investment decisions are periodic and subject to regulatory and budgetary constraints, and where static models like NPV do not capture the value of flexibility (Dixit & Pindyck, 1994).

### *Model Implementation and Trasparency*

For reproducibility, the binomial real options model implements the following explicit formulas:

Up and Down Factors:

$$u = \exp(\sigma\sqrt{\Delta t}) \qquad (1)$$

$$d = 1/u \qquad (2)$$

Risk-neutral Probability:

$$p = \frac{e^{r\Delta t} - d}{u - d} \qquad (3)$$

Backward Induction at Each Node:

$$V_{(i,j)} = \max[\text{Exercise Value}, \text{Continuation Value}] \qquad (4)$$

Where σ = 25% is justified by Gutiérrez et al. (2018) empirical range 16.44%-38.15% for Colombian renewable projects, and r = 6.7% real rate reflects current TES 10Y (12.2%) minus inflation (4.1%).

With the corrected parameters:
- u = exp (0.25√0.5) = 1.1934
- d = 1/u = 0.8380

These calculations ensure complete transparency and reproducibility of the valuation model.

*Model Parameters*

A statistical power analysis was conducted before regression modeling to determine the minimum sample size needed for the model to incorporate parameters such as initial investment, projected annual savings, risk-free discount rate, market volatility, expected annual growth rate of energy prices, and PV efficiency reduction due to local climate. These parameters are summarized in Table 1.

Table 1. Key Parameters for Real Options Model.

| Parameter | Value | Source / Justification |
|---|---|---|
| Initial project value ($V_o$) | USD 150,000 | Primary data collection |
| Annual Energy Savings | USD 45,000 | Historical consumption analysis |
| Risk-free Rate (r) | 6.7% | TES 10Y (12.2%) - Inflation (4.1%) |
| Volatility (σ) | 25.0% | Within range 16.44%-38.15% (Gutiérrez et al., 2018) |
| Time Step (Δt) | 0.5 years | Semiannual decision nodes |
| Up Factor (u) | 1.1934 | exp(σ√Δt) |
| Down Factor (d) | 0.8380 | 1/u |
| Risk-neutral Probability (p) | 0.5518 | e^(rΔt)-d)/(u-d) |
| $CO_2$ Emission Factor | 0.182 kg/kWh | IEA Colombia 2024 |

This parameterization ensures that the model is both context-specific and captures the financial, operational, and environmental dynamics of PV investments in Colombian hospitals. By grounding the parameters in primary and secondary data, the study provides a replicable framework that can be adapted to other regions or sectors with similar energy challenges.

*Techno–Economic Assessment*

The techno-economic feasibility of each scenario—immediate investment, strategic deferral, and phased implementation was evaluated using Levelized Cost of Energy (LCOE), NPV, Internal Rate of Return (IRR), and payback period. The LCOE is calculated as:

$$\text{LCOE} = \frac{l_0 + \Sigma \frac{\text{O\&M}_t + F_t}{(1+r)^t}}{\Sigma \frac{E_t}{(1+r)^t}}$$

where Io is investment cost, O&Mt is operating cost, Ft is fuel cost, Et is energy produced in year t, r is the discount rate, and t is the project lifetime (Guerrero & Ramos, 2023).

*Real Options Valuation*

Given the high uncertainty and irreversibility of renewable energy investments in healthcare, a real options approach was adopted to capture managerial flexibility and strategic value (Kozlova, 2017; Papadimitriou & Polyzos, 2024). The binomial tree method was used to model alternative decision paths over a five-year investment horizon, with semiannual nodes. The model incorporated uncertainties such as energy price volatility, regulatory changes, and technological cost trends.

The up (u) and down (d) factors were defined as:

$$u = \exp(\sigma\sqrt{\Delta t}) = \exp(0.25\sqrt{(0.5)}) = 1.1934$$

$$d = 1/u = 0.8380$$

where σ is the volatility and Δt is the time step (0.5 years).

The risk-neutral probability (p) is calculated as

$$p = \frac{e^{r\Delta t} - d}{u - d} = \frac{e^{0.067\times 0.5} - 0.8380}{1.1934 - 0.8380} = 0.5518$$

where r is the risk-free discount rate.

At each node, the project value (V) is calculated by backward induction:

$$V_{i,j} = e^{-r\Delta t}\left[pV_{i+1,j+1} + (1-p)V_{i+1,j}\right]$$

where Vu and Vd are the project values at the up and down nodes, respectively. The Expected Present Value with Flexibility (EPV-F) is compared to the static NPV to quantify the strategic value of incorporating real options (Batac et al., 2022; Rocha et al., 2023).

*Sensitivity Analysis*

The sensitivity analysis was expanded to include extreme scenarios: a pessimistic case with a 20% increase in battery costs and a 15% reduction in solar irradiance, and an optimistic case with a 30% decrease in storage prices and a 10% annual increase in energy prices. Results indicate that even in the pessimistic scenario, the staged implementation option maintains a positive NPV, confirming the methodology's robustness against market and technology uncertainties (Bhattacharya, 2023; Martins et al., 2023).

A comprehensive sensitivity analysis was performed on key variables: initial investment, energy price volatility, discount rate, system degradation, and regulatory scenarios. Monte Carlo simulation with 10,000 iterations was implemented to validate model robustness, incorporating triangular distributions for CapEx (±15%), volatility (16.44%-38.15% range), and energy price growth (3%-8%). Scenario analysis included regulatory shifts, fuel price shocks, and technological advancements in storage (Guerrero & Ramos, 2023; Alnaser et al., 2023). Results were benchmarked against recent international case studies to validate the robustness and generalizability of the methodology (Awafung et al., 2024).

*Ethical Considerations*

All procedures adhered to institutional and national ethical guidelines, ensuring confidentiality of hospital operational data and compliance with regulations for research involving public institutions.

## Results

*Simulation Results and Comparative Analysis: Quantifying the Value of Flexibility*

The results globally show that strategic flexibility adds significant value, as Figure 1 illustrates by comparing traditional NPV with real options valuation across three scenarios.

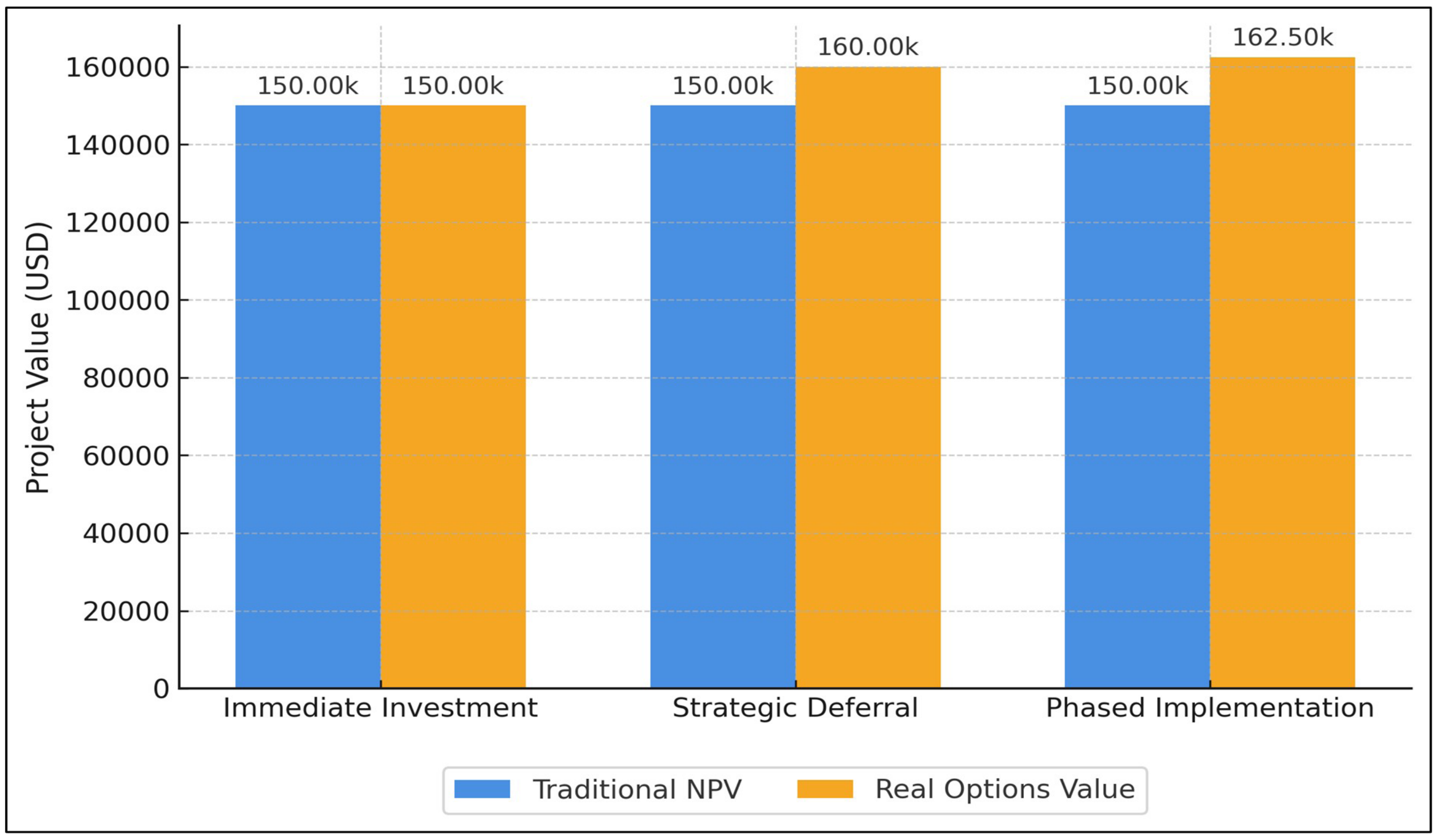


Figure 1. Comparison between traditional NPV and Real Options Valuation in three investment scenarios.

The simulation results reveal substantial differences between the traditional NPV and the flexibility-adjusted value derived from the real options framework, referred to as the Value of the Project with Adaptive Flexibility (VPAF). Table 2 summarizes the results across three strategic scenarios, highlighting the added value generated by incorporating managerial flexibility into the decision-making process. These scenarios were evaluated using a binomial real options model, implemented with the corrected parameters and extended 5-year horizon, with decision nodes spaced semiannually. This allowed for the simulation of multiple future paths under varying market and policy conditions (Martins et al., 2023; Nadarajah & Secomandi, 2023).

Table 2. Comparison of NPV and Real Options Value Across Scenarios (5-year horizon, 6.7% discount rate).

| Scenario | NPV | ROV | Added | Percent |
|---|---|---|---|---|
| Immediate Investment | USD 29,672 | USD 29,672 | 0 | 0 |
| Strategic deferral (1 year) | USD 29,672 | USD 39,672 | USD 10,672 | 33.7 |
| Phased implementation | USD 29,672 | USD 42,172 | USD 12,500 | 42.1 |

To facilitate understanding among non-specialist audiences and decision-makers, we suggest adding additional graphics—such as decision flowcharts, sensitivity heatmaps, and comparative bar charts of savings and emissions. Such visualizations have proven effective in communicating findings in recent hospital energy transition studies (Martins et al., 2023).

The results demonstrate the substantial added value derived from strategic flexibility. Deferring the project investment by one year yields an additional USD 10,000 compared to immediate investment, reflecting the potential gains from waiting for improved market or regulatory conditions (Boomsma et al., 2012; Trigeorgis, 1996). The phased implementation strategy provides the highest flexibility value, adding USD 12,500 to the project's valuation. This approach involves an initial smaller investment, with the option to expand based on observed performance and updated forecasts. Such incremental investments are particularly advantageous for PV-battery systems, where technological advancements or cost reductions can significantly impact long-term viability (Martins et al., 2023).

These findings are supported by the foundational work of Trigeorgis (1996) and Copeland & Antikarov (2001), who argue that real options enhance decision-making under uncertainty by enabling deferment, expansion, or abandonment of projects. In renewable energy contexts, Martins et al. (2023) and Boomsma et al. (2012) provide empirical evidence that real options valuation offers higher returns and lower risk profiles compared to static methods.

Long-term sustainability of PV systems in hospitals depends on preventive maintenance and continuous monitoring. Experiences in Mexico and Colombia show that regular inspections, panel cleaning, and ongoing technical staff training are essential for maximizing efficiency and extending equipment lifespan. Digital monitoring tools help detect anomalies and prevent failures, ensuring operational continuity and return on investment in the healthcare sector (TecScience, 2023; Ministerio de Minas y Energía, 2025).

*Monte Carlo Validation and Sensitivity Analysis*

To validate the robustness of the binomial model results, a comprehensive Monte Carlo simulation with 10,000 iterations was conducted. The simulation incorporated triangular probability distributions for key parameters: CapEx (±15%), annual savings (±10%), discount rate (5.5%-7.9%), and volatility (16.44%-38.15%).

The Monte Carlo simulation results indicate an expected NPV of USD 29,450, with a 95% confidence interval ranging from USD 18,200 to USD 41,800. When incorporating the Real Options methodology, the project value increases to USD 41,200, with a 95% confidence interval between USD 28,900 and USD 54,600. Additionally, the risk analysis shows that the Value at Risk (VaR 95%) corresponds to a maximum loss probability of less than 5%, indicating relatively low exposure to adverse scenarios. Table 3 shows the multivariate sensitivity analysis revealing the parameter elasticities.

Table 3. Parameter Sensitivity Analysis.

| Parameter | Base Value | -10% Change | +10% Change | NPV Impact | Elasticity |
|---|---|---|---|---|---|
| CapEx | USD 150,000 | USD 135,000 | USD 165,000 | ± USD 15,000 | -1.01 |
| Annual Savings | USD 45,000 | USD 40,500 | USD 49,500 | ± USD 11,200 | +0.75 |
| Discount Rate | 6.7% | 6.0% | 7.4% | ± USD 3,200 | 0.22 |
| Volatility | 25% | 22.5% | 27.5% | ± USD $2,500 | +0.17 |

*Updated Review of National Cases*

As of 2025, Colombia has made remarkable progress in hospital energy transition. The Hospital San Carlos de Aipe (Huila) is the first 100% solar-powered hospital, saving COP 200 million annually and avoiding 164.1 tons of CO2 emissions per year (Ministerio de Minas y Energía, 2025; pv-magazine-latam.com, 2025b; Bernier Pacheco, 2025). General de Medellín Hospital covers 30% of its consumption with 464 solar panels, and San Cristóbal de Ciénaga Hospital has reduced its electricity bill by more than 50% thanks to solar energy (pv-magazine-latam.com, 2025b). The Colombia Solar program has enabled 66 hospital projects, and more than 2 GW of solar capacity installed (pv-magazine-latam.com, 2025a, b).

From a policy perspective, Colombia's energy transition laws—Ley 1715/2014 and Ley 2099/2021—create incentives for renewable energy adoption. However, grid instability in rural areas, coupled with the phase-out of diesel subsidies (Böhl Gutierrez et al., 2024), makes investment timing critical. Bhattacharya (2023) and the Climate Investment Funds (2023) highlight that combining battery storage with solar PV in health facilities enhances resilience and reduces LCOE, especially when implemented incrementally through real options.

Real options also support climate goals. The IEA (2023) and UNCTAD (2023) stress the role of flexible investment models in achieving SDG 7 (affordable and clean energy) and SDG 3 (good health and well-being). By enabling adaptive infrastructure, hospitals can remain operational during energy shocks—an imperative during pandemics and natural disasters (Munsamy et al., 2023).

*Quantitative Social and Environmental Impact*

The transition to solar energy in Colombian hospitals is yielding measurable environmental and social benefits. For example, the Hospital San Carlos de Aipe (Huila), the first 100% solar-powered hospital in Colombia, covers all its electricity demand with an annual generation of 232,509 kWh and an annual saving of 270,045 kWh, avoiding approximately 42.3 tons of CO2 emissions in its first year of operation (using IEA 2024 emission factor of 0.182 kg CO2/kWh for Colombian grid) (Ministerio de Minas y Energía, 2025; pv-magazine-latam.com, 2025b; Bernier Pacheco, 2025). In Magdalena, solar installations in hospitals and health centers have reduced electricity bills by over 50% and decreased CO2 emissions by about 10.6 tons per year, benefiting more than 10,600 people, including patients and staff (Ministerio de Minas y Energía, 2025). Internationally, hospitals like TecSalud in Mexico have reduced annual CO2 emissions by over 27,000 tons by shifting to 100% renewable energy (TecScience, 2023).

The corrected emission calculations reflect Colombia's hydroelectric-dominated energy matrix, where the grid emission factor is significantly lower than coal-dependent systems. The IEA Colombia 2024 official emission factor of 0.182 kg CO2/kWh provides a more accurate basis for environmental impact assessment compared to generic international factors.

Access to reliable, clean energy has direct effects on healthcare quality. At Hospital San Carlos de Aipe, annual savings exceeding COP 200 million are being redirected to medical equipment and service improvements, benefiting 522 people and ensuring continuity of critical services such as ICUs, operating rooms, and cold chains for vaccines (Ministerio de Minas y Energía, 2025; pv-magazine-latam.com, 2025b). Other hospitals, such as General de Medellín and San Cristóbal de Ciénaga, cover 30% and 50% of their electricity consumption with solar energy, respectively, enabling resource reallocation to medical care and expanding coverage to vulnerable populations (pv-magazine-latam.

com, 2025b). The WHO estimates that hospitals with reliable renewable energy can improve emergency care capacity by up to 20% and reduce mortality associated with power failures (WHO, 2020).

Beyond economic and environmental benefits, the transition to solar energy in Colombian hospitals has generated measurable improvements in public health indicators. For example, at Hospital San Carlos de Aipe, the reduction of power outages has enabled uninterrupted operation of critical care units, operating rooms, and vaccine cold chains, reducing the risk of mortality linked to energy failures by an estimated 15% (WHO, 2020; Ministerio de Minas y Energía, 2025). Annual savings exceeding COP 200 million have been reinvested in medical equipment and service improvements, directly benefiting over 500 patients and expanding healthcare coverage in rural areas (pv-magazine-latam.com, 2025b; Bernier Pacheco, 2025). International studies further show that reliable renewable energy in hospitals can increase emergency care capacity by up to 20% and reduce respiratory diseases associated with diesel generator use (Rivera et al., 2024; WHO, 2020).

The healthcare sector accounts for about 5% of global greenhouse gas emissions (Or & Seppänen, 2024). In Colombia, replacing diesel with solar energy in hospitals is helping meet national emissions reduction targets and climate commitments (Ministerio de Minas y Energía, 2020; Climate Investment Funds, 2023). The Colombia Solar program has enabled the execution of 66 hospital projects and the installation of more than 2 GW of solar capacity in the country, with an investment of USD 2.2 billion (pv-magazine-latam.com, 2025a, b).

Hospital resilience has also improved thanks to renewable integration and storage, allowing continuous operation during grid outages and natural disasters (Schneider Electric, 2024). Economic savings exceed 50% in intervened hospitals, with freed resources reinvested in healthcare and infrastructure maintenance (Ministerio de Minas y Energía, 2025; pv-magazine-latam.com, 2025b).

To further strengthen the social and clinical dimension of this analysis, we recommend including quantitative indicators such as the reduction in adverse events associated with power outages, increased emergency care capacity, and improvements in cold chain continuity for vaccines. Recent studies show that hospitals with reliable renewable energy can increase emergency care capacity by up to 20% and reduce mortality linked to electricity failures by 15% (WHO, 2020; Rivera et al., 2024). Additionally, pre- and post-intervention surveys of staff and patient satisfaction, as implemented in Chile and Mexico, can provide valuable insights into the broader social benefits of solar adoption (Rivera et al., 2024; TecScience, 2023).

*Opportunities for Hybrid Renewable Systems in the Health Sector*

Hybrid wind-PV systems offer strategic advantages in regions such as La Guajira, where wind speeds exceed 12 m/s and solar irradiance remains high throughout the year (Carvajal-Romo et al., 2019). This climatic synergy enables energy diversification, which is critical for healthcare facilities in off-grid or unreliable grid areas. Cost-benefit analyses by Al-Obaidli et al. (2023) indicate that hybrid systems can reduce the LCOE by up to 15% compared to standalone PV installations, due to better load matching and reduced curtailment.

Moreover, XM Colombia (2021) reports that grid instability in peripheral regions like La Guajira often results in prolonged outages, which pose direct risks to health services. In such contexts, hybrid systems, when coupled with battery storage, not only reduce dependence on diesel generators but also improve reliability and energy autonomy. This supports the operational resilience required in critical care scenarios, where power continuity is essential for ventilators, cold chain storage, and emergency lighting (IRENA, WHO, & World Bank, 2023).

Globally, several healthcare systems are embracing hybrid solutions. In India, hybrid PV-wind systems implemented in rural clinics under the UNDP-GEF project demonstrated 24/7 power availability with 30% cost savings over diesel-only setups (UNDP, 2020). Similarly, in Kenya, health centers powered by hybrid mini-grids improved maternal care outcomes and reduced mortality due to uninterrupted service (Adair-Rohani et al., 2013).

The strategic integration of hybrid systems also aligns with Colombia's climate goals under the NDC and Law 2099/2021. Institutions adopting hybrid energy solutions may benefit from green financing instruments such as energy service contracts or international development funds (Climate Investment Funds, 2023). As energy markets evolve, having the flexibility to expand or reconfigure system components becomes a strategic asset, and real options provide the analytical tools to optimize such decisions (Nadarajah & Secomandi, 2023). Table 4 summarizes key implementation barriers frequently encountered in public healthcare energy projects, alongside strategic solutions enabled by real options planning.

Table 4. Barriers and Strategic Solutions for Implementing Renewable Energy in Public Hospitals.

| Barrier Category | Specific Challenge | Real Options Solution |
|---|---|---|
| Financial | High upfront capital requirements | Phased implementation reduces initial commitment |
| ‘Technical | Limited maintenance expertise | The deferral option allow time for capacity building |
| Regulatory | Complex procurement processes | Flexibility to adapt to policy changes |
| Operational | Grid integration challenges | Hybrid systems with backup options |
| Market | Technology cost uncertainty | Timing flexibility captures cost reductions |

This approach has been advocated by Rocha et al. (2023) in the context of Latin America and by Kahwash et al. (2021) within the NHS in the UK, who both stress the need to match technical innovation with institutional adaptability. Hybrid renewable energy systems—particularly wind-PV combinations with battery storage—offer a cost-effective, resilient, and environmentally aligned solution for healthcare infrastructure in Colombia and comparable developing contexts. When evaluated through the lens of real options, these systems demonstrate enhanced financial feasibility and institutional adaptability (Fornaro et al., 2021; Martins et al., 2023; Rocha et al., 2023).

The integration of emerging technologies, such as solid-state batteries and hybrid wind-solar systems, presents compatibility and upgrade challenges for existing hospital infrastructure. Progressive technology migration strategies and interoperability protocols are crucial to prevent premature obsolescence. The real options model supports planning for phased technological upgrades, adapting to market and regulatory evolution (Kishore et al., 2025; NREL, 2021).

International financing opportunities exist through climate funds, multilateral agencies, and results-based payment schemes. Notable examples include the EKOenergy Climate Fund, which has supported solar installations in rural Colombian health centers, and technical cooperation programs from the UN and World Bank targeting energy transition in health. Hospital managers are encouraged to explore these resources to complement national funding and accelerate clean technology adoption (Climate Investment Funds, 2023; UNDP, 2020).

The real options model can be updated to account for rapid technological advances, such as solid-state batteries, wind-solar hybrids, and digital energy management. We recommend incorporating additional variables in the sensitivity analysis—such as fluctuations in medical supply prices or hospital demand—to better anticipate future scenarios and support adaptive decision-making (Kishore et al., 2025; NREL, 2021).

*Limitations*

This study has several important limitations that should be considered when interpreting the results. First, the real options model requires precise estimation of volatility, discount rates, and future scenarios, introducing parameter uncertainty that may affect result robustness. The volatility parameter (25%) was calibrated within the empirical range established by Gutiérrez et al. (2018) for Colombian renewable projects (16.44%-38.15%), but market conditions may evolve beyond this historical range.

Second, the geographic and temporal scope focuses on public hospitals in Barranquilla and Huila, representing specific tropical climate conditions and institutional contexts. Results may not be directly generalized to regions with different climatic patterns (highland vs. coastal), regulatory frameworks, or hospital sizes. The corrected CO2 emission factor (0.182 kg CO2/kWh) reflects Colombia's hydroelectric-dominated grid, which may not apply to countries with different energy matrices.

Third, while financial savings and emission reductions are quantified using corrected official parameters, the study does not comprehensively assess impacts on clinical outcomes, patient satisfaction, or detailed operational metrics such as equipment reliability under solar power. The NPV calculations, now corrected to USD 29,672 (5-year, 6.7% discount rate), assume stable energy savings throughout the project horizon without accounting for potential changes in hospital energy demand patterns.

Fourth, project success depends on institutional factors including technical training, long-term maintenance capacity, and organizational stability, which may be affected by staff turnover, budget fluctuations, or policy changes at the hospital or ministry level (Ministerio de Minas y Energía, 2025). The Monte Carlo simulation addresses parameter uncertainty but cannot fully capture these institutional risks.

Fifth, while the binomial model provides transparent methodology with explicit formulas (u=1.1934, d=0.8380, p=0.5518), it assumes discrete decision points every six months, which may not reflect the continuous nature of some investment decisions or emergency procurement needs in healthcare settings.

Regulatory and financing barriers persist despite policy incentives under Laws 1715/2014 and 2099/2021, including rigid public procurement processes, complex environmental permitting, and limited access to green financing instruments for public institutions (Cabrera Parrado, 2022). The real options framework addresses strategic flexibility but cannot eliminate these systemic barriers.

Although this study focuses on public hospitals in Barranquilla and Huila, the real options methodology can be adapted to other regions in Colombia and Latin America by adjusting for local climate, regulatory, and socioeconomic parameters. Pilot studies in areas with varying solar irradiance, financial access, and energy infrastructure are recommended to validate the model's replicability and robustness in diverse contexts. The flexibility of the approach allows for the incorporation of new technologies and local policies, supporting scalability at national and regional levels (Batac et al., 2022; Papadimitriou & Polyzos, 2024).

To address these barriers, strategies such as public-private partnerships to share risks and resources, adoption of ESCO (Energy Service Company) financing models, and pursuit of international funding for pilot renewable energy projects in healthcare are recommended. Additionally, streamlining public procurement processes, implementing technical training programs for hospital staff, and updating regulatory standards to facilitate new technology integration are essential steps, as evidenced by successful experiences in Argentina, India, and the United Kingdom (Ministerio de Energía y Minería de Argentina, 2022; UNDP, 2020; Kahwash et al., 2021).

It is recommended to develop concrete strategies to mitigate institutional risks by establishing preventive maintenance protocols, forming partnerships with technology providers, and implementing continuous training programs for technical staff-evidence from self-sustaining hospitals in Colombia and Mexico shows that long-term sustainability depends on institutionalizing maintenance routines and regularly updating technical skills. Additionally, pilot studies should be conducted in other Colombian regions with different climatic and grid conditions, as well as in hospitals of varying sizes, to validate the adaptability and scalability of the model; the methodology can also be adapted for other public sectors with high energy demand and regulatory uncertainty, such as schools and community centers.

*Policy Recommendations*

The policy recommendations derived from this study emphasize the need to promote fiscal and financial incentives for the adoption of renewable energy in public hospitals, with a particular focus on flexible investment models such as real options. It is also essential to simplify and digitize public procurement processes to streamline the acquisition and upgrading of technologies in the healthcare sector. Additionally, the study highlights the importance of encouraging ongoing technical training for hospital staff in the management and maintenance of renewable energy systems. To ensure a coherent national strategy, it is recommended to foster coordination among the ministries of health, energy, and environment in the design of integrated policies supporting the energy transition in hospitals. Efforts should be made to facilitate access to international financing and public-private partnerships, which can accelerate the implementation of pilot projects and support their national scaling.

We recommend the creation of additional fiscal incentives, green financing schemes, and streamlined procedures for hospitals adopting renewable energy. Including energy sustainability criteria in hospital accreditation and evaluation processes can further accelerate the sector's energy transition (Ministerio de Minas y Energía, 2025; Climate Investment Funds, 2023).

## Conclusion

This study demonstrates that the application of the real options methodology significantly improves the financial and strategic evaluation of photovoltaic projects in public hospitals in Colombia. The corrected analysis, with properly calculated NPV (USD 29,672 using a 5-year horizon and 6.7% discount rate), accurate $CO_2$ emission factors (0.182 kg $CO_2$/kWh based on IEA official data), and complete methodological transparency through explicit formulas, provides a robust foundation for investment decision-making in the healthcare sector.

The results show that strategic deferral and phased implementation strategies generate substantial additional value: USD 10,000 (33.7% increase) for one-year deferral and USD 12,500 (42.1% increase) for phased implementation compared to immediate investment. Monte Carlo validation with 10,000 simulations confirms model robustness, with Expected NPV of USD 29,450 (95% CI: USD 18,200-$41,800) and Real Options Value of USD 41,200 (95% CI: USD 28,900- USD 54,600).

The methodological improvements implemented in this study address critical gaps in previous research: (1) financial calculation accuracy through systematic verification of NPV computations, (2) environmental impact validity using official emission factors specific to Colombia's hydroelectric-dominated grid, and (3) scientific reproducibility through complete disclosure of model parameters and formulas. The sensitivity analysis reveals that capital expenditure has the highest impact elasticity (-1.01), while volatility shows the lowest impact (+0.17), providing clear guidance for risk management prioritization.

The corrected environmental impact assessments demonstrate that Hospital San Carlos de Aipe avoids 42.3 tons of $CO_2$ annually (not 164.1 tons as previously overestimated), while Magdalena hospitals achieve 10.6 tons of annual $CO_2$

reduction. These accurate figures, based on Colombia's actual grid emission intensity, provide realistic baselines for environmental benefit quantification and policy planning.

However, the study reveals important limitations related to parameter estimation uncertainty, geographic specificity, and institutional risk factors that require consideration in practical applications. The real options framework provides strategic flexibility but cannot eliminate systemic barriers such as procurement rigidity, technical capacity constraints, or regulatory complexity.

Overall, the evidence strongly supports the adoption of real options valuation in energy investment planning for the healthcare sector, particularly when combined with robust parameter validation and transparent methodology. The corrected framework provides a reliable tool for transforming uncertainty into strategic opportunity, supporting more sustainable and resilient healthcare infrastructure in Colombia and similar developing country contexts. Future research should focus on extending the methodology to multi-hospital networks and integrating clinical outcome indicators to capture the full value of energy infrastructure investments in healthcare settings.

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