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C5 Electricity Markets and Regulation**PS1 Market designs and non-market approaches to support the energy transition****Energy Hubs in Brazil: A Proposal for Feasibility Assessment
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alp1@poli.br****Roberto DIAS****Clean Horizon****POLI-UPE****France/Brazil****roberto.dias@upe.br****Manoel MARINHO****POLI-UPE****Brazil****marinho75@poli.br****SUMMARY**

The paper presents a methodology for evaluating the feasibility of large-scale Energy Hubs (EHs) using Real Options Analysis (ROA), emphasizing the growing relevance of such hubs for global decarbonization. Energy Hubs integrate multiple renewable sources with technologies for conversion, storage, and consumption—such as hydrogen electrolysis, batteries, and digital infrastructure—offering a coordinated way to optimize multi-energy flows. Brazil's Northeast region is highlighted as especially suitable for these systems due to its excellent solar and wind resources, port infrastructure, and emerging regulatory frameworks supporting hydrogen and renewable energy markets.

A detailed case study models a hybrid EH in Suape (a maritime industrial complex in Pernambuco state, Brazil) combining 300 MW of solar PV, 200 MW of wind, 25 MWh/100 MWh of battery storage, a 100 MW electrolyzer, and a 20 MW data center. Uncertainties in hydrogen price, electricity price, CAPEX, and renewable generation were represented using lognormal distributions.

The options to delay, expand, and abandon add considerable value, particularly the abandonment option, which provides strong downside protection. When combined, these flexibilities shift the project from an unfeasible baseline to a positive expected value of about USD 386 million, demonstrating that managerial flexibility is essential for the economic viability of complex Energy Hubs under uncertainty.

KEYWORDS

Energy Hubs, Brazil's Northeast region, Real Options Analysis, Longstaff-Schwartz algorithm

1 Introduction

The global energy transition demands innovative infrastructures capable of integrating multiple renewable energy sources with advanced storage and conversion technologies. Within this context, Energy Hubs (EHs) have emerged as a pivotal concept for enabling large-scale decarbonization and optimizing the flow of energy carriers such as electricity, heat, hydrogen, and synthetic fuels across interconnected systems [1-3]. Recent studies highlight their strategic role in linking renewable generation—onshore and offshore wind, solar photovoltaic (PV), and hybrid storage solutions—to energy-intensive applications such as hydrogen production and data centers powered by low-carbon electricity [4].

Brazil represents a particularly promising case for the deployment of integrated energy hubs due to its abundant renewable resources and growing industrial demand for clean power [5]. The Northeast region offers exceptional solar irradiance and wind capacity factors, creating favourable conditions for hybrid renewable projects and the emerging green hydrogen (H₂V) economy. Additionally, the region's coastal infrastructure, exemplified by the Suape Industrial and Port Complex in Pernambuco, provides logistical advantages for hydrogen export and the establishment of energy-intensive digital infrastructures, such as data centers supporting artificial intelligence and cloud computing. These developments align with global decarbonization policies and Brazil's recent legislative framework—specifically Federal Laws 14.948/2024 and 14.990/2024—which promote renewable integration, carbon pricing mechanisms, and hydrogen market regulation.

However, the investment feasibility of Energy Hubs is challenged by significant uncertainties. These include fluctuations in renewable energy prices, technological cost trajectories (e.g., electrolyzers and battery systems), exchange rate volatility, and evolving international regulatory frameworks such as the Carbon Border Adjustment Mechanism (CBAM) and Renewable Fuels of Non-Biological Origin (RFNBO) directives of European Union. To address these limitations, the Real Options Analysis (ROA) framework provides a powerful alternative by explicitly valuing managerial flexibility.

This research proposes a computational tool to perform techno-economic and financial feasibility analyses of Energy Hubs in Brazil, integrating Monte Carlo simulation for risk quantification with Real Options Analysis for decision optimization. A case study of an Energy Hub located in Northeast Brazil, potentially in Suape's Port Complex, demonstrates the tool's applicability. The simulated configuration emphasizes the joint production of green hydrogen for export and clean electricity for data centers, reflecting Brazil's strategic position in the global green energy supply chain.

2 Energy Hub Concept and Global Applications

In recent years, the EHs paradigm has evolved to include hydrogen-based and Power-to-X (PtX) pathways, as well as the integration of data centers as controllable, high-demand loads and potential sources of waste heat. Hydrogen enhances system flexibility by enabling seasonal storage and the production of e-fuels such as ammonia or methanol. Simultaneously, data centers—whose global energy use is rapidly increasing—offer a unique opportunity for sector

coupling. Their high and predictable electrical demand provides stability to renewable-dominated grids, while their waste heat can be captured and reintegrated into district heating networks or industrial processes within the EH. When co-located with PtX facilities, data centers can further improve overall energy efficiency by using curtailed renewable electricity and enabling heat recovery for hydrogen or methanol synthesis processes [4].

Globally, EH applications are gaining momentum. In Northern Europe, Denmark, the Netherlands, and Germany have been analysing large-scale renewable energy hubs coupling offshore wind, hydrogen electrolysis, e-fuel synthesis, and digital infrastructure [6, 7]. In Asia, Japan, Singapore, and South Korea are developing green-data-hub models that integrate hydrogen production with high-performance computing [8].

A growing body of literature refines the EH concept through modelling, optimization, and techno-economic analysis. Dachet *et al.* [4] introduce a formal taxonomy for Energy Hubs, defining a mathematical structure that represents locations, technologies, commodities, imports, exports, by-products, and local opportunities. Giehl *et al.* [9] present an optimization model for a Power-to-X energy hub operation, focusing on e-methanol production from renewable electricity. This model was applied to Denmark's Kassø facility (304 MW PV, 52 MW electrolysis), to evaluate levelized cost of methanol (LCOM), emissions, and sensitivity to investment and efficiency parameters.

3 Real Options Analysis (ROA) Framework

ROA is a framework that extends traditional financial valuation by explicitly incorporating managerial flexibility and uncertainty into investment decision-making. In simple terms, ROA treats real (tangible) investment opportunities — such as building a factory, developing a new technology, or expanding a renewable energy project — as options that managers can exercise, delay, expand, contract, switch, or abandon, depending on how future market conditions evolve. This is analogous to financial options in capital markets but applied to “real” assets rather than securities [10, 11].

Among the classical methods for investment analysis in a well-behaved business environment, the calculation of Net Present Value (NPV) and Internal Rate of Return (IRR) stand out, as they seek to identify projects that generate value for the company based on pre-established financial criteria. However, such models assume that the initial conditions of the projects remain unchanged throughout their lifecycle. Real Options Analysis enables, for example, the assessment of the advantage of postponing an investment until market conditions become clearer; the possibility of starting the project on a smaller scale and expanding it over time; or even the decision to abandon a project should the scenario become economically unviable. It also allows for the simulation of technological changes over time or entry into new markets using the installed infrastructure [11, 12].

In essence, Real Options Analysis is structured as a decision-making process that balances opportunities for value creation with unpredictable challenges, like other optimization problems under uncertainty.

The Table 1. presents the main Real Options available during a project's investment and operational phases. In the investment phase, firms may delay, stage, or abandon investments to manage uncertainty in costs, prices, and policy. They can also change technologies as better alternatives emerge or choose locations that create future synergies with storage, ammonia, or other energy uses. During the operational phase, flexibility continues through the options to expand or contract capacity, depending on market conditions. Firms may switch inputs (such as between grid and renewable power) or switch outputs (e.g., hydrogen, ammonia, methanol) to capture higher value. Finally, storage and hybrid-operation options allow arbitrage and coordinated use of assets to optimize performance under uncertainty [10-13].

Table 1 - Real Options most commonly used. Adapted from [10-13.]

Real Option Types for Investment Phase	Description / Example
Option to Delay (Wait to Invest)	Defer the final investment until uncertainties in CAPEX, energy prices, or policy incentives are resolved.
Option to Stage Investment (Sequential Expansion)	Build electrolyzers or methanol modules in stages ; expand after early modules prove profitable.
Option to Change Technology	Upgrade from alkaline to PEM electrolysis or add solid-oxide cells when prices fall.
Option to Abandon / Postpone	Terminate or postpone investment if unfavorable price or policy shocks occur.
Option to Co-locate (Synergy Option)	Choose hub location allowing later coupling with storage, ammonia, or data-center loads.
Real Option Types for Operational Phase	Description / Example
Option to Expand	Increase electrolyzer or CHP capacity when hydrogen prices rise.
Option to Contract or Mothball	Shut down during periods of low prices and restart later.
Option to Switch Inputs	Use grid or renewable electricity depending on spot prices.
Option to Switch Outputs	Produce hydrogen, ammonia, or methanol depending on demand.
Option to Store / Arbitrage	Operate BESS or H ₂ storage to exploit hourly price spreads.
Option to Combine / Hybrid Operation	Coordinate CHP and H ₂ storage to minimize cost under uncertainty.

One particularly interesting reference regarding the practical application of ROA is study [14], which develops an integrated framework combining Mixed Integer Linear Programming (MILP) and Real Options Analysis (ROA) to optimise hydrogen transport infrastructure in the US state of Wyoming, taking demand uncertainty into account. The analysis assesses new hydrogen pipelines, repurposed natural gas pipelines, and truck transport. The ROA reveals that a phased investment strategy — starting with smaller pipelines (36 inches) and adding trucks and repurposed infrastructure as demand grows — provides optimal flexibility and cost efficiency. The Wyoming case study highlights how strategic infrastructure planning using ROA can balance economic viability with the need for scalable and resilient hydrogen networks in emerging markets.

Fabianek, Glensk, and Madlener [15] analyzes the economic feasibility of investing in renewable energy plants for hydrogen (Power-to-Hydrogen, P2H) in Germany and California using Real Options Analysis. The focus of the analysis is on the blending of green hydrogen into natural gas grids, considering natural gas prices as a key uncertainty. The study concludes that more robust policy measures—such as higher carbon taxes, mandatory hydrogen blending, or feed-in tariffs—are essential to make green hydrogen production economically attractive.

It is important to note that many companies already possess substantial expertise in strategic management. However, this knowledge is often concentrated in the minds of a few senior

executives. By documenting and quantifying strategy through the Real Options Analysis (ROA) methodology, strategic thinking becomes accessible across the organization.

4 Case Study: Energy Hub in Northeast Brazil (Suape)

This study implements a computational framework for the economic valuation of a hybrid renewable energy hub located in Suape, Pernambuco (Brazil). The hub integrates multiple technologies—photovoltaic (PV), onshore wind power, battery energy storage (BESS), a hydrogen electrolyzer, and an information technology (IT) data center—operating in a coordinated manner to produce electricity and green hydrogen. The system’s topology and data used in this study is presented in Figure 1 and Table 2 [16-19].

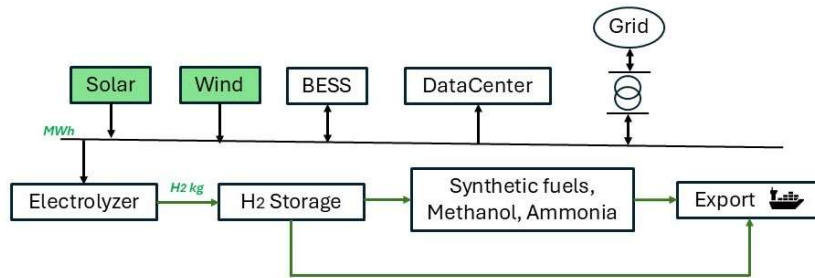


Figure 1 – Suapes’s Energy HUB

Table 2 – Technologies Integrating Energy Hub located in Suape, Pernambuco (Brazil). Adapted from [16-19]

Equipment	Installed Capacity	Unit Cost (USD)	Function
Solar PV Plant	300 MW	650 \$/kW	Produces renewable electricity during the day.
Wind Farm	200 MW	1 200 \$/kW	Generates electricity mainly at night and complements PV.
Battery Storage (BESS)	25 MW / 100 MWh	350 \$/kWh	Stores energy and supports system reliability.
Electrolyzer System	100 MW	800 \$/kW	Converts surplus electricity into green hydrogen.
Data Center (IT Load)	20 MW	9 000 \$/kW_IT	Consumes part of the renewable electricity for digital services.

The study evaluates the investment through Real Options Analysis (ROA) using Monte Carlo simulation to account for uncertainty in future market and technical variables, such as 1) hydrogen price; 2) electricity price; 3) capital expenditure; and 4) renewable generation (PV and Wind). The parameters used for Real Options Analysis are presented in Table 3 [3, 16-19]. Some of these values are based on engineering and industry practice rather than on specific literature references.

Table 3 – Parameters for Real Options Analysis (ROA). Adapted from [3, 16-19]

Category	Parameter	Value	Unit / Notes
Project Horizon & Discounting	Project life	20	years
	Discount rate (real WACC)	0.08	–
Annual Capacity Factors	PV capacity factor	0.25	–
	Wind capacity factor	0.45	–
Efficiencies & Utilization	BESS round-trip efficiency	0.88	–
	BESS annual utilization factor	0.8	-

	Electrolyzer utilization	0.80	–
	Data center PUE (Power Usage Effectiveness)	1.25	–
O&M Assumptions for Renewable Generation and BESS	Fixed O&M	2% of CAPEX	per year
	Variable O&M	3.0	USD/MWh (renewable generation)
Baseline Prices	Baseline hydrogen price	3.5	USD/kg
	Baseline electricity price	35.0	USD/MWh
	Price premium for arbitrage-driven electricity sold	1.2 * Baseline electricity price	USD/MWh
	Revenue from digital services	2,000.00	USD/kW _{ITload} (annual earnings per kilowatt of IT load)
Hydrogen Conversion	H ₂ production factor	21.0	kg per MWh (30 × electrolyzer efficiency)
O&M Assumptions for Hydrogen Production	Fixed and Variable O&M	2% of CAPEX	per year
Hydrogen Conversion	H ₂ production factor	21.0	kg per MWh (30 × electrolyzer efficiency)
O&M Assumptions for Data Center	Fixed O&M	2% of CAPEX	per year

To incorporate uncertainty into the economic evaluation of the Energy Hub system, all the following key variables were modeled using lognormal probability distributions: a) hydrogen price; b) electricity price; c) capital expenditure; d) annual wind generation; and e) annual photovoltaic generation.

The hydrogen price was assigned a volatility of 30%, while the electricity price used to power the electrolyzer was modeled with 25% volatility, reflecting typical medium-term variability in these markets. Capital Expenditure (CAPEX) uncertainty was represented with a 15% volatility, using a normalized baseline equal to one, so that simulated values correspond to cost multipliers. For renewable energy availability, both photovoltaic and wind annual generation were modeled with 20% volatility, consistent with typical interannual variations observed in wind and irradiation resource assessments.

The BESS was strategically designed to deliver a main value stream by utilizing energy storage to balance renewable power with its end-use loads, which include Hydrogen (H₂) production and a co-located Information Technology (IT) data center. The BESS's first primary benefit is the reduction of wasted renewable energy. The system's crucial storage capacity allows for the efficient capture and retention of a surplus of renewable energy inside Energy Hub, that under normal circumstances, would be curtailed. This stored energy is then redirected to maximize the overall output and revenue of the Energy Hub. Specifically, the stored power is used to: 1) generate extra H₂ production through the electrolyzer; or 2) critically, provide firming power supply by serving the high-priority data center load when the output from the intermittent PV and wind sources is naturally low or insufficient.

The second significant BESS's benefit is the energy arbitrage strategy. The system can charge its storage assets when the wholesale electricity prices are at their lowest - a scenario that often occurs when the Brazil's grid is flush with surplus, near-zero marginal cost energy from its renewables. Conversely, the system can discharge and inject power back to the grid when market prices are higher. This optimized process thereby maximizes the use of Hub's BESS.

To incorporate the two BESS's benefits into an annual-step Monte Carlo valuation, the first step is to embed its effect directly into the yearly energy balance of each simulated scenario. For every Monte Carlo draw, the model already produces annual photovoltaic and wind generation, electricity and hydrogen prices, and the internal energy demand of the electrolyzer and data center. By comparing annual renewable supply with annual load, the model identifies whether the system faces net surplus energy—normally curtailed or sold at low value—or a net deficit that would require electricity imports or reduced hydrogen production. The BESS modifies this balance by shifting a portion of the surplus to periods of deficit, even though the simulation works at annual resolution.

This shift can be represented through simple annual rules. The battery's technical limits - its 100 MWh of energy capacity, 25 MW of power, and an assumed number of cycles per year - define the maximum amount of energy it can charge/discharge annually. A BESS annual utilization factor reflects that only part of the simulated surplus occurs in hours suitable for charging. The discharged energy is then allocated to the hub's revenue streams: some portion increases hydrogen production by using recaptured surplus power; another portion offsets electricity imports for the electrolyzer or data center; the remainder can be considered arbitrage-driven energy sold at a price premium.

At the business model applied to this study, the Energy Hub not only supplies power to a co-located data center but also owns and operates it, generating revenue from digital services such as cloud computing, colocation, edge processing, and AI workloads. In this configuration, the financial contribution of the data center appears directly in the project's cash flows through annual revenues linked to the installed IT capacity, often expressed as earnings per kilowatt or per megawatt of IT load. Although the electricity used by the data center is produced internally, its consumption still generates an opportunity cost because each MWh routed to digital services could otherwise be sold to the grid or used for hydrogen production.

This integrated model can be particularly attractive because digital services create far more value per unit of energy than conventional electricity sales or hydrogen production. Its suitability is highest in contexts where project sponsors seek to establish a renewable-powered digital infrastructure hub or where regional development strategies—such as those being pursued in Suape—actively promote “green data center” initiatives.

No research paper in the current literature provides a direct, up-to-date industry benchmark for “revenues per kW of IT load” for owner-operated data centers. Most available numbers refer to colocation pricing, and owner-operator digital-services revenue per kW remains highly variable and proprietary. Even so - these colocation price levels can serve as a rough proxy or lower bound for what an operator might get per kW of IT load. Since the values we are looking for is proprietary, our value of 2,000.00 USD\$/kW_IT_load (Table 3) were based on synthesizing public data from various market reports and news articles about the digital economy and data center infrastructure [20-22].

4.1 Baseline Valuation

This part of the analysis captures the project's risk profile and expected profitability under uncertainty. The total CAPEX for this Baseline valuation comes from Table 2 and is 730 million

USD. The Figure 2 displays the histogram of the baseline Net Present Value (NPV) results. The distribution is skewed, with a long tail toward negative values, showing more likelihood of negative outcomes. The dashed red line represents the expected NPV, which is significantly below zero, reinforcing that direct investment carries a high probability of negative returns (Prob(NPV < 0: 94.60%).

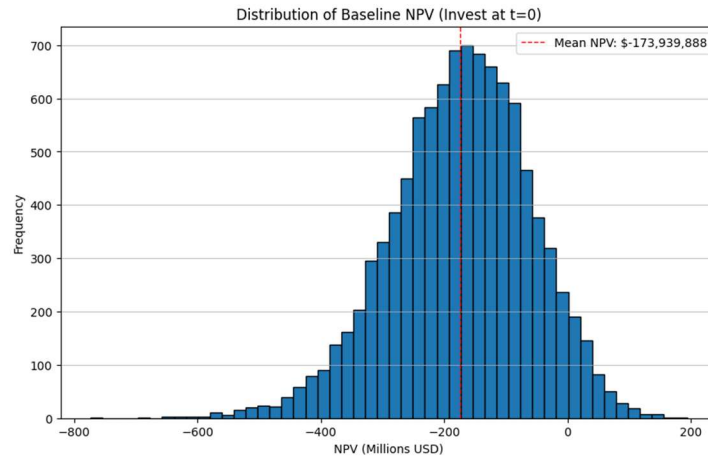


Figure 2 – Baseline Valuation

In addition to this baseline valuation, the program applies Real Options Analysis (ROA) to capture the managerial flexibility that investors have under uncertainty. Three strategic options are considered. The first option is the Option to Delay. Specifically to delay the investment for up to five years, using a Least-Squares Monte Carlo (LSM) algorithm to identify in which simulated conditions it is better to wait or to invest immediately. The objective is to estimate both the value of the delay option and the probability of exercise in each year. The second is the Option to Expand the hub's capacity after the project has been built. Five years after investment, the program evaluates whether it is economically attractive to expand generation and hydrogen production by 50%, considering the additional investment required and the resulting increase in revenues. The third option is the combination of these components (Option to Delay + Option to Expand) with the Option to Abandon.

4.2 Option to Delay – Results and Interpretation

The Option to Delay analysis serves as a critical component in understanding project valuation within uncertain environments, specifically by quantifying the strategic advantage derived from managerial flexibility. Essentially, this option represents the right, but crucially, not the obligation, to defer an initial investment for a predetermined period. Rather than committing capital at time zero, a firm can choose to wait and observe how key market drivers, such as commodity prices, operational costs, or demand forecasts, evolve. This capacity to postpone the investment decision provides immense value, as it allows the project to proceed only if conditions become sufficiently favorable, thereby mitigating downside risks associated with immediate commitment and simultaneously capturing upside potential if market dynamics improve.

Least-Squares Monte Carlo (LSM), often referred to as the Longstaff-Schwartz algorithm [23, 24], stands as a sophisticated numerical technique primarily employed for the valuation of

American-style options, which, by definition, can be exercised at any point up to their maturity. The method ingeniously marries the statistical power of Monte Carlo simulation with the analytical rigor of regression analysis. The process start with the generation of numerous future trajectories for the underlying stochastic variables that influence the option's payoff, such as asset prices or cash flows, through a Monte Carlo simulation. Following this, the core of LSM involves a backward induction procedure. At each discrete time step, moving backward from the option's expiration, the decision rule for optimal exercise is determined.

The Option to Delay simulation reveals that having the flexibility to postpone the investment decision significantly adds value to the project, with an estimated option value of approximately \$7.84 million at time zero. This value arises from the ability to wait for more favorable market conditions before committing to the project. When examining the exercise probabilities, it's evident that there's a relatively low likelihood of exercising the option immediately or in the early years of the delay period, with probabilities ranging from about 3.55% to 4.64% for years 0 through 4. This suggests that in most scenarios, it is beneficial to wait.

The ability to wait for more favorable market conditions is precisely why the 'Option to Delay' has value. It also quantifies how much that flexibility is worth, giving us a specific option value (approximately \$7.84 million). So, while 'waiting for favorable conditions' is the strategic intent, the simulation offers concrete financial and temporal details about that strategy.

4.3 Option to Expand – Results and Interpretation

The Option to Expand analysis quantifies the inherent flexibility a project possesses to scale up its operations after initial investment. This real option grants the project owner the right, but not the obligation, to increase capacity by a predefined expand factor at a specific time following the initial investment. In essence, it captures the value of being able to respond to favorable market conditions by growing the project. The analysis specifically evaluates this one-shot expansion opportunity by comparing the potential incremental Net Present Value (NPV) generated by the expansion against the associated expansion capital expenditure. If the incremental NPV from expanding exceeds the cost, the option is considered “in the money” and its value contributes to the project's overall valuation. By simulating various especific years to do the expansion investment and different expand factor magnitudes, we can identify which strategies maximize the value derived from this operational flexibility, providing critical insights for strategic investment decisions.

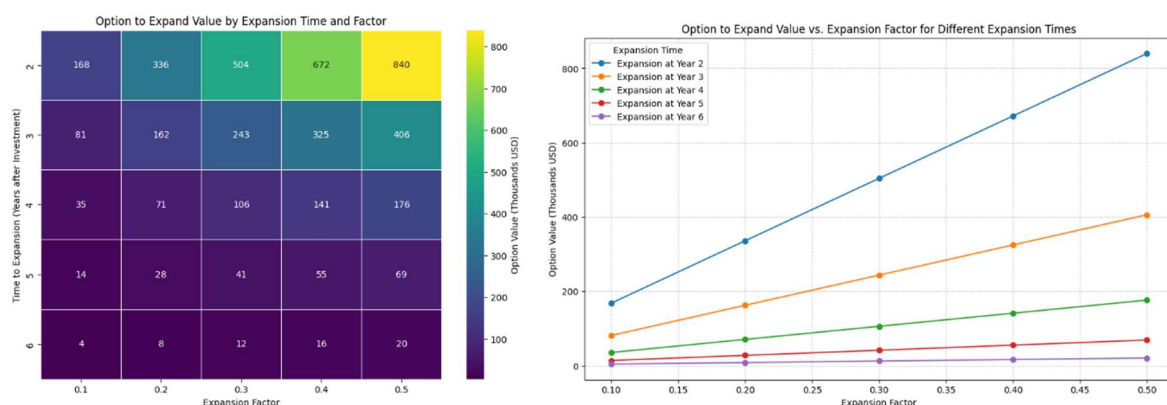


Figure 3 – Option to Expand Values

The analysis of the Option to Expand values reveals several critical insights regarding the timing and scale of expansion. A fundamental finding is that the option to expand holds a significantly higher value when exercised earlier in the project timeline. The highest option values are distinctly observed when the expansion occurs at $t = 2$ years after the initial investment. Conversely, as the time to expansion increases, the option value exhibits a consistent and pronounced decrease. This decline is evident across all analyzed plots, clearly indicating that delaying the expansion opportunity substantially reduces its economic benefit. This trend is principally attributed to two factors: the time value of money due to discounting, and the reduced remaining project life available to realize the financial benefits from the increased capacity.

Combining these factors, the analysis identifies the optimal combination that maximizes the option's value, Figure 3. The most valuable expansion opportunity arises when the option is exercised at $t = 2$ years after investment with the maximum expand of 0.5, which yields an estimated option value of approximately USD\$ 840,000. In contrast, the least valuable option within the analyzed range occurs with the longest delay and smallest scale, specifically at $t = 6$ years and an expand factor = 0.1, resulting in a minimal option value of approximately USD \$4,000.

In conclusion, to maximize the economic benefit and inherent value of the expansion option, the strategic decision should prioritize exercising the option at $t = 2$ years and utilizing the largest feasible expansion factor.

4.4 Options Combined

When the Option to Delay and the Option to Expand are combined with the Option to Abandon, the cumulative project value shifts dramatically to USD\$ 386 millions, showing how managerial flexibility can fundamentally reshape the project's financial outlook. The Option to Expand strengthens the project's upside potential by ensuring that scale can be increased precisely when economic signals turn favorable, thereby allowing the system to capture additional returns without imposing unnecessary upfront commitments. At the same time, the Option to Abandon mitigates downside risk by offering a clear exit strategy that safeguards capital if adverse market trajectories prevail. Together with the Option to Delay—an additional mechanism that permits optimal timing of the initial investment—these real options transform the project's risk–return profile.

What begins as a highly risky venture with a deeply negative expected NPV evolves into an opportunity with positive expected value and significant strategic benefits. In essence, real options provide a robust framework for quantifying managerial flexibility, enabling investors to mitigate risk, capture upside opportunities, and ultimately convert a financially unattractive project into a strategically compelling one.

The data analysis highlights the central role of Real Options in reshaping the financial viability of the Energy Hub project. The salvage value used to support the Option to Abandon was set at 30% of the baseline investment, corresponding to \$208,510,500, and this mechanism alone generated an option value of \$559,143,524, reflecting its substantial contribution to risk mitigation. In contrast, the baseline project—evaluated without any optionality—presented a

mean Net Present Value (NPV) of USD\$-173,939,888 and a 94.60% probability of negative returns, clearly indicating that it would be highly unviable under a static investment strategy.

Additional flexibility was introduced through the Option to Expand, which, in its optimal form, added \$839,631 by allowing the project to scale capacity when market conditions improve. When these components are brought together—baseline NPV, expansion value, and abandonment value—the cumulative project value shifts to \$386,043,266. This result demonstrates how strategic optionality can transform a significantly negative baseline project into one with positive economic potential, emphasizing the importance of incorporating managerial flexibility into investment evaluations under uncertainty.

5 Conclusions

This study demonstrates that Energy Hubs integrating renewable generation, hydrogen production, energy storage, and digital infrastructure represent a promising pathway for Brazil's energy transition, particularly in the Northeast region. However, their feasibility cannot be properly assessed using traditional static valuation methods, as these projects face deep uncertainties in prices, technological evolution, regulatory frameworks, and renewable resource availability. By applying Real Options Analysis combined with Monte Carlo simulation, the study shows that managerial flexibility fundamentally reshapes investment outcomes. While the baseline scenario indicates a high probability of negative returns, the strategic options to delay, expand, and abandon the project significantly enhance its economic resilience, transforming an initially unviable venture into one with positive expected value. These results highlight the crucial role of Real Options Analysis in unlocking opportunities in complex, capital-intensive energy infrastructures. The proposed computational framework offers a practical and transparent tool for decision-makers, helping them navigate uncertainty and design more robust investment strategies. Future research should deepen the representation of hourly operational dynamics, incorporate transmission constraints, and explore additional synergies between hydrogen production and digital services to further refine the economic potential of Energy Hubs in Brazil.

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