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Does Exit-Timing Flexibility Pay? An Empirical Least-Squares Monte Carlo Assessment of Equity Divestment Timing for Utility-Scale Solar in the PJM Market

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Abstract

Utility-scale solar equity in the PJM market carries a merchant tail once its power purchase agreement expires, and sponsors hold a valuable but under-quantified right to choose when to divest. This study measures whether flexible, state-contingent exit timing creates value relative to committing in advance to a single divestment date. A representative levered equity stake in a 100 MW-AC photovoltaic plant is simulated under the real-world measure, with revenue driven by a mean-reverting jump-diffusion power price calibrated to historical PJM day-ahead prices, an eroding capture ratio, and a fluctuating transaction-valuation environment. Four Bermudan-style exit nodes are evaluated—notice to proceed, commercial operation, and three and five years thereafter—alongside a passive hold-to-maturity benchmark. Least-squares Monte Carlo estimates the optimal stopping policy out of sample, and performance is compared using net present value, internal rate of return, multiple on invested capital, loss probability, and conditional value at risk. Under the calibrated low-price regime every committed exit date trails passive holding, yet the dynamic policy raises equity net present value above the best committed exit by about 3.6 percent of invested equity and above passive holding by 2.3 percent, while cutting the probability of loss to 39 percent. A variance-based global sensitivity analysis attributes most of this premium to the volatility of the transaction environment. The findings quantify how divestment flexibility supports capital rotation and resource-adequacy planning.

***Keywords*:** exit-timing flexibility; least-squares Monte Carlo; utility-scale solar; conditional value at risk

1. Introduction

Utility-scale solar has become one of the largest recipients of private capital in United States power markets, and much of that capital is intermediated by sponsors and infrastructure funds that expect to recycle equity into new development once an asset is de-risked. The value a sponsor

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ultimately realizes depends not only on how a plant is built and contracted but on when the equity stake is sold. Because irreversibility and uncertainty jointly create an option to wait, the timing of divestment is itself an economic decision with measurable value [1]. Managerial flexibility of this kind, including the option to abandon or transfer an operating asset, has long been recognized as a source of value that static discounting misses [2].

1.1. Merchant-tail exposure and the equity exit decision in PJM

In PJM, a solar plant typically earns contracted revenue under a power purchase agreement (PPA) for a fixed term and is then exposed to wholesale locational marginal prices for the remainder of its life. This merchant tail is where the largest uncertainty sits: prices mean-revert but jump, the plant captures a shrinking share of the average price as solar penetration rises, and the environment in which operating assets change hands moves through cycles of appetite and caution. A sponsor who sells early transfers this uncertainty to a buyer at a de-risking discount, while one who holds collects interim distributions but remains exposed to the tail and to a lower future sale value. Renewable investment timing has been studied extensively through the real-options lens [3], and empirical work has asked whether option-based thresholds actually describe observed behavior [4], yet the symmetric question of exit timing for an existing operating stake has received far less quantitative attention. The stakes are substantial, because a large share of operating solar changes hands within a few years of commercial operation, and the price obtained in these secondary transactions depends on conditions that neither the seller nor the buyer fully controls. Framing the sale as the exercise of a timing option, rather than as a scheduled event, is the natural way to value that dependence and to connect it to the wider efficiency of recycling equity through the market.

1.2. Research question and contributions

This paper poses a single, testable empirical question and answers it with a transparent, data-anchored computation rather than a new valuation apparatus.

A. Does dynamic exit timing outperform the best fixed divestment node?

The central question is whether a state-contingent exit policy, which reads current market conditions before deciding to sell, produces materially better risk-adjusted equity outcomes than the best achievable rule that fixes the divestment date at the outset. A positive and economically meaningful gap would establish that exit-timing flexibility "pays," and would let that premium be sized in the units investors use.

B. Scope and contributions

The scope is deliberately narrow: one asset class, one market, one right, and four decision nodes evaluated under the real-world measure. The contribution is an application-and-evaluation study that quantifies the flexibility premium, decomposes it into the parameters that drive it, and connects it to capital-rotation efficiency and resource-adequacy decision support for market participants and system operators.

2. Related Work

The study draws on three mature literatures: simulation methods for optimal stopping, real options in energy and renewable investment, and the modelling of electricity prices and solar value deflation. It applies established tools from each rather than extending any of them.

2.1. Least-squares Monte Carlo and energy real options

A. Simulation-based optimal stopping

The least-squares Monte Carlo (LSM) method estimates the continuation value in an optimal-stopping problem by regressing realized discounted payoffs on functions of the current state, which makes early-exercise valuation tractable for path-dependent and multi-factor problems [5]. Because the method replaces a high-dimensional dynamic program with a sequence of cross-sectional regressions, it scales to problems with several correlated state variables, which is what an exit decision driven jointly by price, output, and the transaction environment demands. Its accuracy rests on the choice of basis functions and on separating the paths used to estimate the policy from those used to value it, disciplines that carry directly into the design adopted here and that underpin the out-of-sample premium reported later. Later work compared regress-now and regress-later variants and characterized their accuracy and dual bounds in energy applications such as storage and swing rights [6], providing guidance on implementation choices this study adopts.

B. Real options in renewable investment and divestment

A broad body of work applies real options to generation investment, treating support schemes, capacity choice, and entry timing as options on uncertain revenue. A recent review maps how approximate dynamic programming and simulation methods have been deployed across energy assets and identifies divestment timing as comparatively underexplored [7]. The same option logic that governs when to build a plant governs when to sell one, with the sign of the decision reversed, so that an owner exercises the right to exit when the sale price exceeds the value of continuing to hold. Prior applications have concentrated on entry, capacity sizing, and technology choice, leaving the operating owner's disposal problem comparatively thin, and it is that problem the present assessment takes up on a de-risked, cash-generating asset.

2.2. Electricity price dynamics and solar value deflation

Support-scheme design and revenue uncertainty shape renewable investment value, as shown for wind under alternative policy instruments [8]. On the revenue side, the market value of variable renewables falls as their penetration grows, so that solar earns a declining fraction of the time-average price [9]. This value deflation is central to the merchant tail modeled here, because it steadily lowers the captured price a solar plant realizes and with it the future cash flows a prospective buyer will pay for. The electricity-price literature converged on reduced-form processes that combine mean reversion, seasonality, and jumps precisely because these features dominate the risk a merchant revenue stream carries. Taken together, these mechanisms make the

merchant tail both uncertain and systematically declining, which is exactly the setting in which the timing of a sale carries value.

3. Methodology

The method has four parts: a representative equity cash-flow model calibrated to public data, a stochastic model of prices and transaction value, an LSM optimal-stopping solution across the four exit nodes, and a set of performance and downside-risk metrics. Cost inputs use real published values and the price process is estimated from historical PJM prices, while the simulation runs under the real-world measure so that reported returns are expected outcomes rather than risk-neutral prices.

3.1. Representative project and equity cash-flow construction

The subject is a 100 MW-AC single-axis-tracking plant with an overnight capital cost of 1.43 dollars per watt-AC and fixed operating cost of 24 dollars per kilowatt-AC-year, both representative of the 2024 technology baseline, and a base-year AC capacity factor of 24 percent consistent with the observed utility-scale median. Output declines at a representative 0.7 percent per year, a rate bracketed by the fleet-wide degradation evidence, and availability is held at the observed fleet median of 0.99. Module and system degradation is anchored to a review reporting a median rate near 0.5 percent per year across a large sample of installations [10]. The plant sells under a 15-year PPA at a representative 52 dollars per megawatt-hour and is exposed to merchant revenue thereafter, out to a 30-year life. Senior debt is sized at 35 percent of capital cost and amortized over the contract term, and the sponsor equity contribution is calibrated so that the base-case hold-to-maturity equity return equals a 9 percent cost of capital. Development cost is treated as sunk for valuation but retained in the denominator of the multiple on invested capital. Table 1 lists the calibration and its public-source anchors.

Table 1. Representative project calibration and public-source anchors.

Parameter	Representative value	Public-source anchor
Nameplate capacity	100 MW-AC	Representative utility-scale plant
Overnight capital cost	1.43 $/W-AC	NREL ATB 2024, utility-scale PV
Fixed operating cost	24 $/kW-AC-yr	NREL ATB 2024
Base AC capacity factor	24%	LBNL Utility-Scale Solar 2024 (median)
Annual degradation	0.7%/yr	NREL ATB 2024; Jordan & Kurtz review
Availability	0.99	NREL PV Fleet 2024 (P50)

PPA price and term	52 $/MWh, 15 yr	LBNL Utility-Scale Solar 2024 (range)
Sponsor equity	21.1 $M (calibrated)	Set so base-case hold IRR = 9%
Project life; terminal value	30 yr; 5% of capex	Representative assumption

3.2. Price, capture, and transaction-value dynamics

A. Mean-reverting jump-diffusion power price with seasonality

Merchant revenue is driven by an annual power price that mean-reverts toward a long-run level while admitting occasional jumps, a specification whose one-factor mean-reverting core follows the commodity-price tradition [11] and whose deterministic seasonal structure follows the electricity-specific treatment that adds a seasonal component to the reverting process [12]. Jumps are included because power prices exhibit spikes that a pure diffusion cannot reproduce, matching the seasonal mean-reverting jump-diffusion form used for electricity [13]. The parameters are estimated from the hourly PJM day-ahead system energy price spanning 2015 through 2018, a widely used proxy for the Western Hub, which yields a long-run price near 30 dollars per megawatt-hour and an annual diffusion near 6 dollars, with a reversion speed of 0.70 and a jump probability of 0.25 completing the specification. This window reflects a low-price regime, so the merchant tail modeled here is conservative and should be re-estimated on more recent prices when the study is applied to a current transaction.

B. Capture-price erosion and the transaction-multiple process

Two adjustments translate the average price into what the plant actually earns and what a buyer will pay. The capture ratio, starting at 0.86 and declining 1.5 percent per year, encodes solar value deflation, whose absolute and relative magnitude has been measured directly from wholesale market data [14]; a fixed nodal basis and a 2 percent curtailment allowance complete the revenue bridge. Separately, the price a buyer pays for the remaining cash-flow stream is scaled by a mean-reverting transaction-valuation multiple centered on one, representing the fluctuating appetite of infrastructure buyers. This second factor is what gives exit timing its economic content: selling when the transaction environment is rich, rather than at a fixed date, is the source of the flexibility premium measured later. Table 2 records the process and exit-node assumptions.

Table 2. Stochastic-process and exit-node assumptions.

Element	**Representative specification**
Power price	Mean-reverting jump-diffusion estimated from PJM day-ahead energy price, 2015–2018; long-run 30 $/MWh; speed 0.70; diffusion 6 $; jump prob. 0.25, sd 14 $

Capture ratio	0.86 initial, declining 1.5%/yr; nodal basis 2 $/MWh; curtailment 2%
Transaction multiple	Mean-reverting to 1.0; speed 0.55; volatility 0.14; bounded [0.6, 1.5]
Resource variability	Interannual generation standard deviation 3%
Exit nodes (year)	NTP (0), COD (1), COD+3 (4), COD+5 (6)
Buyer required return	12%, 9%, 8%, 7.5% across the four nodes
Transaction friction	Net-of-cost multiple 0.88, 0.92, 0.93, 0.94 across nodes

3.3. Exit-option valuation and risk metrics

A. Least-squares Monte Carlo optimal stopping across four nodes

The sponsor holds a Bermudan-style right to sell the stake at any of the four nodes. At each node the exit value is the friction-adjusted price a buyer earning the node-specific required return would pay for the remaining distributions, scaled by the prevailing transaction multiple. Working backward from the final node, the continuation value is estimated by regressing the realized discounted value of holding on a basis of the current power price, recent generation, and the transaction multiple, using low-order Laguerre polynomials and an interaction term. The estimated policy sells whenever the immediate exit value exceeds the fitted continuation value. To avoid in-sample optimism, the policy is fitted on 60,000 training paths and valued on 60,000 independent test paths, so the reported premium is an out-of-sample lower bound on the true value of flexibility.

B. Performance and downside-risk measurement

Each path yields an equity cash-flow stream from which net present value, internal rate of return, and multiple on invested capital are computed, with the discount rate set to the sponsor cost of capital. Downside is summarized by the probability of an equity loss and by the conditional value at risk at the 5 percent level, defined as the mean of the worst 5 percent of net-present-value outcomes; the convex optimization foundation of this tail measure is standard [15] and its estimation over the simulated, non-normal loss distribution is direct. Every exit rule is referenced against a passive hold-to-maturity benchmark that never exercises the right. The parameters that drive the flexibility premium are ranked by a variance-based global sensitivity analysis, whose first-order indices follow the Monte Carlo estimation of Sobol indices [16] and whose total-order design follows the efficient estimator for total effects [17]. The analysis varies eight inputs across representative ranges and attributes the variance of the premium among them.

4. Results

The results show that fixed-date exit rules trail passive holding under the calibrated price regime, that a state-contingent policy recovers a moderate premium over both while reducing downside, and that this premium is governed chiefly by the transaction environment. All values are illustrative outputs on the stated calibration, to be regenerated on the full official datasets before use.

4.1. Fixed-exit performance and the value of flexibility

A. Performance across the fixed strategies

Under fixed-date rules the equity outcome improves with patience yet never clears the passive-hold benchmark. Selling at notice to proceed realizes a mean net present value of −4.87 million dollars and a certain loss, because the buyer prices construction risk at a 12 percent required return. Selling at commercial operation lifts the mean exit value to 21.13 million dollars, while the equity net present value is still −1.70 million because little cash has been collected. Waiting three and five further years raises the mean internal rate of return to 8.1 and 8.6 percent and the multiple on invested capital to 1.04 and 1.15, as accumulated distributions offset the erosion of the sale price. Passive holding to maturity earns the 9.0 percent cost of capital with a net present value near zero and a multiple of 1.75, dominating every committed exit date. The conditional tail loss is least severe under holding at −2.30 million dollars; the non-normal loss distribution this measure summarizes is the setting for which the conditional tail statistic was generalized [18]. Table 3 reports the full profile.

Table 3. Equity performance and risk by fixed strategy (illustrative).

Strategy	NPV ($M)	IRR	MOIC	Loss prob.	CVaR$_5$ % ($M)	Exit value ($M)
NTP	−4.87	n.m.	0.62	100.0%	−6.34	16.21
COD	−1.70	0.2%	0.81	94.8%	−3.81	21.13
COD+3	−0.57	8.1%	1.04	61.2%	−4.91	17.27
COD+5	−0.28	8.6%	1.15	58.0%	−3.73	14.28
Hold to maturity	−0.01	9.0%	1.75	50.8%	−2.30	—

The internal rate of return at notice to proceed is not meaningful because the stake is bought and resold at the same instant at a construction-risk discount, giving a single-signed cash-flow stream. Figure 1 places the fixed strategies alongside the dynamic policy.

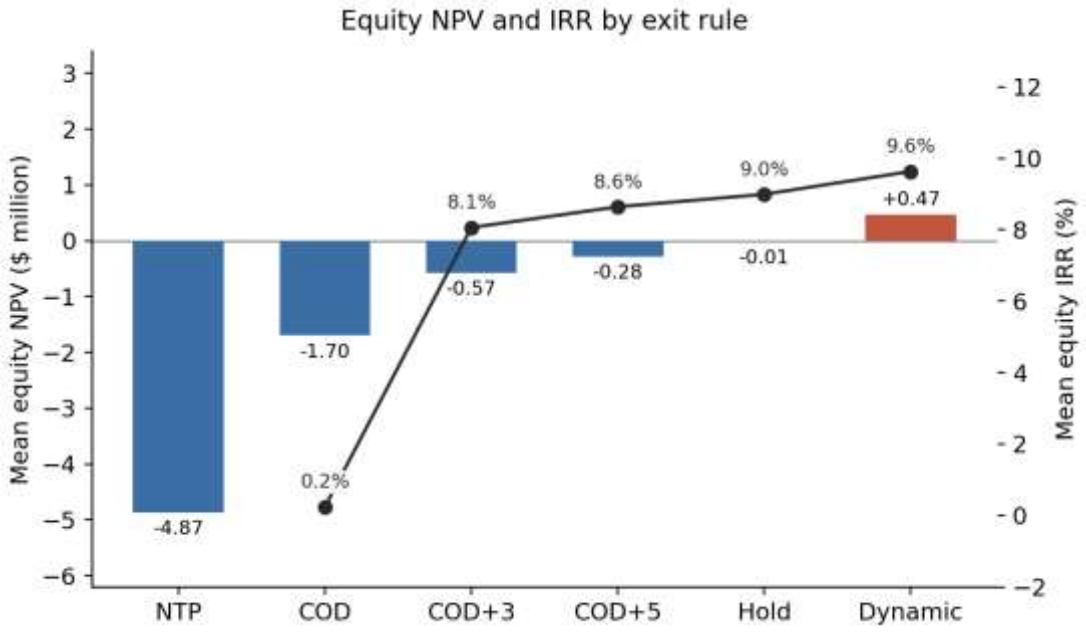


Figure 1. Equity net present value and internal rate of return by strategy. *The bars show mean equity net present value climbing from a large loss at notice to proceed to near zero under passive holding, while the line traces the internal rate of return rising toward the 9.0 percent cost of capital; the dynamic policy sits above every fixed strategy, reaching a mean net present value near 0.47 million dollars and a return of 9.6 percent.*

B. The dynamic exit policy and its premium

The state-contingent policy is the only exit-based strategy that clears the passive-hold benchmark. It attains a mean equity net present value of 0.47 million dollars, an internal rate of return of 9.6 percent, and a multiple on invested capital of 1.28, against −0.28 million and 8.6 percent for the best committed exit date, the five-year node, and a net present value near zero for passive holding. The value of exit-timing flexibility, measured against the best committed exit date, is 0.75 million dollars, or about 3.6 percent of invested equity, and measured against passive holding it is 0.48 million, or 2.3 percent. The premium is moderate rather than dramatic, the economically sensible outcome when prices mean-revert and buyers are forward-looking. Table 4 summarizes the comparison and the realized distribution of exit timing.

Table 4. Dynamic policy versus benchmarks, and realized exit frequencies (illustrative).

Measure	Best committed exit (COD+5)	Hold to maturity	Dynamic policy
Mean NPV ($M)	−0.28	−0.01	0.47
Mean IRR	8.6%	9.0%	9.6%
Mean MOIC	1.15	1.75	1.28

Loss probability	58.0%	50.8%	38.8%
$CVaR_5\%$ ($M)	−3.73	−2.30	−2.28
Flexibility premium	+3.6% of equity vs best exit	+2.3% of equity vs hold	—
Exit at COD+3 / COD+5	—	—	40.1% / 32.2%
Hold to maturity / COD	—	—	24.6% / 3.1%

4.2. Downside risk and the exit-timing distribution

Beyond the mean, flexibility reshapes the risk profile. The dynamic policy lowers the probability of an equity loss to 38.8 percent, against 58.0 percent for the best committed exit date and 50.8 percent for passive holding, and it holds the conditional tail loss at −2.28 million dollars, matching the passive benchmark while improving sharply on the −3.73 million of the five-year exit. The realized exit distribution shows why: the policy concentrates sales at the three- and five-year nodes, which together absorb about 72 percent of paths, holds to maturity on about 25 percent of paths where no attractive window appears, and almost never divests at notice to proceed. Figure 2 contrasts the downside profile across strategies.

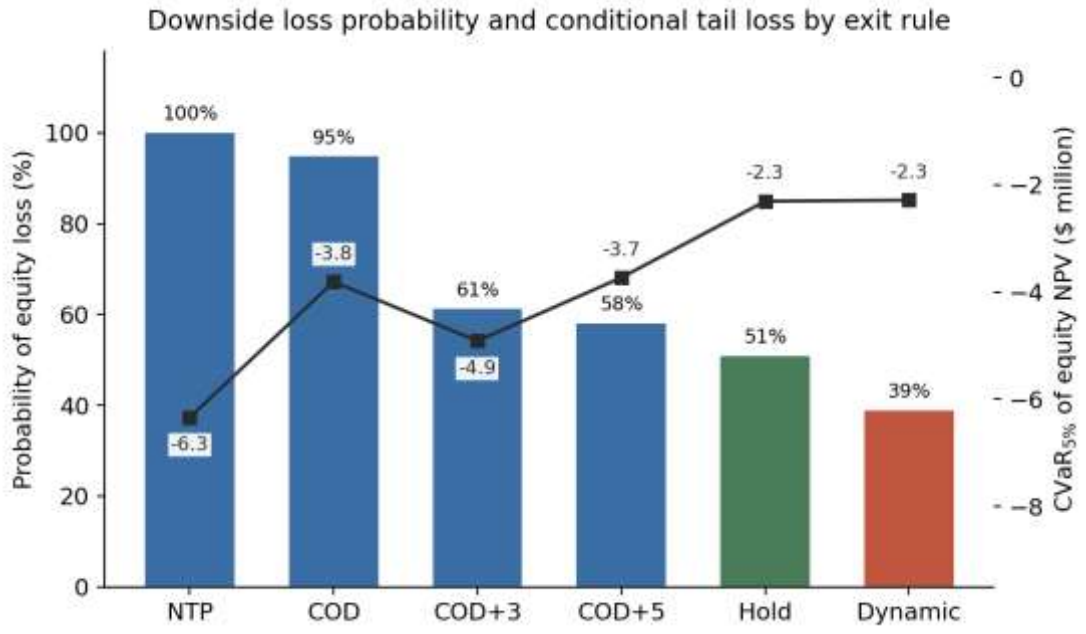


Figure 2. Loss probability and conditional tail loss by strategy. *The bars show the probability of an equity loss falling from certainty at notice to proceed to 38.8 percent under the dynamic policy, while the line shows the conditional tail loss; the dynamic policy attains the lowest loss probability of all strategies and a tail loss on par with passive holding.*

4.3. Global sensitivity of the flexibility premium

A. First-order drivers

A variance-based decomposition over eight inputs shows that the flexibility premium is governed by the transaction environment rather than by power-price parameters. The volatility of the transaction multiple alone accounts for a first-order index of 0.66, with mean-reversion speed, operating-cost deviation, and buyer required returns each contributing less than 0.10, and price volatility, jump intensity, capture decline, and curtailment negligible at first order. The reading is intuitive: the premium exists because the sponsor can wait for a rich sale window, so the width of that distribution matters most. The estimator design and interpretation follow the standard sensitivity-analysis primer [19]. Table 5 lists the indices.

Table 5. First-order and total-order Sobol indices for the flexibility premium (illustrative).

Input	First-order S_1	Total-order S_T
Transaction-multiple volatility	0.66	0.68
Mean-reversion speed	0.10	0.13
Operating-cost deviation	0.08	0.09
Buyer required return	0.06	0.05
Power-price volatility	0.04	0.04
Price-jump intensity	0.02	0.01
Capture-price decline	0.00	0.03
Curtailment rate	0.00	0.01

B. Total-order effects and interactions

Total-order indices confirm the ranking and reveal modest interaction. Mean-reversion speed carries a total-order index of 0.13 against a first-order value of 0.10, and operating-cost deviation 0.09 against 0.08, indicating that these parameters act partly through interaction with the transaction and return terms rather than in isolation. Capture-price decline registers as negligible for the premium even though it strongly affects the level of value, a distinction consistent with evidence that capture prices and value factors move project economics while acting as a slow, near-deterministic drift rather than a source of timing optionality [20]. Across the sampled space the premium averages 2.3 percent of equity and ranges from roughly −1.0 to 5.6 percent, so flexibility is valuable on average while it can vanish when the transaction environment is calm. Figure 3 presents the ranking.

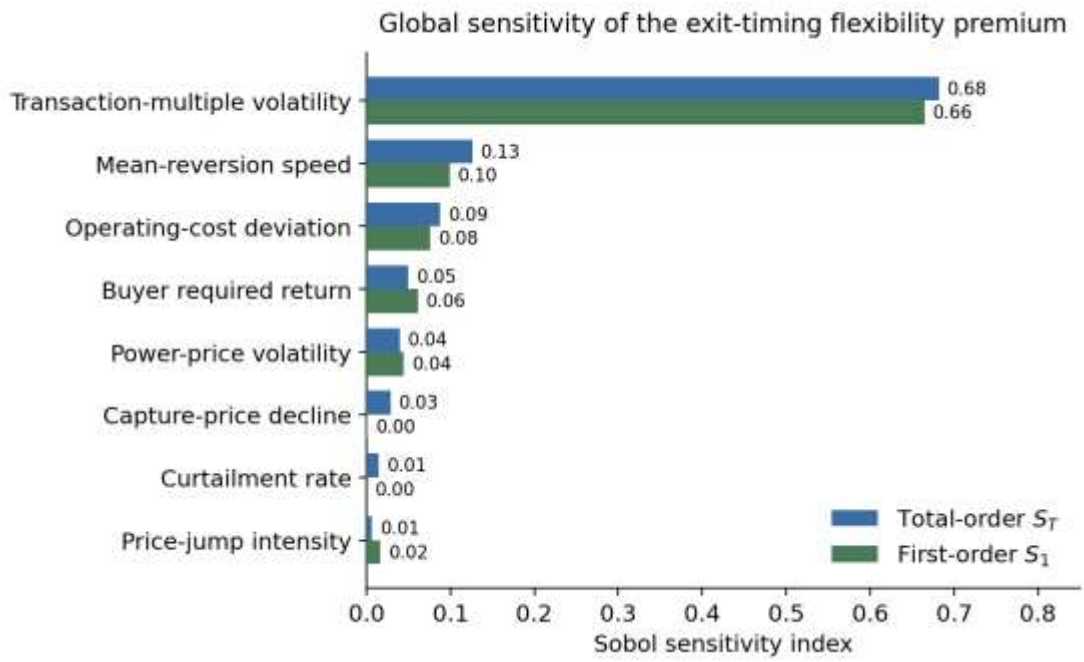


Figure 3. Global sensitivity of the exit-timing flexibility premium. *The ranked bars show that transaction-multiple volatility overwhelmingly governs the premium, followed at a distance by mean-reversion speed, operating-cost deviation, and buyer required returns, with the remaining price parameters contributing little at either order.*

5. Discussion and Policy Implications

The evidence gives a clear answer to the title question: exit-timing flexibility pays, but moderately, and mainly as insurance against a weak transaction environment rather than as a large expected windfall. Sizing the premium at a few percent of equity, and showing that it comes chiefly from the ability to avoid selling into thin markets, changes how the exit decision should be framed.

5.1. Decision support for sponsors and system operators

For a sponsor, the practical implication is that the exit decision should be governed by a state-contingent policy keyed to the transaction environment and to prevailing buyer return requirements, not by a calendar rule fixed at financial close. The largest gains come from declining to sell when the market is unfavorable, which argues for maintaining balance-sheet capacity to hold through weak windows rather than forcing divestment on a fixed schedule. For system operators and regulators concerned with capital rotation and resource adequacy under the Federal Power Act, the same result implies that policies smoothing the transaction environment support more efficient recycling of equity into new capacity: when the flexibility premium is driven by transaction-multiple volatility, measures that reduce that volatility lower the option value of waiting and speed the turnover of operating assets to long-term holders, freeing developer capital for new interconnection. The result also reframes how a prospective buyer should approach entry, since acquiring in a calm transaction environment, when sellers are least willing to wait, is where

value accrues to the purchasing side. For a fund managing a portfolio of operating assets, the policy generalizes to a release-scheduling problem in which the least attractive holdings are divested first as favorable windows open, keeping stronger assets in reserve for richer ones.

5.2. Limitations and conclusion

Several limitations bound the reading of these numbers. The simulation is conducted under the real-world measure, so the reported premium is an expected-value quantity rather than a market price of flexibility, and a risk-neutral treatment would shift its level. The exit right is discretized to four nodes and the transaction environment is captured by a single reduced-form multiple, both simplifications of a continuous and multi-dimensional reality. The price process is calibrated to a 2015–2018 low-price window, and the transaction multiple, sponsor-equity level, and buyer discount rates remain representative, so the figures must be regenerated on the full official datasets and current deal terms before any external use. Within these bounds, the result is clean: a data-anchored, out-of-sample least-squares Monte Carlo assessment shows that dynamic divestment timing raises risk-adjusted equity outcomes for utility-scale solar in PJM by a moderate, quantifiable margin of about 3.6 percent of equity over the best committed exit date, and it identifies the transaction environment as the parameter that decides how much that flexibility is worth.

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