Peak-Load Pricing and Investment Cost Recovery with Duration-Limited Storage

Daniel Shen
Department of Electrical Engineering & Computer Science
Massachusetts Institute of Technology
Cambridge, USA
oski@mit.edu

Marija Ilic
Department of Electrical Engineering & Computer Science
Massachusetts Institute of Technology
Cambridge, USA
ilic@mit.edu

John Parsons
Center for Energy and Environmental Policy Research
Massachusetts Institute of Technology
Cambridge, USA
jparsons@mit.edu

***Abstract*—Energy storage shifts energy from off-peak periods to on-peak periods. Unlike conventional generation, storage is duration-limited: the stored energy capacity constrains the duration over which it can supply power. To understand how these constraints affect optimal pricing and investment decisions, we extend the classic two-period peak-load pricing model to include duration-limited storage. By adopting assumptions typical of solar-dominated systems, we link on- and off-peak prices to storage investment costs, round-trip efficiency, and the duration of the peak period. The bulk of the scarcity premium from on-peak prices is associated with the fixed costs of storage as opposed to variable costs stemming from round-trip efficiency losses. Unlike conventional generators, the binding duration constraints lead storage to recover energy capacity costs on a per-peak-event basis instead of amortizing these costs over total peak hours. A numerical example illustrates the implications for equilibrium prices and capacity investment.**

***Index Terms*—electricity markets, energy storage, peak-load pricing, scarcity pricing**

I. Introduction

The installation of grid-scale energy storage is accelerating. In the United States, storage comprised 29% of expected new generation capacity in 2025, up from 23% in 2024 and 17% in 2023 [1]. Unlike conventional generators, storage does not generate electricity directly, but rather shifts an amount of electricity from off-peak hours of low net load to on-peak hours of high net load. This arbitrage reduces the utilization of more expensive generators and decreases system costs.

These distinct characteristics and accompanying benefits have motivated consideration of how storage can be further integrated into electricity markets. For instance, in the United States, FERC Order 841 (passed in 2018) directed market operators to remove barriers to the participation of battery storage in wholesale markets, with the goal of enabling storage to compete alongside conventional generators. This growth of grid-scale energy storage prompts the following questions:

- *What market prices will incentivize efficient investment in generation and storage?*
- *How are such prices linked to the characteristics of the storage technology?*

The electricity literature empirically addresses these questions. For instance, prior work establishes that storage reduces the price spread between high and low net demand periods [2], [3], [4]. We build upon these results from an alternative conceptual lens, aiming for a more foundational understanding of storage in power systems. For example, a canonical benchmark is that in equilibrium, peakers are sized to just break even on their fixed costs during scarcity hours. What would the corresponding principles be for systems with storage?

Our lens aligns with an analytically-focused strand of the literature where storage shapes equilibrium outcomes. Reference [5] examines the equilibrium prices in a system consisting solely of variable renewable energy (VRE), storage, and demand response. Their "new merit order" has steps in the price schedule corresponding to efficiencies of different storage technologies. In contrast, [6] utilizes a duration-curve incorporating VRE, storage, and conventional generation, and shows that storage-induced prices support capacity investments in equilibrium. However, these works critically make the assumption that storage is power-limited but duration-*unlimited*, i.e. the stored energy constraint is nonbinding.

This duration limit is a defining characteristic of storage, since a unit that depletes its stored energy during a peak period cannot continue to provide supply. To preserve this characteristic while gleaning analytical insights, we extend the Steiner/Boiteux peak-load pricing model [7], [8]. Although simple, this peak-load model captures the fundamental dynamics affecting resource investments and prices. Prior extensions of such models to incorporate storage make a duration-unlimited assumption [9] or duration-limited but power-unlimited assumption regarding the storage resource [10]. In contrast, we impose limits on both the power *and* stored energy capacity to analyze the scarcity premium asso-

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$$
\underset{K,\, E,\, q,\, \ell}{\text{maximize}} \quad \sum_{i=1}^{2} T_i \left(\int_0^{\ell_i} p_i(z)\, dz - \sum_{g \in \mathcal{G}} c_g q_{gi} \right) - \frac{1}{n} \left(\sum_{g \in \mathcal{G}} I_g K_g + I_{s,q} K_s + I_{s,E} E \right) \tag{1a}
$$

$$
\begin{aligned}
\text{subject to} \quad T_i(\ell_i - q_{B,i} - q_{P,i} + q_i^+ - q_i^-) &= 0 & \forall i \quad & [\lambda_i] & \text{(1b)}\\
q_{gi} T_i &\le K_g T_i & \forall i, g \quad & [\pi_{gi}] & \text{(1c)}\\
-q_{gi} T_i &\le 0 & \forall i, g \quad & [\psi_{gi}] & \text{(1d)}\\
q_i^+ T_i &\le K_s T_i & \forall i \quad & [\sigma_i^+] & \text{(1e)}\\
q_i^- T_i &\le K_s T_i & \forall i \quad & [\sigma_i^-] & \text{(1f)}\\
-q_i^+ T_i &\le 0 & \forall i \quad & [\zeta_i^+] & \text{(1g)}\\
-q_i^- T_i &\le 0 & \forall i \quad & [\zeta_i^-] & \text{(1h)}\\
\sum_{i=1}^{2} (q_i^- T_i - q_i^+ \eta T_i) &\le 0 & & [\mu] & \text{(1i)}\\
\sum_{i=1}^{2} q_i^+ \eta T_i &\le E & & [\gamma^+] & \text{(1j)}\\
\sum_{i=1}^{2} q_i^- T_i &\le E & & [\gamma^-] & \text{(1k)}\\
0 &\le K_B, K_P, K_S, E & & & \text{(1l)}
\end{aligned}
$$

ciated with these constraints. By applying several simplifying assumptions which are reasonable in a system where the net load peak is periodic, predictable, and accompanied by long off-peak periods, we relate electricity prices in equilibrium to storage parameters. [1] In particular, we find:

- Scarcity prices are primarily driven by storage fixed costs, rather than operating costs from round-trip losses.
- Duration limits introduce a fixed cost component to the on-peak price which contributes per peak event instead of per total peak duration, so scarcity events cannot be fully aggregated into load durations to evaluate storage.
- If the storage is optimally sized and operated, the resulting prices guarantee investment cost recovery.

The paper proceeds as follows: Section II presents our two-period peak-load model. Section III derives analytic expressions for the price schedule and demonstrates the points above. Section IV presents a numerical example to illustrate how storage reshapes the capacity mix and price structure. Finally, Section V concludes.

II. Model

A. Setup

In the classic peak-load model, a social planner jointly optimizes investment and operation of conventional generators to maximize total surplus net of investment costs. We add a duration-limited storage resource to this basic peak-load model; our formulation is given by (1). We consider two periods indexed by i, with duration T_i. Electricity demand per period follows a downward-sloping inverse demand function p_i. The decision variables are investments in K (power capacity) and E (stored energy capacity) along with the operating decisions q (per-period injections) and ℓ (per-period consumptions). Dual variables associated with each constraint are denoted in square brackets.

Baseload and peaker generators have fixed investment costs I_B and I_P per unit of power capacity; these investment costs are normalized by the number of peak cycles n per year. Each technology $g \in \{B, P\}$ can produce up to its installed capacity K_g at a constant operating cost c_g.

In each period, supply and demand must balance per (1b). The dual of (1b) is the energy price λ_i in each period. Energy can be supplied by either the baseload, peaker, or storage unit, while energy can be demanded by consumers or by storage for charging. The storage unit can charge or discharge at a constant rate q_i^+ or q_i^- in each period, as long as this power is below the unit's power capacity K_S. Any energy charged is subject to a round-trip efficiency η per (1i). Nontrivial storage operation entails charging in one period and discharging in the other. Thus, the aggregate energy balance (1i) across both periods suffices to characterize storage operation in our setting. Equations (1j) and (1k) impose a stored energy limit E.

B. Optimality Conditions

The Lagrangian associated with (1) yields the following subset of KKT conditions which are relevant to our results:

$$
\frac{\partial \mathcal{L}}{\partial q_i^+} = 0 = -\lambda_i T_i - \sigma_i^+ T_i + \zeta_i^+ T_i + \mu \eta T_i - \gamma^+ T_i \eta \tag{KKT-1}
$$

[1] Our assumptions mirror that of Schmalensee in [10], who couches his system setup in a solar-dominated grid.

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$$\frac{\partial \mathcal{L}}{\partial q_i^-} = 0 = \lambda_i T_i - \sigma_i^- T_i + \zeta_i^- T_i - \mu T_i - \gamma^- T_i \quad \text{(KKT-2)}$$

$$\frac{\partial \mathcal{L}}{\partial K_s} = 0 = -\frac{1}{n} I_{s,q} + \sum_i T_i(\sigma_i^+ + \sigma_i^-) \quad \text{(KKT-3)}$$

$$\frac{\partial \mathcal{L}}{\partial E} = 0 = -\frac{1}{n} I_{s,E} + \gamma^+ + \gamma^- \quad \text{(KKT-4)}$$

III. Optimal Prices

A. On-Peak Prices

We now characterize the relationship between on- and off-peak prices. To obtain closed-form expressions relating these prices to the parameters of the storage technology, we impose the following three simplifying assumptions, with their associated implications indicated by the $\Longrightarrow$ symbol:

Assumption 1: Price ordering. The optimal consumption ℓ for each period creates a difference between on-peak and off-peak prices sufficient to induce storage investment. [2] $\Longrightarrow$ There is a nonzero amount of storage capacity investment; storage charges off-peak and discharges on-peak.

Assumption 2: Sufficient off-peak duration. The off-peak period satisfies $T_{\text{onpeak}} < \eta T_{\text{offpeak}}$ $\Longrightarrow$ The storage power constraint binds only during on-peak discharge.

Assumption 3: No inter-period carryover value. Stored energy has no continuation value during the off-peak period. $\Longrightarrow$ Stored energy is zero at the end of the on-peak period.

These assumptions can reflect systems with a single dominant daily peak and long periods of low net demand, as may be typical of solar-heavy systems where storage charges midday and discharges to meet the evening peak.

Combining conditions (KKT-1) and (KKT-2) gives:

$$\mu = \frac{\lambda_i + \sigma_i^+ + \gamma^+ \eta - \zeta_i^+}{\eta} \quad (2)$$
$$= \lambda_j - \sigma_j^- - \gamma^- - \zeta_j^- \quad \forall i, j \in \{\text{on-peak, off-peak}\}$$

Substituting i = off-peak and j = on-peak:

$$\lambda_{offp} + \sigma_{offp}^+ + \gamma^+ \eta - \zeta_{offp}^+ = \eta(\lambda_{onp} - \sigma_{onp}^- - \gamma^- - \zeta_{onp}^-) \quad (3)$$

Assumption (1) implies constraints (1g) and (1h) are not binding and the corresponding duals ζ_{offp}^+ and ζ_{onp}^- are zero. Similarly, Assumption (2) yields $\sigma_{offp}^+ = 0$. Substituting $\zeta_{offp}^+ = \zeta_{onp}^- = \sigma_{offp}^+ = 0$ and rearranging:

$$\lambda_{offp} = \eta \lambda_{onp} - \eta \left(\sigma_{onp}^- + \gamma^+ + \gamma^- \right) \quad (4)$$

Assumptions (2) and (3) taken together imply that of the storage power capacity constraints (1e), (1f), only the on-peak discharging constraint is binding:

$$\sigma_{onp}^- > 0, \sigma_{onp}^+ = \sigma_{offp}^+ = \sigma_{offp}^- = 0 \quad (5)$$

Combining (5) with (KKT-3) and (KKT-4) allows us to eliminate all dual variables from (4) which are not associated with the power balance constraint (1b). The final relationship between energy prices in the on-peak and off-peak periods under duration-limited storage is thus:

$$\boxed{\lambda_{onp} = \frac{\lambda_{offp}}{\eta} + \frac{1}{n} \left(I_{s,E} + \frac{I_{s,q}}{T_{onp}} \right)} \quad (6)$$

Equation (6) decomposes the on-peak price into a variable-cost component and a fixed-cost component. The first component λ_{offp}/η reflects the costs of purchasing energy for use later and is analogous to the variable cost of a conventional generator. The second component reflects the additional premium required to cover the fixed investment costs of the storage system. This mirrors the cost-recovery condition for a peaker plant in the canonical two-period model:

$$\lambda_{onp} = c_P + \frac{1}{n} \left(\frac{I_P}{T_{onp}} \right) \quad (7)$$

but with (6) including an additional term $I_{s,E}/n$ that reflects the fixed costs of stored energy capacity. Notably, this energy capacity term is not scaled by the on-peak duration T_{onp}; the energy capacity premium is independent of the total duration of on-peak hours across a year (nT_{onp}) and is solely dependent on the *number* of peaks n during a year. This differs from (7) where the resource's fixed costs are amortized over the total duration of peaks.

In practice, the price differential in (6) is dominated by the fixed costs rather than efficiency losses. For lithium-ion batteries, the NREL Annual Technology Baseline reports annualized fixed costs of approximately $I_{s,q} =$ \$36k/MW-year and $I_{s,E} =$ \$31k/MWh-year. Assuming an off-peak price of \$20/MWh, a round-trip efficiency of $\eta = 85\%$, and an on-peak duration of $T_{onp} = 4$ hours, the efficiency-related term contributes a price premium of \$23.5/MWh, while the fixed-cost term contributes \$109.6/MWh. Fixed costs account for nearly five times the price impact of efficiency losses — equilibrium on-peak prices must rise well above variable operating costs to provide adequate incentives for storage investment. [3]

B. Cost Recovery

Next, we show that setting energy prices in the "standard" manner – the dual λ of the power balance constraint (1b) – guarantees cost recovery for the storage system if the three assumptions in Section III-A hold.

The total storage investment costs are $I_{S,q} K_S + I_{S,E} E$. The operating profits are the difference between revenues from energy sold during on-peak periods and the cost of energy purchased during off-peak periods. Under dual-based pricing

[2] Two alternatives are possible here. First, if the price difference is below a threshold, storage will not be economical and the problem reduces to a standard peak-load model without storage. Second, if the off-peak price is the higher price due to the shape of the demand functions, we can simply relabel the period with the higher price as the "on-peak" period.

[3] Constraint (1b) permits prices of either sign. Our results thus depend only on the magnitude of price *spread* and not on the sign of price levels. When both prices are negative, storage is remunerated by off-peak charging, and the on-peak period acts as a binding rate constraint on resetting the energy state.

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TABLE I: Technology Cost Parameters (Stylized from NREL Annual Technology Baseline Values)

Technology	**Operating Cost**	**Annualized Investment Cost**		**Round-Trip Efficiency**
	($/MWh)	**Power ($/MW-year)**	**Energy ($/MWh-year)**	**(-)**
Peaker	100	120,000	–	–
Baseload	20	240,000	–	–
Storage	–	36,000	31,000	0.85

using (1b), the break-even condition equating investment costs to operating profits over n cycles is:

$$I_{S,q}K_S + I_{S,E}E = n\left(\lambda_{onp}T_{onp}q^-_{onp} - \lambda_{offp}T_{offp}q^+_{offp}\right) \quad (8)$$

The efficiency constraint (1i) and Assumption (3) imply the $T_{onp}q^-_{onp}$ units of energy sold on-peak must be matched by $\frac{1}{\eta}T_{onp}q^-_{onp}$ units of energy purchased during the off-peak period, or:

$$T_{offp}q^+_{offp} = \frac{1}{\eta}T_{onp}q^-_{onp} \quad (9)$$

The optimal action for storage is to discharge at full capacity K_S during the on-peak period. If this were not the case, there would be uneconomical slack in the power capacity. Thus,

$$q^-_{onp} = K_S \quad (10)$$

Combining (6), (8), (9), and (10) allows us to complete the proof of cost recovery:

$$\begin{aligned}
&n\left(\lambda_{onp}T_{onp}q^-_{onp} - \lambda_{offp}T_{offp}q^+_{offp}\right)\\
&= nK_S\left(\lambda_{onp}T_{onp} - \frac{1}{\eta}\lambda_{offp}T_{onp}\right)\\
&= nK_ST_{onp}\left[\left(\frac{\lambda_{offp}}{\eta} + \frac{1}{n}\left(I_{S,E} + \frac{I_{S,q}}{T_{onp}}\right)\right) - \frac{1}{\eta}\lambda_{offp}\right]\\
&= K_ST_{onp}I_{S,E} + K_SI_{S,q}\\
&= EI_{S,E} + K_SI_{S,q}
\end{aligned} \quad (11)$$

Equation (11) verifies the break-even condition in (8) holds exactly. The final step equates K_ST_{onp} to E because the optimal energy capacity E is sized to support discharging at the full power capacity K_S throughout the entire on-peak period. Thus, uniform pricing set by the energy balance dual (1b) in each period ensures an optimally sized storage unit will recover its investment costs through energy profits alone.

IV. Example

We illustrate the results of the preceding section with a stylized numerical example that highlights how storage alters equilibrium prices and capacity investments. We construct two scenarios: one "with storage" and conventional generation and a counterfactual "without storage" that only has conventional generation. The model is constructed in Pyomo [11] and solved with Gurobi v12.0.3.

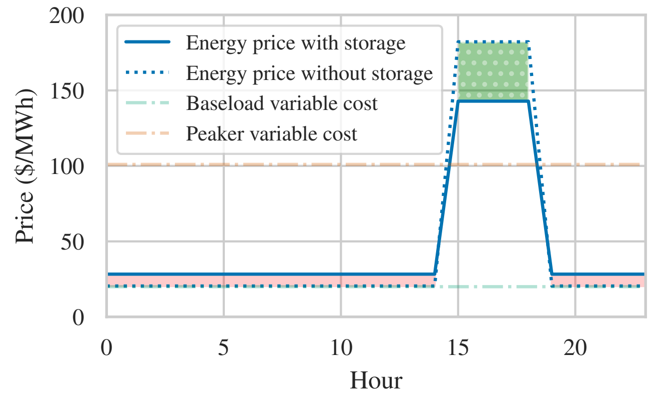

Fig. 1: On- and off-peak energy prices with and without storage. The dotted green area highlights where storage decreases prices and the red area highlights where storage increases prices relative to the "without storage" scenario.

The system operation is treated as a representative day repeated n = 365 times to form an annual cycle. Each day has an on-peak period and an off-peak period of a duration of four and twenty hours, respectively. The demand in each period follows a linear inverse demand function $p_i(z_i) = a_i - b_i\ell_i$; the demand elasticity is set to 0.1 at baseline points of 10 GW & $20/MWh for the off-peak period and 15 GW & $100/MWh for the on-peak period.

Table I lists the technology characteristics used in the example. The resulting prices and dispatch decisions in each period are provided in Table II. The electricity prices are also shown in Fig. 1 for a 24 hour period. Table III lists the geberation capacity investments in each scenario.

With storage, on-peak prices are $182/MWh and exceed the variable cost associated with charging prices and efficiency losses. Analogous to the classic peak-load pricing result, this price level reflects the scarcity of generation and enables investment recovery — (6) shows that the bulk of this scarcity premium is driven by the storage's fixed costs, rather than the operating costs associated with efficiency losses.

Our example utilizes parameters characteristic of lithium-ion storage. For technologies with substantially lower round-trip efficiencies (e.g. hydrogen, where efficiencies are 20 – 40%), the price premium associated with round-trip losses would be higher. However, realistic scarcity prices reflecting the value of lost load can easily exceed $1000/MWh, dwarfing the variable costs associated with efficiency losses even for low-efficiency technologies. Thus, regardless of the storage technology, investment costs will likely contribute to the bulk

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TABLE II: On-Peak and Off-Peak Prices and Dispatch Decisions

Scenario	On-Peak					Off-Peak				
	λ ($/MWh)	ℓ (GW)	q_P (GW)	q_B (GW)	q^- (GW)	λ ($/MWh)	ℓ (GW)	q_P (GW)	q_B (GW)	q^+ (GW)
w/ storage	142	14.4	0	10.5	3.9	28	9.6	0	10.5	0.9
w/out storage	182	13.8	3.8	10.0	–	20	10.0	0	10.0	–

TABLE III: Generation Capacity Investments (GW and GWh)

Scenario	K_B	K_P	K_S	E
w/ storage	10.5	0	3.9	15.5
w/out storage	10.0	3.8	–	–

of on-peak equilibrium prices.

V. Conclusions

This paper extends the peak-load pricing model to include storage that is constrained in both power and stored energy capacity. The resulting two-period model, together with a set of simplifying assumptions regarding storage viability, off-peak duration, and the intertemporal value of stored energy, admits closed-form expressions linking scarcity prices to storage technology parameters and the length of peak periods.

The on-peak prices required to support storage investment decompose into a variable-cost component, driven by round-trip efficiency losses, and a fixed-cost component, driven by storage investment and peak-period duration. For realistic parameter values, the latter fixed-cost component accounts for the bulk of the equilibrium scarcity premium. The structure of this fixed-cost premium differs from that of a conventional generator: the duration constraint results in energy-capacity costs being recouped on a per-event basis, rather than being amortized over the annual total of scarcity hours. Our results reaffirm the importance of considering distinct scarcity events when evaluating storage, rather than aggregated load durations.

We make strong assumptions to simplify our results as a function of the on-peak period and the storage parameters, with the resulting benefit of one-to-one comparison to the known results for peaker plants in the classic peak-load model. Relaxing these assumptions would introduce additional terms associated with the off-peak period; exploring these outcomes remains for future work. However, our underlying takeaway — duration limits restrict stored energy capacity costs from being amortized over *all* scarcity hours — still holds without adopting these assumptions.

Additionally, the two-period model assumes that storage investment costs are solely recovered during a peak period. In practice, "shoulder" periods of load can also provide arbitrage opportunities. However, the inelasticity of electricity demand in conjunction with scarcity prices (e.g. the value of lost load) which exceed standard energy costs by several orders of magnitude suggest that even if some profits can be collected during shoulder periods, the majority of cost recovery will occur during peak periods. Arbitrage opportunities across multiple periods reduce the level of scarcity prices needed to support storage investment, but scarcity periods will likely remain the primary source of cost recovery in equilibrium. Future extensions could incorporate uncertainty in peak durations or multi-period arbitrage opportunities to better reflect these real-world conditions and evaluate the robustness of our claims.

The numerical example illustrates that adding storage reshapes equilibrium outcomes with a narrowing of price spreads, substitution for peaker generation, and synergistic investment with baseload generation.

From a regulatory perspective, our analysis demonstrates that similar to peaker generators, cost recovery for storage relies on scarcity prices which dramatically exceed variable costs. If scarcity prices are administratively capped without accompanying compensation mechanisms (e.g. capacity payments), storage will be under-incentivized, leading to a suboptimal capacity mix and lower total system welfare.

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