Economic Analysis and Optimal Sizing of Battery Storage for Residential Consumers with Solar

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Key Question

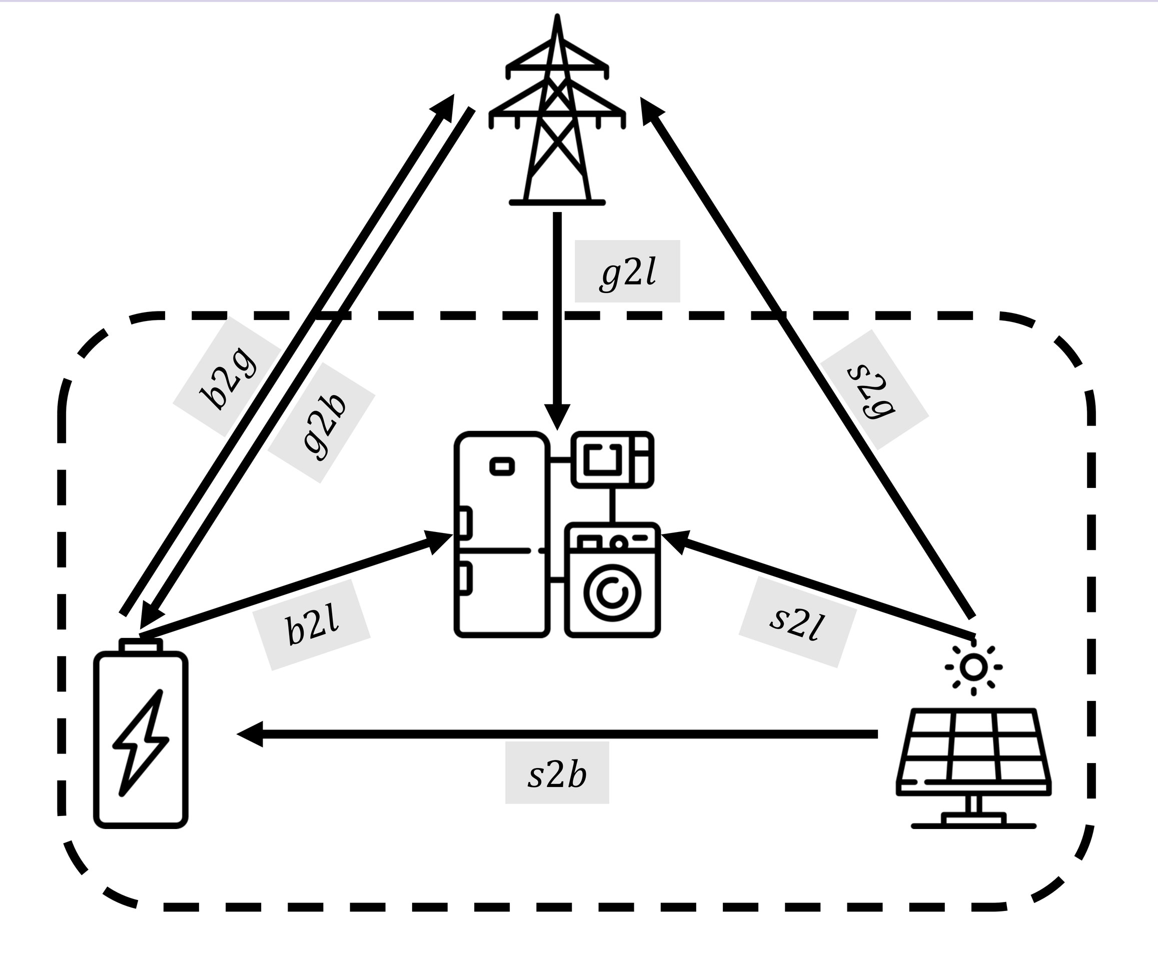
Is battery storage economically viable for residential solar owners?

Our Answer: YES! With proper sizing, returns of 10-16% IRR are achievable.

What We Did

- **Developed** a comprehensive framework combining optimal control with economic analysis
- **Optimized** battery operations hourly using forecast solar generation
- **Evaluated** lifetime economics using Internal Rate of Return (IRR)
- **Identified** optimal battery specifications for maximum returns on investment.

System Overview



Key Components & Variables:

- **Solar PV**: Generation S_t at time t (weather-dependent)
- **Battery**: Energy capacity E_{cap}, Power capacity P_{cap}
  - State of Charge: SOC_t
  - Efficiency: η_c (charging), η_d (discharging)
- **Grid**: Buying price π_t^{buy}, Selling price π_t^{sell}
- **Load**: Household consumption L_t at time t

Decision Variable: Battery charge/discharge power P_t^{batt} at each hour t (negative = charging, positive = discharging)

Why Battery Degradation Matters

The Challenge: Complex real-world battery aging model.

Key Degradation Factors:

- **Cycle degradation**: Deeper discharge cycles = faster wear
  - Non-linear relationship: doubling depth ≈ 4x degradation
  - Tracked using Rainflow counting algorithm (no closed-form solution!)
- **Calendar aging**: Time-based degradation (~2%/year)
- **Early-life effects**: Higher initial degradation (SEI formation)

Result: Battery reaches end-of-life (70% capacity) after 8-12 years depending on usage

How We Optimize: Stochastic MPC

The Approach: Look ahead 24 hours, act on the current hour.

At Each Hour:

1. Generate multiple solar forecast scenarios for next 24 hours
2. Solve for cost optimization considering all scenarios and operating constraints
3. Execute only the first hour's decision
4. Move on to the next hour with updated forecasts

Optimization Objective:

$$\min \mathbb{E}\left[\sum_t \left(\pi_t^{buy} P_t^{buy} - \pi_t^{sell} P_t^{sell} + \alpha_{deg}|P_t^{batt}|\right)\right]$$

Total Cost = Electricity Bought - Solar Sold + Degradation Cost

Subject to:

- Power balance between solar PV, battery, load and grid transactions.
- Battery operation within physical limits.
- Approx. linear degradation cost coefficient: α_{deg} (tunable parameter)

Solar Forecast: Managing Uncertainty

The Challenge: Generate solar forecasts based on historical data: **mean-reverting** process with parameter fitting to preserve temporal correlations.

Our Solution: Ornstein-Uhlenbeck (OU) process for forecast errors

Forecast Generation:

$$\epsilon_t = (1-\phi)\cdot\epsilon_{t-1} + \sigma\cdot\xi_t$$

$$\log(F_t) = \log(H_t) + \epsilon_t$$

where H_t = historical solar, F_t = forecast, $\xi_t \sim \mathcal{N}(0,1)$

- **Mean reversion parameter** $\phi = 0.37$: Controls error persistence
- **Volatility** $\sigma = 0.42$: Controls forecast uncertainty
- Generates 10 realistic scenarios in each hour's stochastic MPC problem

Economic Evaluation Methodology

From Optimization to Investment Analysis:

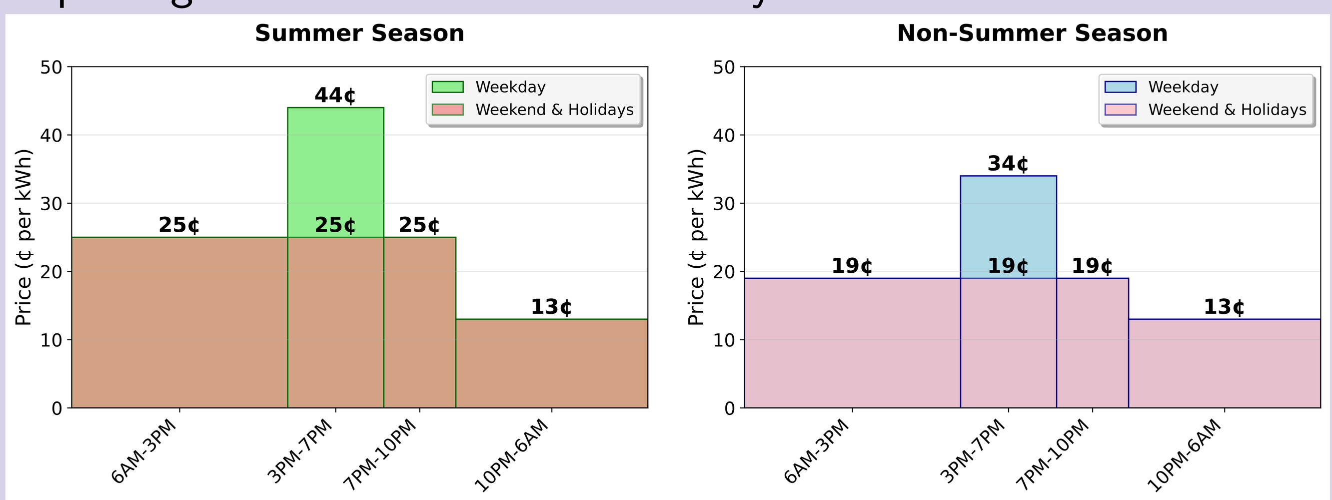
1. **Year 1 Simulation**: Full year of optimized operations
   - Net revenue: $R_{annual} = R_{with\ battery} - R_{baseline}$
   - Degradation: ΔD_{annual} via Rainflow algorithm
2. **Multi-year Projection**: Account for capacity fade
   - Year y capacity: $C(y)$ based on degradation
   - Year y revenue: $R_{annual}\cdot C(y)$

End-of-life when capacity drops below 70%

Real-World Case Study: Austin, Texas

Dataset: One year of real-world hourly data from Pecan Street

- Residential consumption scaled to US average of 30 KWh per day.
- Rooftop PV generation scaled to 7.5 KW system.

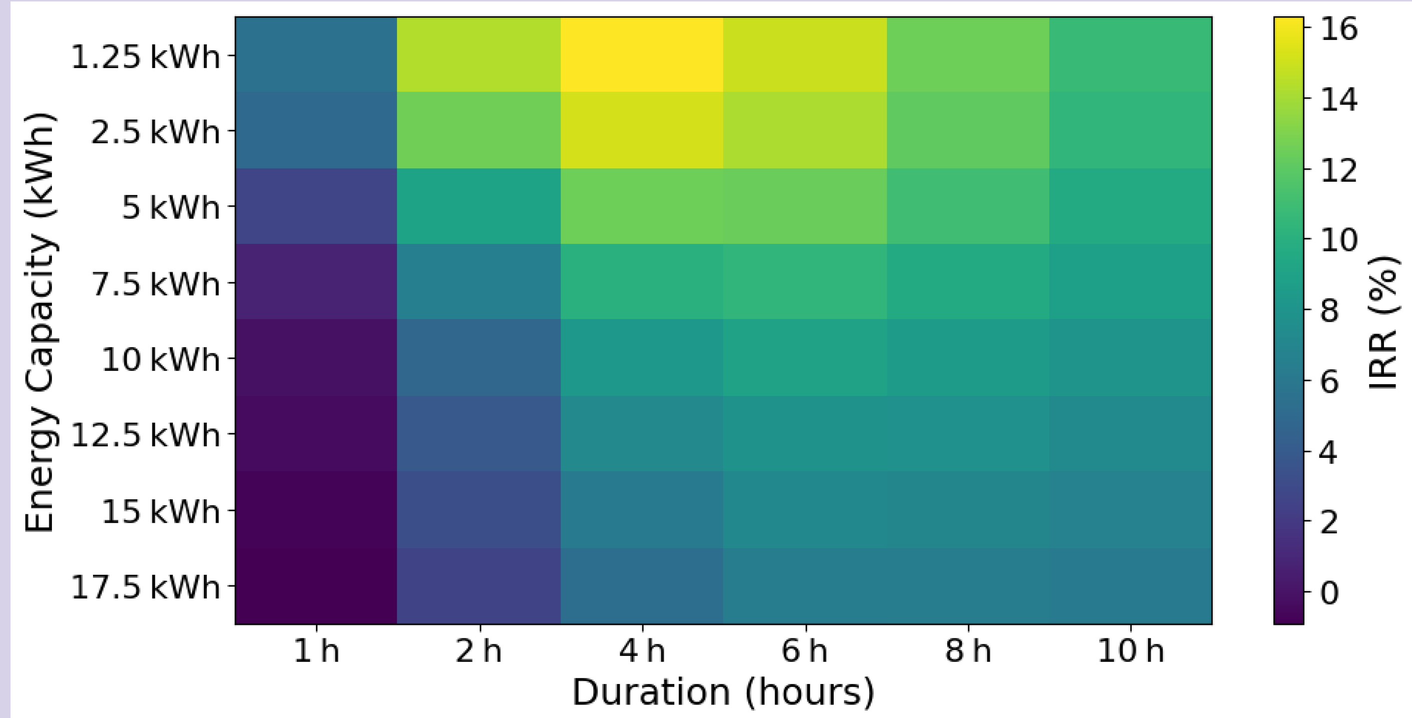


- **Peak hours (3-7 PM)**: Up to 44 cents/kWh summer
- **Off-peak**: As low as 13 cents/kWh
- **Solar selling price**: 9.91 cents/kWh (flat rate, no arbitrage opportunity)
- **Battery costs by 2040**: \$200/kWh (energy storage) + \$300/kW (inverter)

Opportunity: Store cheap solar/off-peak energy for expensive peak hours!

Main Results: Optimal Battery Sizing

Sweet Spot: 2.5-7.5 kWh capacity, 4-6 hour duration
Returns: 10-16% IRR (better than many investments!)



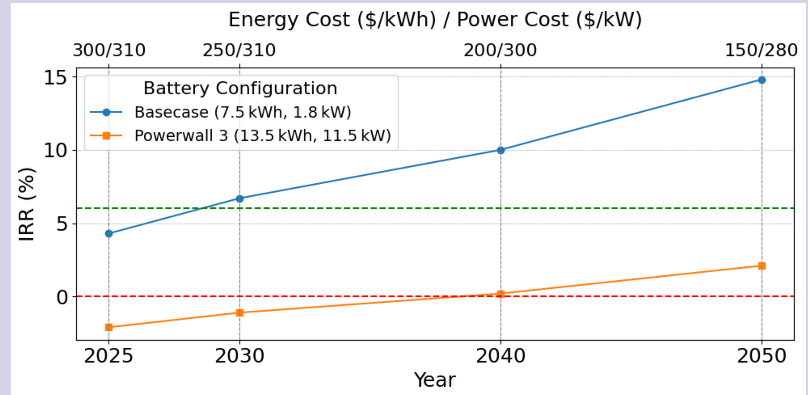
Key Investment Benchmarks:

- **Small battery (2.5 kWh, 4h)**: 15.2% IRR with \$680 investment cost
- **Medium battery (7.5 kWh, 4h)**: 10.0% IRR with \$2,040 investment cost
- **Powerwall 3 specs (13.5 KWh, 11.5 KW)**: 0.2% IRR with \$6,150 investment cost. Oversized for average homes!

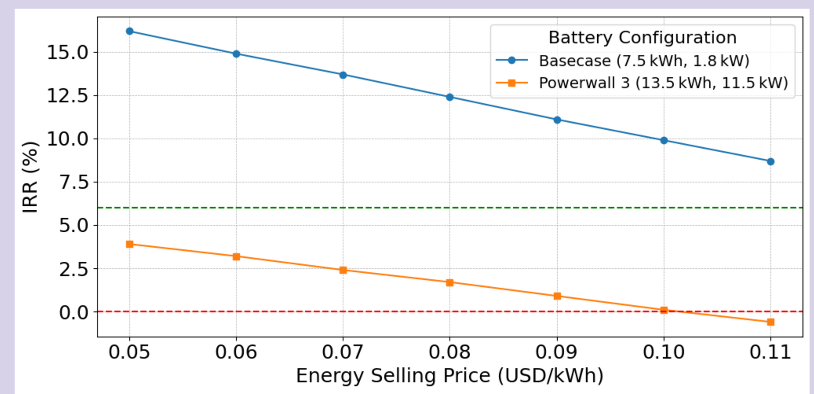
Why smaller is better:

- Fully utilized daily (no wasted capacity)
- Lower initial investment
- Diminishing returns with size

Sensitivity Analysis



Future Cost Projections



Impact of Solar Selling Price

Key Insights:

- Battery costs dropping → IRR improving
- Lower solar selling prices → Higher battery value
- By 2030: Even large batteries become viable (>6% IRR)

Take-Home Messages

For Homeowners:

- Battery storage profitable with proper sizing
- Don't oversize - smaller batteries give better returns
- 4-6 hour duration is optimal for most homes

For Researchers:

- Accurate degradation modeling crucial for economics
- Stochastic MPC effectively handles solar uncertainty
- IRR provides fair comparison across configurations

Acknowledgments

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