Optimal Storage and Solar Capacity of a Residential Household under Net Metering and Time-of-Use Pricing

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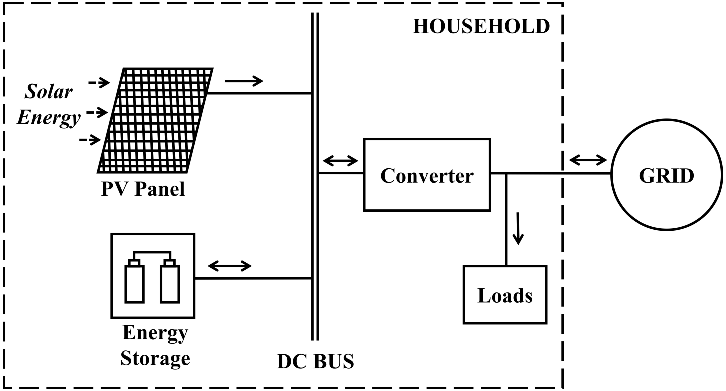
Outline

Background

- Incentive programs and ongoing reduction in costs are driving installation of solar PV panels and storage systems in residential households.
- The United States installed a record 6GW of residential PV and 1.537GWh of residential storage in 2022.
- There is a need for optimal investment decisions to reduce the electricity consumption costs of the residential sector.

Schematic of a single household with solar and energy storage interconnected to the grid



Pricing Scenario

- Each day is divided into two fixed continuous periods; peak (h) and off-peak (l) with ToU pricing and net metering billing mechanisms.
- The homeowner is compensated for the net generation at price μ.
- Otherwise, the homeowner is required to pay the net consumption at price λ for the energy consumed from the grid.
- Prices satisfy:

$$\lambda_h > \mu_h > \lambda_l > \mu_l$$

Daily cost expression of household

- For a random variable X, its expectation is written as $\mathbb{E}[X]$.
- Peak and off-peak consumption random processes denoted by H_h and H_l.
- Let $F_{H_h}(x) = \int_{-\infty}^{x} f_{H_h}(x)\,dx$ and $F_{H_l}(x) = \int_{-\infty}^{x} f_{H_l}(x)\,dx$ be the cumulative distribution functions, where $f_{H_h}(x)$ and $f_{H_l}(x)$ are the probability density function of H_h and H_l respectively.
- The daily expected electricity consumption cost of the household (without solar and storage) with time-of-use pricing is

$$C = \lambda_h \mathbb{E}[H_h] + \lambda_l \mathbb{E}[H_l] \tag{1}$$

Assumptions and considerations for storage investment

- Consider a household with energy storage capacity B and daily capital cost λ_b
- Selling price at peak period μ_h is higher than buying price λ_l at off-peak period. So, storage is fully discharged during peak period, charged during off-peak period
- We assume $(\mu_h - \lambda_l) \geq \lambda_b$ for viable arbitrage opportunity
- Household uses storage first and purchases any deficit $(H_h - B)$ from utility at peak period price λ_h
- Excess energy $(B - H_h)$ sold back to utility at peak period price μ_h
- During off-peak period, storage is fully charged and household purchases energy $(H_l + B)$ at the lower price λ_l
- Ideal operating conditions of the storage unit are assumed

Condition for optimal investment in storage capacity

The expected cost of the household is

$$J(B) = \lambda_b B + \mathbb{E}[\lambda_h (H_h - B)^+ - \mu_h (B - H_h)^+ + \lambda_l (H_l + B)] \tag{2}$$

where $(x)^+ = max\{x, 0\}$ for any real number x. Optimal storage capacity:

$$B^0 = \arg\min \ J(B)$$

Theorem 1. The optimal storage investment decision B^0 is given by

$$F_{H_h}(B^0) = \frac{\lambda_h - \lambda_l - \lambda_b}{\lambda_h - \mu_h} \tag{3}$$

The optimal cost is given by

$$J(B^0) = \lambda_h \mathbb{E}[H_h | H_h \geq B^0] + \mu_h \mathbb{E}[H_h | H_h < B^0] + \lambda_l \mathbb{E}[H_l] \tag{4}$$

Assumptions and considerations for investment in solar PV

- Homeowner with energy storage B^0 now considering solar PV panels with area a.
- H_h, H_l, S_h, S_l: random variables of household consumption and irradiance during a day.
- Peak period: uses solar and storage first, purchases deficit $(H_h - aS_h - B^0)$ at peak price λ_h.
- Excess energy $(aS_h + B^0 - H_h)$ sold back to utility at peak price μ_h.
- Off-peak period: storage charged to full. Uses solar first, purchases deficit $(H_l + B^0 - aS_l)$ at lower price λ_l.
- Excess solar energy $(aS_l - B^0 - H_l)$ sold back to utility at lower off-peak price μ_l.
- λ_a: daily capital cost of panel area, amortized over lifespan.
- PV panels operate under ideal conditions.

Condition for optimal investment in solar PV

The expected cost of the homeowner is:

$$\begin{aligned} J(a) = \lambda_b B^0 + \lambda_a a + \mathbb{E}[\lambda_h (H_h - aS_h - B^0)^+ \\ - \mu_h (aS_h + B^0 - H_h)^+ + \lambda_l (H_l + B^0 - aS_l)^+ \\ - \mu_l (aS_l - B^0 - H_l)^+] \end{aligned} \tag{5}$$

The homeowner will invest in a solar panel area,

$$a^0 = \arg\min \; J(a) \quad \text{subject to} \quad 0 \leq a \leq a_{max}$$

Theorem 2. The optimal investment decision a^0 area of solar PV panel under the condition $\lambda_h = \mu_h$ and $\lambda_l = \mu_l$ is given by:

$$a^0 = \begin{cases} a_{max} & \text{if} \quad \lambda_h \mathbb{E}[S_h] + \lambda_l \mathbb{E}[S_l] \geq \lambda_a \\ 0 & \text{else} \end{cases} \tag{6}$$

Conditions of solar PV investment decision

- For the case of $\lambda_h > \mu_h$ and $\lambda_l > \mu_l$, finding an analytical solution seems to be harder.
- We can still observe that the cost is convex.
- The peak and off-peak distribution functions need to be approximated from the data and the numerical methods are needed to compute the solution.

Model limitations

- Our model is designed for mathematical tractability and simplicity, ignoring complex pricing mechanisms, storage efficiency, device degradation, and operating costs.
- In reality, there can be multiple time periods with different prices, storage and solar devices can degrade, and storage devices can have different charging and discharging efficiencies.
- While analytical solutions can be arrived at for some of these conditions separately, a numerical simulation-based approach is needed for a comprehensive analysis that includes all conditions.

Simulation case study

- We study a single household located in a residential area of Austin, Texas, planning to invest in PV rooftop panels with a storage unit.
- Data is sourced from the Pecan Street project with the prosumer code of the household being 26.
- The study covers the entire year of 2016, with the average monthly consumption of the household being 1000 kWh.
- Household consumption and solar irradiance data are divided into peak (8 hrs to 22 hrs) and off-peak (22 hrs to 8 hrs) periods.
- A standard rooftop solar PV panel produces 183 W at an irradiance of 1000 W/m^2 for a panel area of 1 m^2.
- Considering a 93% PV system efficiency, the panel output reduces to 170 W.

Results

- Without storage and solar, the total expected cost for the household is \$4,021.49.
- After investing in optimal storage capacity B^0, the cost reduces to \$2,993.50, leading to 25.56% in savings for one year.
- Every 0.5 kW of solar PV panel investment (3 m^2 panel area) results in an additional cost reduction of \$134, or 3.3% savings.

Conclusion

- We studied the impact of optimal investment decisions for storage and solar PV panels under net metering billing mechanism with time-of-use pricing and obtained some analytical results.
- We presented a case study using load consumption and solar irradiance data and investigated how optimal investment decisions affect the net electricity consumption cost.
- We showed that through optimal investments in storage and solar, significant cost benefits can be attained.
- This work provides useful information for the prosumer to consider before investing in solar and storage resources under the new billing mechanism.

Future Work

- We plan to derive joint investment decision of a prosumer who would invest in both solar PV and storage unit simultaneously.
- We also plan to consider scenarios like more prices in a day, price uncertainties, battery degradation etc. in our analysis.
- Since an analytical solution is not likely, we plan to derive a solution using numerical methods.