Sizing and Profitability of Energy Storage for Prosumers in Madeira, Portugal

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Introduction

This work proposes a framework to select the best-suited battery for co-optimizing for peak demand shaving, energy arbitrage and increase self-sufficiency in the context of power network in Madeira, Portugal.

- Uses *profit per cycle per unit of battery capacity* and *expected payback period* as indices for selecting the best-suited storage parameters to ensure profitability.
- Introduces a friction coefficient to increase the value of storage by reducing the operational cycles and eliminate low returning transactions.

Context and Data Collection

The power network in Madeira Archipelago imposes [1]:

- Zero feed-in-tariff;
- Time-of-Use (ToU) electricity prices for consumption (Fig. 1);
- 8 levels of Peak Power Consumption (PPC): 3.45, 4.6, 5.75, 6.9, 10.35, 13.8, 17.25 and 20.7 kVA width daily cost of 0.1643, 0.2132, 0.2590, 0.3080, 0.4532, 0.5981, 0.7436 and 0.8892 respectively.

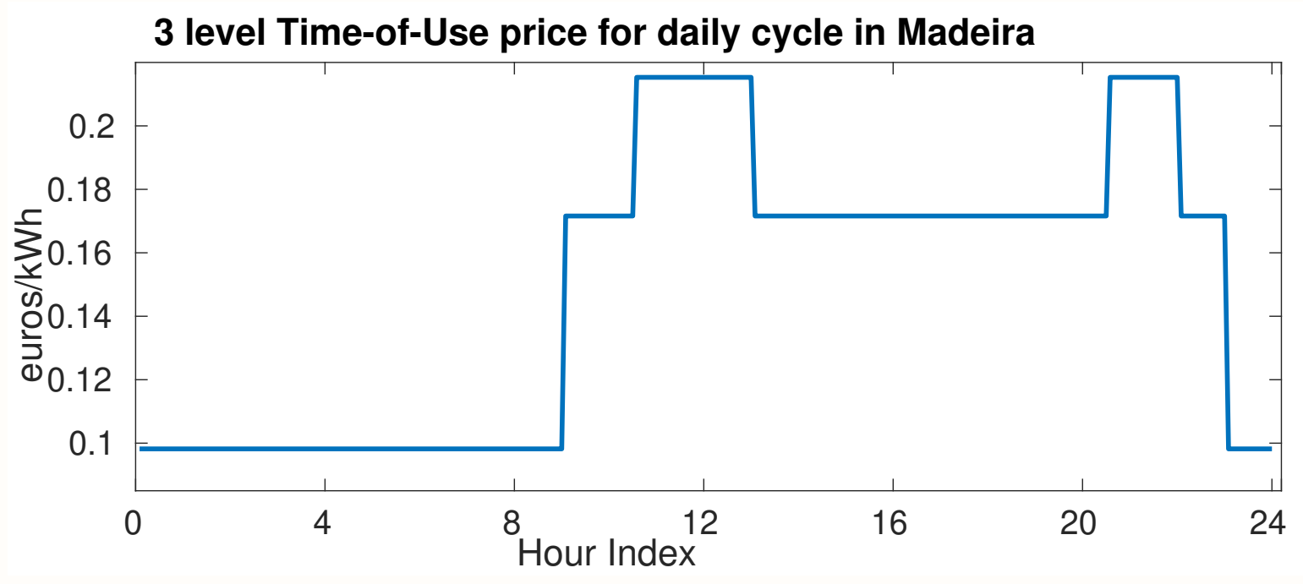

Figure 1: Time-of-use (ToU) electricity prices.

The development of better control strategies for battery energy storage systems (BESS) is one of the goals of **H2020 SMILE** (`https://www.h2020smile.eu`), an EU co-funded research project. Under the scope of SMILE, PV production (PV) and power consumption (`Load`) measurements were taken from 14 prosumers in the island [2, 3]. The prosumers are categorized based on their inelastic load and PV generation:

- (A) PV generation slightly higher than the inelastic load;
- (B) Active management of load to match PV generation;
- (C) PV generation comparable to inelastic load;
- (D) PV generation significantly higher than the inelastic load.

In this work, one prosumer was selected from each category (Fig. 2).

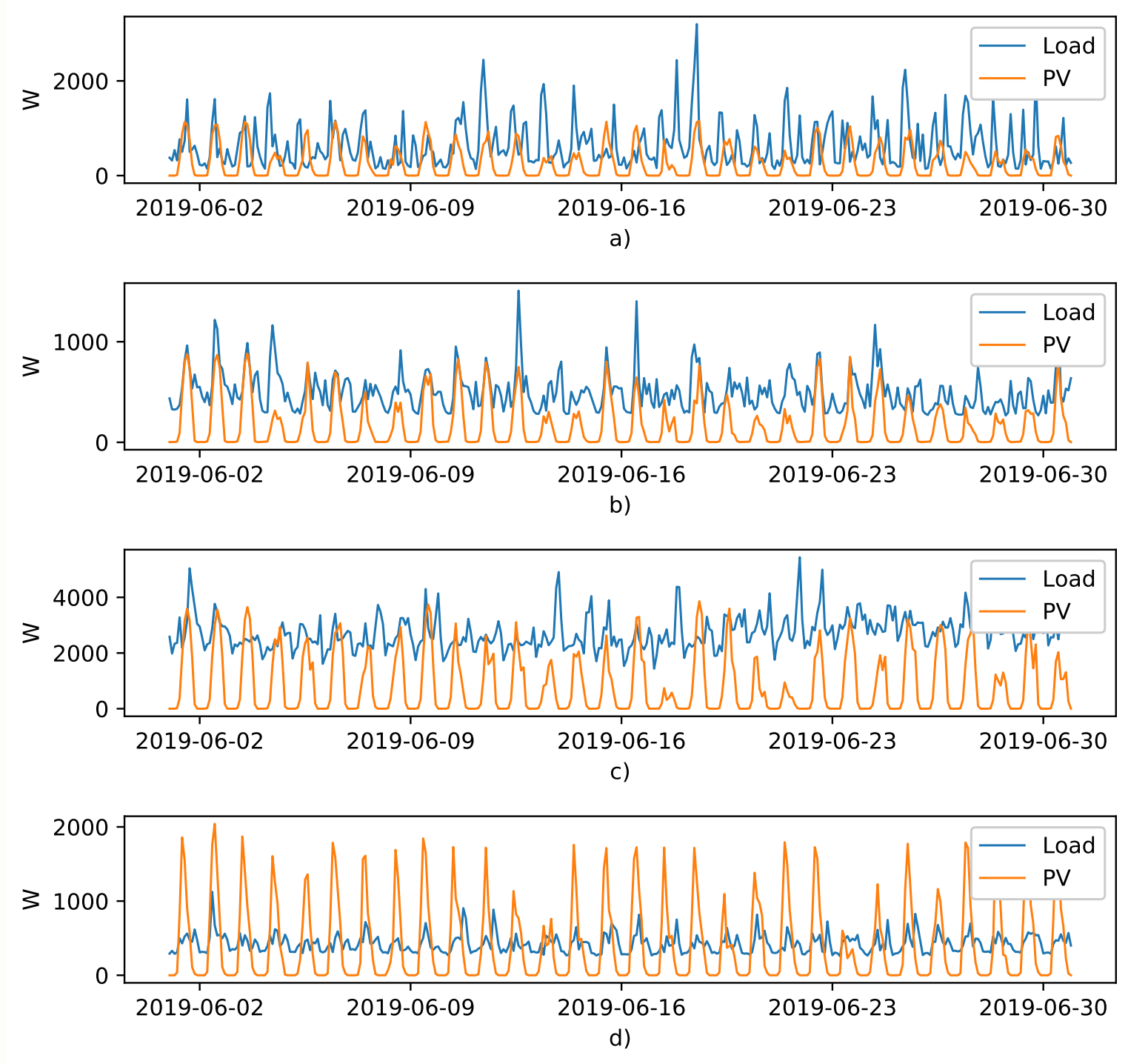

Figure 2: PV and inelastic load for 4 types of prosumers.

System Model and Storage Co-Optimization

System and Battery Model

At time instant i, the information available is the end user consumption d_i, the renewable generation r_i and the storage energy output s_i.

- *Load without storage:* $z_i = d_i - r_i$
- *Load seen by grid:* $L_i = d_i - r_i + s_i$
- *Efficiency of charging and discharging:* $\eta_{ch}, \eta_{dis} \in (0, 1]$
- *Change in battery energy level:* $x_i{=}h\delta_i$, where δ_i denotes storage ramp rate at time instant i such that $\delta_i \in [\delta_{\min}, \delta_{\max}], \forall i$.
- *The energy output of storage in the i^{th} instant:* $s_i = \frac{[x_i]^+}{\eta_{ch}} - \eta_{dis}[x_i]^-$, where $[x]^+{=}\max(0, x)$ and $[x]^-{=}-\min(0, x)$

The *ramping constraint* induce limits on s_i given by

$$s_i \in [\delta_{\min} h \eta_{dis}, \delta_{\max} h/\eta_{ch}], \quad \forall i. \tag{1}$$

The energy stored in the battery is denoted as b_i, defined as $b_i = b_{i-1} + x_i$. The *battery capacity constraint* is given as

$$b_i \in [b_{\min}, b_{\max}], \quad \forall i. \tag{2}$$

where $b_{\min}$ and $b_{\max}$ are minimum and maximum permissible battery charge levels respectively.

We use xC-yC notation to represent the relationship between ramp rate and battery capacity. xC-yC implies battery takes 1/x hours to charge and 1/y hours to discharge completely.

Co-Optimization Formulation

The co-optimization formulation is developed in [1] and given as

$$
\begin{aligned}
(P_{opt}) \quad \underset{s_i}{\text{minimize}} \quad & \sum_{i=1}^{N} p_{elec}(i)\theta_i(s_i)h && \text{(3a)}\\
\text{subject to} \quad & && \\
& \text{Ramping constraint, Eq. 1} \qquad , && \text{(3b)}\\
& \text{Capacity constraint, Eq. 2,} && \text{(3c)}\\
& \text{Self-sufficiency,} \quad \theta_i(s_i) \geq 0, && \text{(3d)}\\
& \text{Arbitrage,} \quad \theta_i(s_i) \geq [z_i + s_i], && \text{(3e)}\\
& \text{Peak shaving,} \quad [z_i + s_i]/h \leq P_{\max}^{set} && \text{(3f)}
\end{aligned}
$$

where $\theta_i(s_i) = \max(0, z_i + s_i)$.

- The PPC threshold, $P_{\max}^{set}$, is selected close to the power level $(P_{\max} + \delta_{\min})$, subject to $P_{\max}^{set} \geq (P_{\max} + \delta_{\min})$.
- $P_{\max}^{set}$ is selected by the electricity consumer as a PPC contract with the utility in Madeira.
- Note that the formulation **prioritizes self-consumption over arbitrage**.

Co-Optimization with Control of Cycles

Following prior work [4], we define a friction function for the active power to model the degradation due to cycles of operation as $P_{fric}^i = \frac{[P_B^i]^+}{\eta_{fric}} - [P_B^i]^- \eta_{fric}$.

- In the original formulation (P_{opt}) the constraint Eq. 3e is modified as $\theta_i \geq [z_i + P_{fric}^i]$.
- The friction coefficient takes a value from 1 to 0.
- η_{fric} needs to be tuned so as the operational life is increased by matching calendar and cycle degradation [4].
- If the battery is not over operating then η_{fric} is set to 1.
- For cases where the battery is over-performing, the low returning transactions is eliminated by decreasing value of η_{fric}.

Energy Storage Profitability

Cost of Storage (inverter + battery)

- *Cost of Inverter:* 100 euros/kWh (6kW SMA Sunny Boy 2.0 [5]);
- *Li-Ion battery:* two components: (a) capacity cost and (b) ramping capability cost, [6];
- The storage cost for per kWh in euros is given as:

$$\text{Storage Cost} = 300 + 0.25 \max(x, y) 100 \quad \text{per kWh}, \tag{4}$$

where x, y denotes the charging and discharging rates as described in the battery model xC-yC.

Profit Considering Degradation

- Battery cycle life equals 4000 cycles at 100% DoD;
- Calendar life equals 7 years.

Considering the Euros per cycle per rated battery capacity for different ramping batteries listed in Table 1, **the battery should perform ≈47.6 cycles per month in order to last 7 years and make more than the values listen in Table 1 to be profitable.**

Table 1: Storage profitability with different ramping per kWh

Battery Model	Inverter Cost/kWh	Battery Cost/kWh	Battery Cost (C_{bat}/kWh)	euros/cycle/b_{rated} (C_{cyc})
0.25C-0.25C	25	400	425	0.1062
1C-1C	100	600	700	0.1750
2C-2C	200	700	900	0.2250

Numerical Results

The numerical simulations use the battery parameters listed in Table 2. Simulations are performed for the month of June 2019.

Performance Indices

- *Arbitrage and self-sufficiency gains* (G_{arb});
- *Peak shaving gains* (G_{PD});
- *Total gains* (G_T): sum of G_{arb} and G_{PD};
- *Gains per cycle* (G_{cyc});
- *Profit per cycle* (P_{cyc}): difference between gains (G_{cyc}) and cost per cycle (C_{cyc});
- *Expected payback period* (ExPB): linear extrapolation of the payback period compared to G_T. ExPB $= C_{bat}/G_T$;
- *Self-sufficiency* (SS);
- *Wasted energy*: Surplus production in kWh.

Table 2: Battery Parameters

$b_{\min}$, $b_{\max}$, b_0 b_{rated}	10%, 100%, 50% of b_{rated} 1, 2, 5 kWh
$\eta_{ch} = \eta_{dis}$	0.95
$\delta_{\max} = -\delta_{\min}$	0.25 b_{rated} W for 0.25C-0.25C, b_{rated} W for 1C-1C, $2b_{rated}$ W for 2C-2C

Co-Optimization and Storage Profitability

The co-optimization results for a prosumer in categories A, C, and D are presented in Tables 3, 4, and 5, respectively.

Table 3: (A) generation slightly higher than inelastic load

Case	G_{PD} Euro	G_T Euro	P_{cyc}	Cycles	ExPB (years)	SS (%)	Waste (kWh)
Load + PV	-	-	-	-	-	26.82	57.4
1 kWh Battery							
0.25C-0.25C	0	10.13	**0.167**	37.01	**3.50**	31.91	30.12
1C-1C	1.39	13.79	**0.086**	52.70	**4.23**	33.56	18.59
2C-2C	2.85	15.48	**0.053**	55.56	**4.84**	33.69	15.39
2 kWh Battery							
0.25C-0.25C	1.39	15.83	**0.079**	42.53	**4.47**	34.96	12.97
1C-1C	2.85	19.26	**0.035**	45.75	**6.06**	35.85	5.15
2C-2C	2.85	19.33	-0.016	46.24	7.76	35.88	3.96
5 kWh Battery							
0.25C-0.25C	1.39	22.46	**0.028**	33.27	7.88	36.38	0.39
1C-1C	2.85	24.67	-0.029	33.91	11.82	36.29	0.19
2C-2C	2.85	24.67	-0.079	33.91	15.20	36.29	0.18

Table 4: (C) Comparable generation and inelastic load

Case	G_{PD} Euro	G_T Euro	P_{cyc}	Cycles	ExPB (years)	SS (%)	Waste (kWh)
Load +PV	-	-	-	-	-	28.02	58.14
1 kWh Battery							
0.25C-0.25C	0	35.62	**0.858**	36.91	**0.99**	28.71	40.68
1C-1C	0	39.42	**0.454**	62.64	**1.48**	29.42	22.69
2C-2C	0	40.02	**0.376**	66.53	**1.87**	29.57	17.88
2 kWh Battery							
0.25C-0.25C	0	40.04	**0.294**	50.01	**1.77**	29.21	27.27
1C-1C	0	44.36	**0.184**	61.75	**2.63**	29.79	10.73
2C-2C	4.31	48.70	**0.177**	60.51	**3.08**	29.79	9.09
5 kWh Battery							
0.25C-0.25C	0	50.44	**0.111**	46.30	**3.51**	29.90	4.80
1C-1C	4.31	58.64	**0.110**	41.06	**4.97**	29.80	1.54
2C-2C	4.31	58.65	**0.059**	41.18	**6.39**	29.80	1.36

Table 5: (D) Generation significantly higher than inelastic load

Case	G_{PD} Euro	G_T Euro	P_{cyc}	Cycles	ExPB (years)	SS (%)	Waste (kWh)
Load + PV	-	-	-	-	-	47.84	158.1
1 kWh Battery							
0.25C-0.25C	0	8.57	**0.192**	28.69	**4.13**	56.91	126.13
1C-1C	0	9.49	**0.110**	33.22	**6.15**	57.72	115.66
2C-2C	0	9.56	**0.073**	35.55	7.85	57.84	106.63
2 kWh Battery							
0.25C-0.25C	0	13.41	**0.056**	41.19	**5.28**	65.00	97.50
1C-1C	0	13.84	**0.021**	35.23	8.43	65.77	81.94
2C-2C	0	13.86	-0.011	32.47	10.82	65.80	70.04
5 kWh Battery							
0.25C-0.25C	0	18.28	-0.007	36.85	9.69	74.90	53.58
1C-1C	0	18.71	-0.075	37.72	15.59	75.66	31.16
2C-2C	0	18.70	-0.125	37.66	20.05	75.65	27.41

Friction Coefficient

- Inclusion of friction coefficient is only relevant for 1 and 2 kWh batteries for the prosumer in category C and 1 kWh battery for the prosumer in category A.
- Table 6 compares the tuned friction coefficients for batteries which performed more cycles than expected.

Table 6: Results with Friction Coefficient

Battery Model	η_{fric}	Profit euros	P_{cyc}	SS (%)	Waste (kWh)	Cycles	ExPB yrs.
For prosumer U2							
1kWh,1C-1C	0.796	12.85	0.096	32.45	25.70	47.38	4.54
1kWh,2C-2C	0.797	14.45	0.079	32.53	24.99	47.44	5.19
For prosumer U8							
1kWh,1C-1C	0.796	38.17	0.680	29.33	26.82	44.62	1.53
1kWh,2C-2C	0.796	38.50	0.582	29.37	25.16	47.65	1.95
2kWh,0.25C-0.25C	0.939	43.98	0.314	29.67	13.71	52.29	1.61
2kWh,1C-1C	0.939	43.47	0.328	29.73	14.34	43.17	2.68
2kWh,2C-2C	0.939	47.85	0.322	29.76	12.91	43.68	3.13

Conclusion

- The marginal value of installing battery decreases with storage size and ramping capability;
- The value of storage for an average net-load comparable to storage ramping rate (category C) leads to profits several folds higher than for otherwise.
- Faster ramping batteries perform much more number of cycles which deteriorates the profit made per 100% DoD cycles per unit of storage capacity, thus making such batteries financially nonviable.
- Inclusion of η_{fric} for over-performing batteries increases P_{cyc}, however, also increases the payback period.

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