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Integration of Solar PV and Battery Energy Storage Systems Towards a Sustainable Street Lighting

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I. Introduction and context

Public street-lighting uses >50 % of municipal electricity in Portugal and represents ≈1 % of total global energy demand. EU climate policy demands renewable, low-carbon solutions also for lighting systems.

The need to transition from fully grid-dependent street lighting to renewable-powered smart lighting has led to innovations in hybrid solar-photovoltaic, wind systems, energy storage, and IoT-based management strategies.

Hybrid solar-photovoltaic (PV) combined with battery energy storage systems (BESS) can shift daytime solar production to night-time demand.

The renewable energy communities (REC) framework can be a vehicle for agregation of multiple production plants and multiple lighting systems when not colocated – often public lighting has multiple circuits fed from distinct grid-connection points.

II. Objectives and motivation

This paper presents and applies a model for optimizing hybrid solar PV and BESS for street lighting, focusing on the challenges of meeting nighttime electricity demand with a daytime-only renewable energy source.

The mixed-integer linear programming model determines the cost-optimal sizing for solar PV and BESS for a given municipal street lighting system in Portugal.

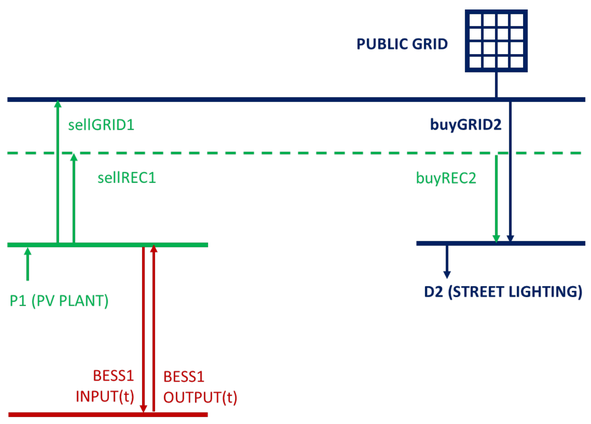
Considering multiple parameters and technical constraints, this paper assesses the techno-economic viability across a realistic range of CAPEX scenarios.

This research provides valuable insights into designing sustainable and cost-effective street lighting systems, enabling municipalities to reduce their reliance on the grid energy and transition towards greater energy sourcing independence. **The results offer a framework for evaluating the economic viability under various cost and operational conditions.**

III. Methodology and case study

The present study develops and implements a renewable energy community, where a normalized profile for the PV generation (in Portugal) is used for a full year (8760 data-points). The profile is scaled-up according to the installed capacity suggested by the model – external input.

- **Model objective function**: minimise annualised street lighting supply cost plus post-processing deduction of the surplus PV exports revenue.
- **Model decision variables**: PV capacity (kW), BESS energy (kWh) - hourly dispatch.
- **Model constraints**: demand balance, BESS state-of-charge, charge/discharge exclusivity, capacity limits, grid-energy arbitrage is not allowed (cannot charge the BESS with grid supplied energy).



As presented in the schematic, a REC concept with two members is used as a case study. REC2 is a lighting electricity consumer and REC1 is an electricity producer holding a PV plant equipped with a BESS. REC1 can invest in PV and in BESS to reduce the total electricity sourcing costs paid by REC2.

- **Case load**: 13 GWh (annum) with 3.17 MW peak demand
- **Case PV profile**: Normalised irradiance (Portugal, Lisboa) scaled by installed capacity; BESS round-trip efficiency 90 %
- **Case scenarios**: PV 400-1200 €/kW and BESS 100-500 €/kWh
- **Case economic parametres**: 20 years; flat 5% interest rate, grid sourced electricity price: 140 EUR/MWh

The surplus PV sales are accounted for in a post-optimization step as an additional revenue stream. These are priced based on the average monthly prices from the day-ahead market (DAM) MIBEL.

IV. Simulation results

The results show potential for a **positive investment case in various scenarios**, which would result in cost savings for the targeted municipality. The selected scenario (**Base Case**) results are highlighted with a black border on the tables:

- **CAPEX:** PV 1000 €/kW, BESS 200 €/kWh
- **Optimal sizing:** 5.4 MW PV + 29.2 MWh BESS
- **Demand self-sufficiency index:** 68 %

The demand self-sufficiency index represents the share of the street lighting consumption that is supplied by renewable energy from the hybrid system. The self-sufficiency index in the Base Case Scenario is 68% which means that **only 32% needs to be sourced from the grid.**

PV capacity in **MW** for various scenarios:

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500				5.9	7.4
BESS 400			5.3	6.3	7.9
BESS 350	4.0	4.7	5.6	6.8	8.3
BESS 300	4.9	**5.4**	6.2	7.6	9.2
BESS 200	5.4	6.1	7.0	8.6	10.4
BESS 100					

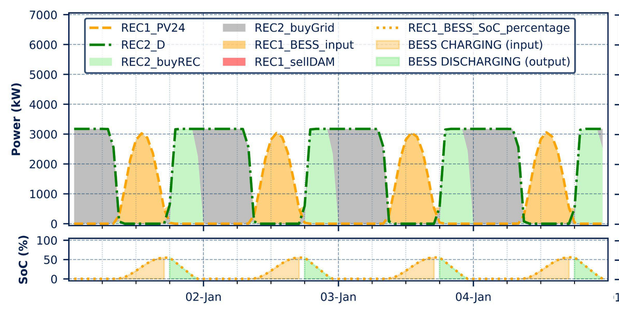
BESS capacity in **MWh** for various scenarios:

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500				24.8	26.8
BESS 400			25.5	26.7	28.4
BESS 350	23.0	25.2	26.8	28.5	30.0
BESS 300	28.5	**29.2**	30.2	32.3	33.7
BESS 200	31.9	33.2	34.6	36.8	38.6
BESS 100					

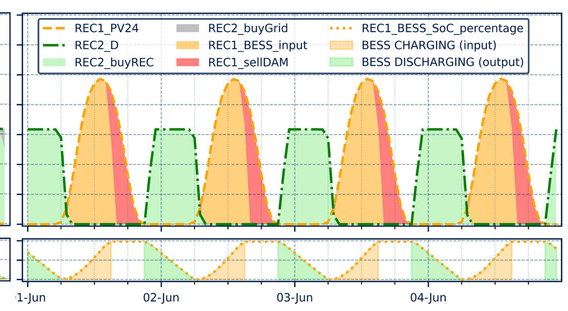
Demand self-sufficiency in **percentage**:

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500				63%	70%
BESS 400			62%	67%	74%
BESS 350	53%	59%	65%	71%	77%
BESS 300	65%	**68%**	72%	78%	83%
BESS 200	70%	74%	78%	84%	89%
BESS 100					

Winter simulation results – 4 consecutive days



Summer simulation results – 4 consecutive days



Highlights:

- PV generation is not enough to fill the storage system capacity, suggesting PV under-sizing for Winter conditions
- Full self-sufficiency in Summer conditions plus surplus generation suggests PV over-sizing in Summer conditions

V. Financial analysis

The results show that the hybrid system can be economically feasible under certain market circumstances. Its merit can be quantified in several metrics, being the main criteria the ability to save costs compared to the full grid supply costs. The overall economic savings considering the revenues from the self-sufficiency, the surplus sold to the grid and the cost of the investment in solar PV and BESS is reflected in the tables. Example for the selected **Base Case**:

- **Annual savings vs grid-only:** 333 k€
- **Life-time Net Present Value (NPV):** 1.86 M€
- **Internal Rate of Return (IRR)**: 6.9 %

Further analsys shows:

- **Financial breakeven is up for grabs** at PV ≤ 1200 €/kW and BESS ≤ 300 €/kWh
- **NPV spans** 0.88–9.48 M€ across the CAPEX scenarios
- **IRR spans** 5.9–16.7 % across the CAPEX scenarios
- **NPV/IRR** contour maps (poster bottom-right) can easily highlight the viable design space

Annual savings vs grid-only in **EUR(1000x)**:

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500				72	181
BESS 400			85	177	296
BESS 350	33	103	190	294	416
BESS 300	253	333	430	546	685
BESS 200	497	591	699	829	984
BESS 100					

Cumulative (Lifetime) results

Investment NPV in **EUR(1 000 000x) :**

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500				3.59	6.01
BESS 400			2.40	3.77	6.36
BESS 350	0.88	1.49	2.54	4.25	6.78
BESS 300	1.21	**1.86**	2.98	5.02	7.88
BESS 200	1.54	2.47	3.77	6.37	9.48
BESS 100					

Internal Rate of Return in **percentage**:

	PV 1200	PV 1000	PV 800	PV 600	PV 400
BESS 500				8.0%	9.8%
BESS 400			7.1%	8.2%	10.2%
BESS 350	5.9%	6.4%	7.3%	8.7%	10.9%
BESS 300	6.2%	**6.9%**	8.0%	9.9%	12.8%
BESS 200	6.8%	7.9%	9.5%	12.5%	16.7%
BESS 100					

VI. Conclusions

As take-home points, we would like to highlight some generic conclusions:

- The results demonstrated the system's efficacy in meeting street lighting demand, storing surplus daytime solar energy for nighttime use, and generating surplus in Summer for sale to the grid
- PV+BESS hybridization can decarbonise municipal street lighting with positive returns as solar panels and energy storage costs fall
- **Economic viability already achieved** at BESS CAPEX ≤ 300 €/kWh with PV CAPEX ≤ 1200 €/kW facing the current Portuguese grid electricity prices - without any other grid-service revenue streams
- This model provides a replicable and adaptable approach for many other municipalities seeking cost savings