Magnitude and Economic Impact of PV Curtailment, and Possible Implications for Soiling Mitigation

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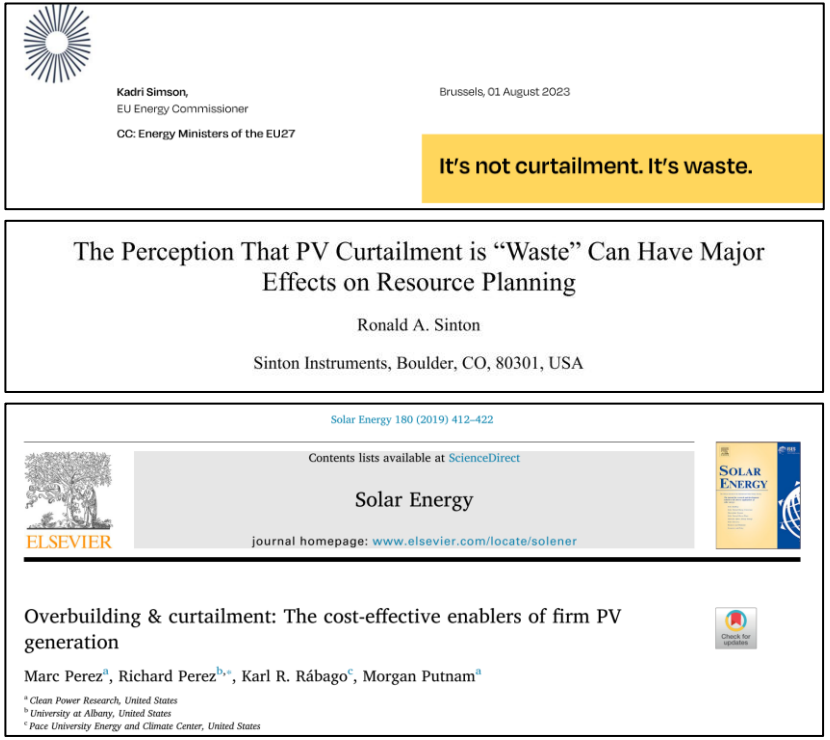
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Motivation

Curtailment ➔ when PV energy cannot be injected into the grid.



Kadri Simson,
EU Energy Commissioner

CC: Energy Ministers of the EU27

Brussels, 01 August 2023

It's not curtailment. It's waste.

The Perception That PV Curtailment is "Waste" Can Have Major Effects on Resource Planning

Ronald A. Sinton

Sinton Instruments, Boulder, CO, 80301, USA

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Overbuilding & curtailment: The cost-effective enablers of firm PV generation

Marc Perez[a], Richard Perez[b,*], Karl R. Rábago[c], Morgan Putnam[a]

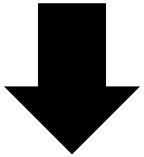
[a] Clean Power Research, United States
[b] University at Albany, United States
[c] Pace University Energy and Climate Center, United States

- Traditionally associated to wind energy.
- Increasingly common in high PV penetration markets (Spain, Germany).
- Often viewed as "waste", but essential for grid balance.

SolarPower Europe, It's not curtailment. It's waste., 2023.
R.A. Sinton, The Perception That PV Curtailment is "Waste" Can Have Major Effects on Resource Planning, Conf. Rec. IEEE PVSC, 2024.
M. Perez, R. Perez, K.R. Rábago, M. Putnam, Overbuilding & curtailment: The cost-effective enablers of firm PV generation, Sol. Energy, 2019.

Aim

Curtailment's **magnitude and economic impact** is rarely quantified.



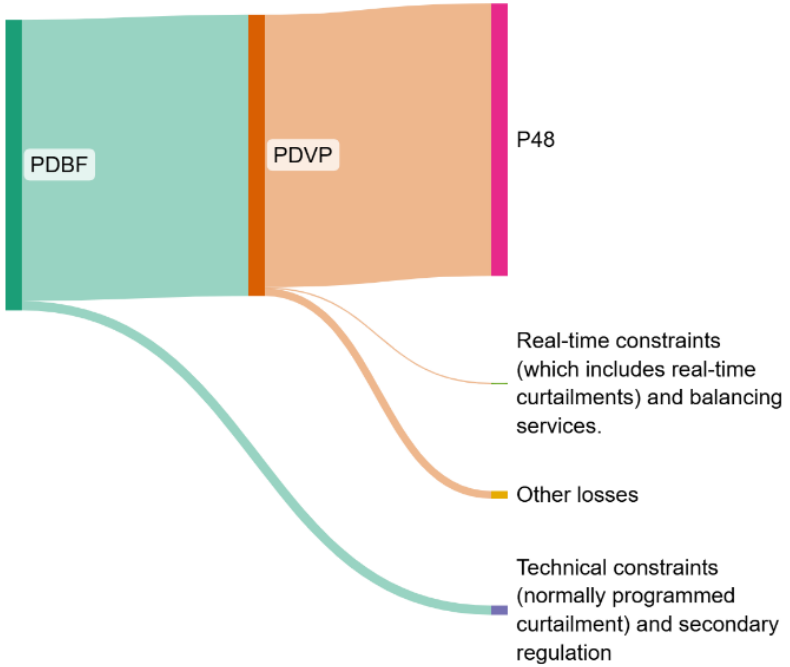
Aim of this work:

- Quantify **energy curtailed** in Spain (2022–2024) and associated **economic losses** (LCOE and NPV).
- Assess **viability of batteries** to mitigate curtailment losses.
- Discuss possible **implications for soiling mitigation** and O&M.

L. Micheli, A. Soria-Moya, D.L. Talavera, B. Abbasi, E.F. Fernández,
Energy and economic implications of photovoltaic curtailment: current status and future scenarios, Sustain. Energy Technol. Assessments, 2025.

Background

Spain: top 10 PV market worldwide
(20-30 GW: PV > 15% of the electricity generated in 2023)



PDBF – PDVP

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Programmed Curtailment

PDVP – P48

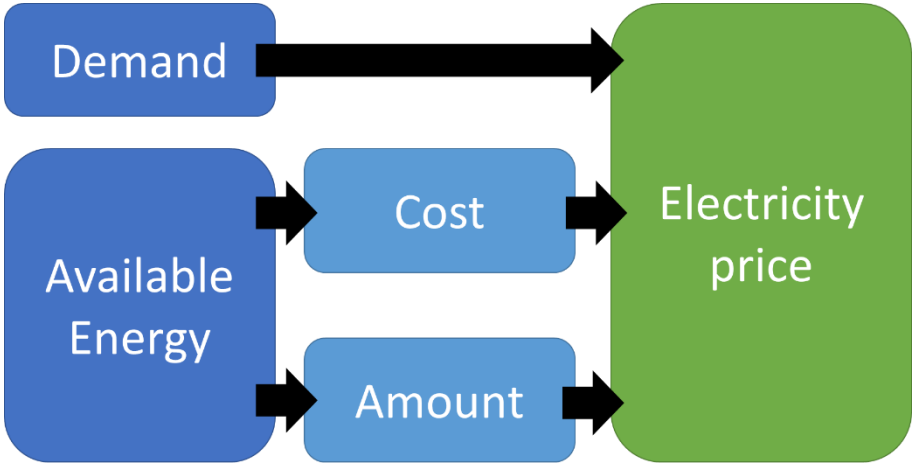
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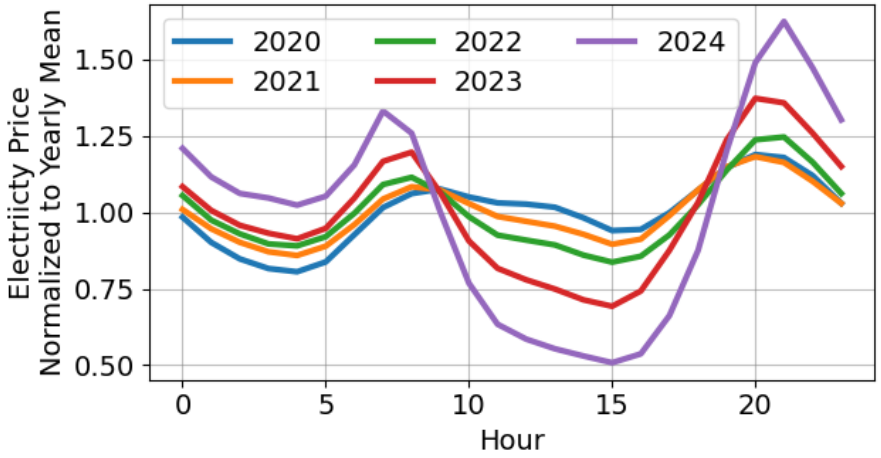
Real-time Curtailment

Methodology: Energy & Economics

- **Curtailment data**: REE
- **PV production**: PVGIS 5.3

- **Electricity prices**: OMIE





Methodology: Economics

The Levelized Cost of Electricity (**LCOE**) quantifies the cost of producing a kWh of electricity. The lower, the better.

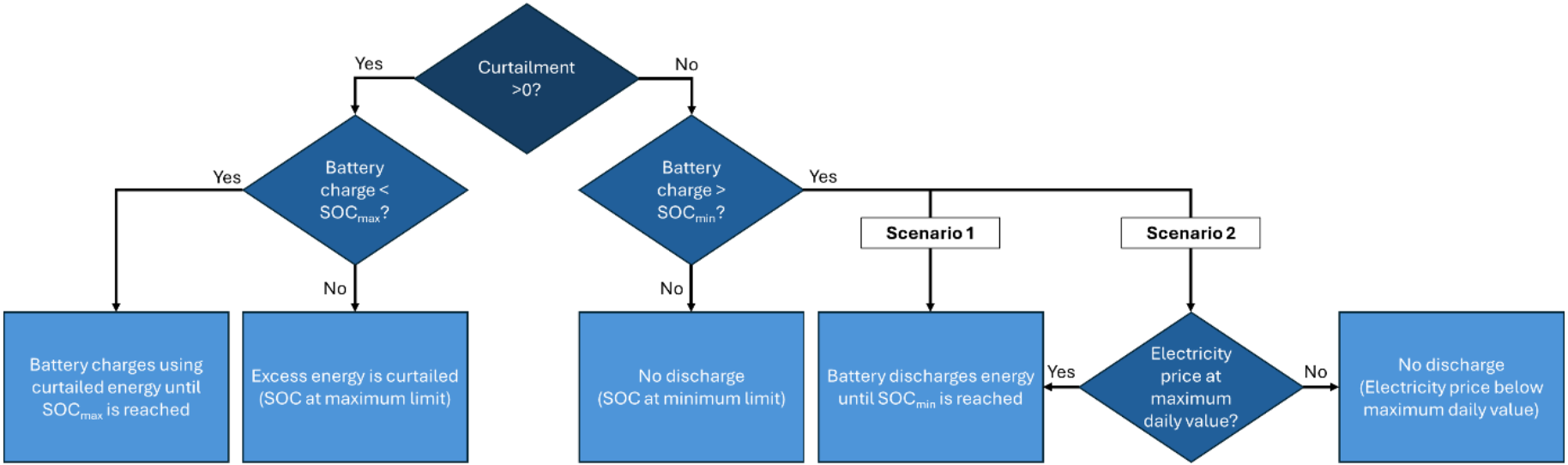
$$LCOE = \frac{Capital\ Expenditure + \sum Yearly\ O\&M\ Costs\ /Discount}{\sum Yearly\ Energy\ Yield\ /Discount}$$

The Net Present Value (**NPV**) is commonly used in the private sector to evaluate the profitability of an investment. The larger, the better.

$$NPV = -Capital\ Expenditure + \sum \frac{Yearly\ Revenues - Yearly\ O\&M\ Costs}{Discount}$$

Methodology: Battery

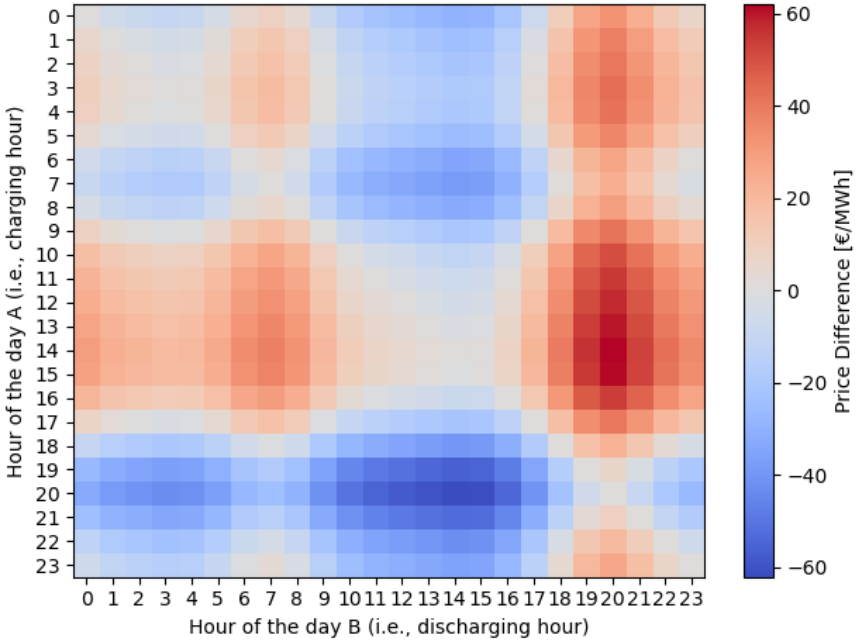
Battery analysis target costing
(max CAPEX increase to maintain same NPV/LCOE).



Scenario 1: immediate release right after curtailment;
Scenario 2: release during the hour of highest electricity price.

Methodology: Battery

⬆ Capital Expenditure (CapEx), ⬆ Energy Yield (Y) , ⬆ Price (p)

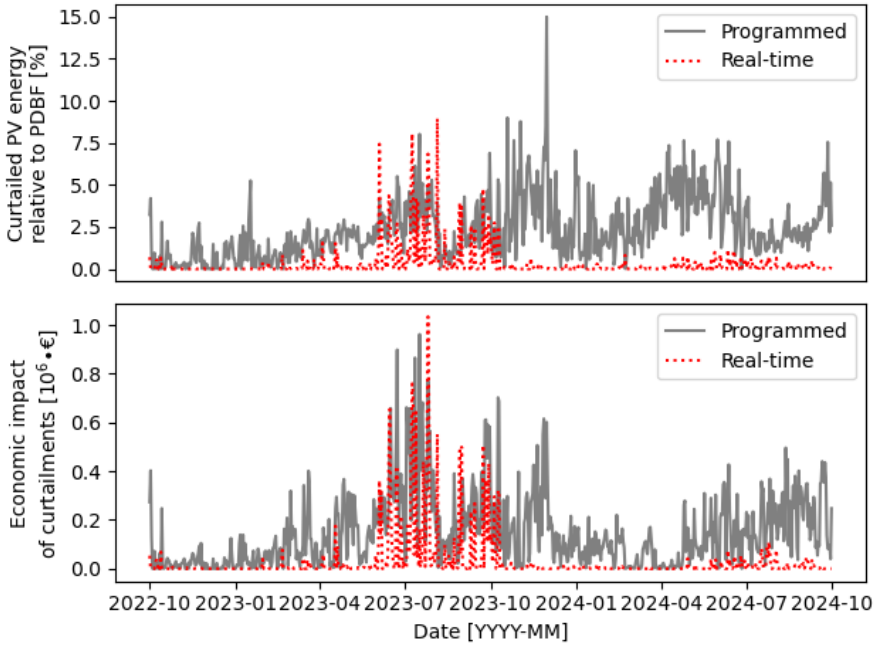


Which are the maximum allowed costs for batteries?

$$maxC_b\colon\ LCOE(CapEx + \mathrm{C_b}, \mathrm{Y_b}) \leq\ LCOE(CapEx, Y)$$

$$maxC_b\colon NPV(CapEx + \mathrm{C_b}, \mathrm{Y_b}, \mathrm{p_b}) \geq\ NPV(CapEx, Y, p)$$

Results: Magnitude



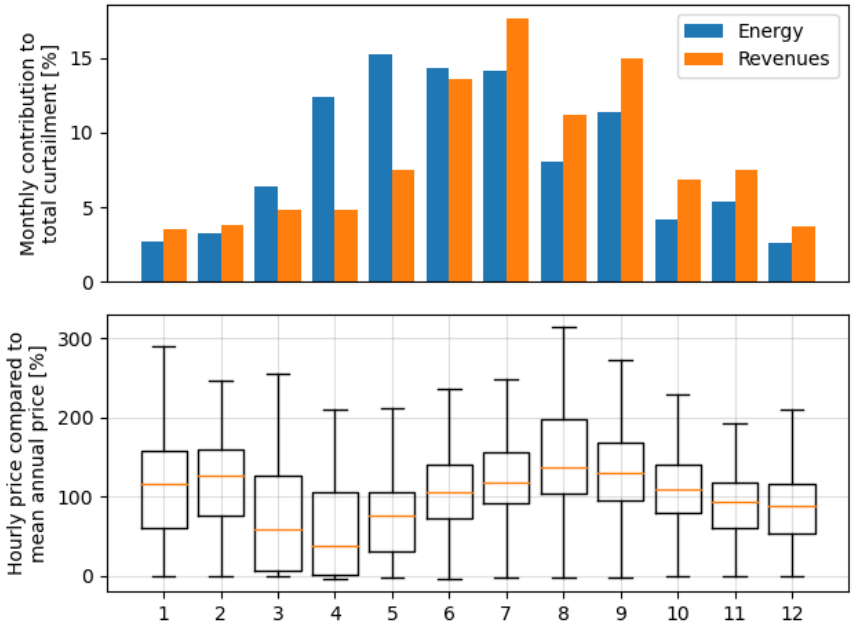
2.9% of the PV energy produced in Spain has been curtailed.

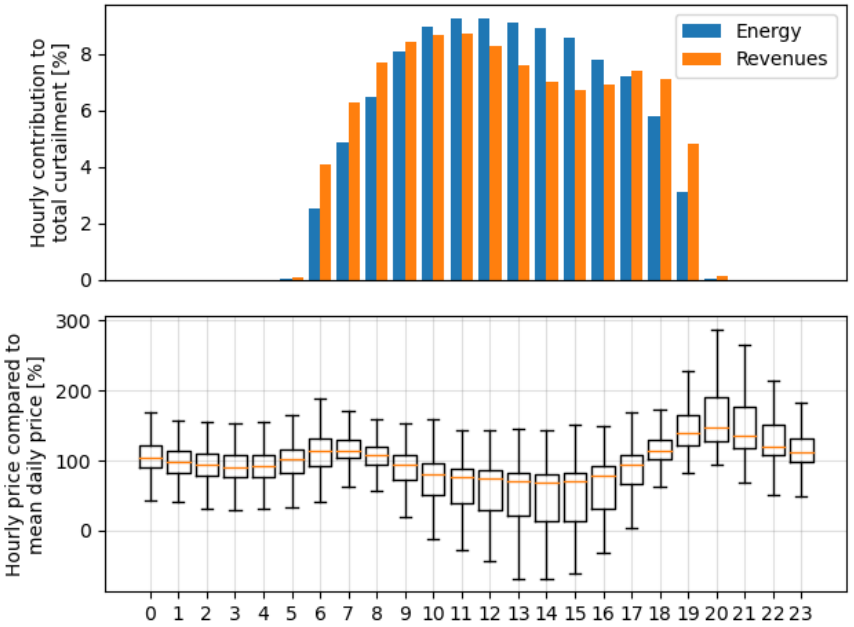
- 2.5% programmed curtailments
- 0.4% real-time curtailments

$146 \cdot 10^3$ €/day lost because of PC

Results: Distribution

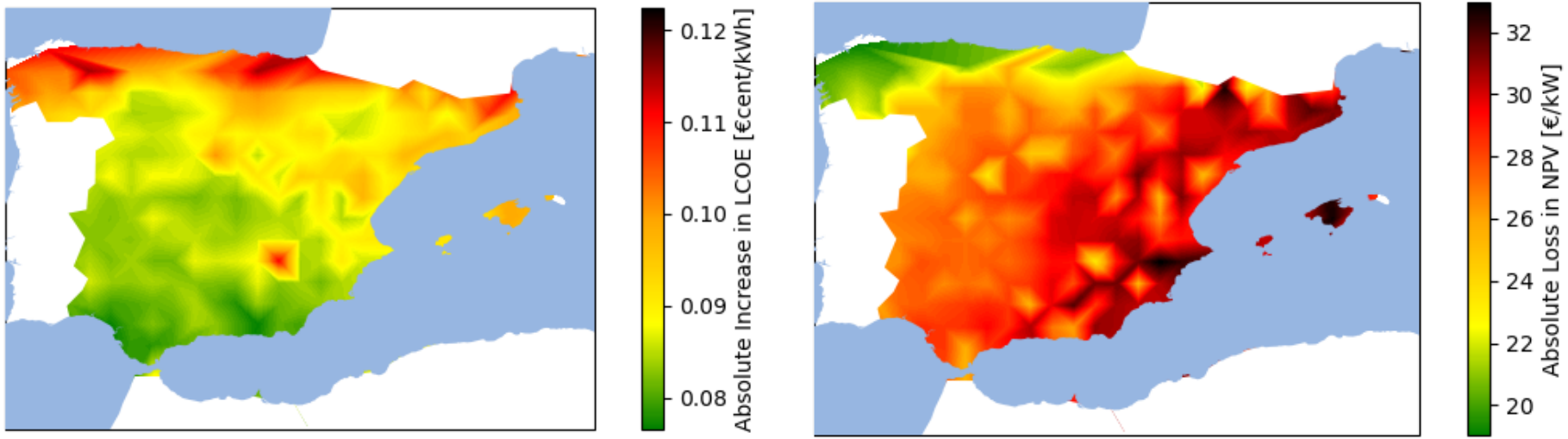
56.1% of the PV energy curtailed is produced between April and July.
75.4% if also August and September are included.





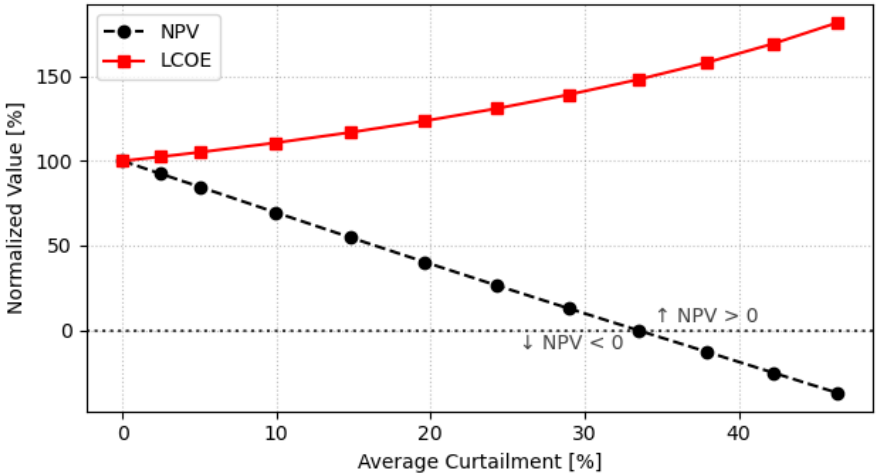
Results: Economic impact

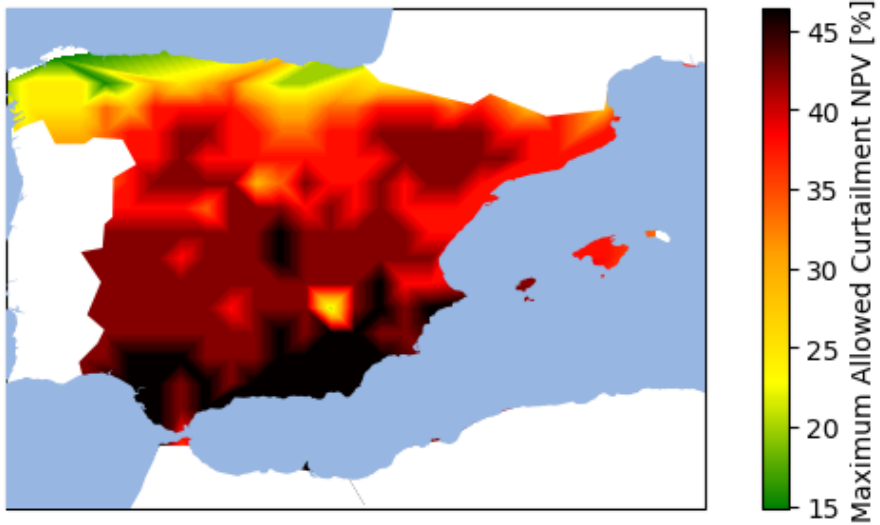
2.5% increase in LCOE, **7.7%** drop in NPV



Results: Future trends

Without appropriate solutions or a paradigm shift in energy consumption, the curtailment rate is expected to rise to values between 35% and 40% [1].



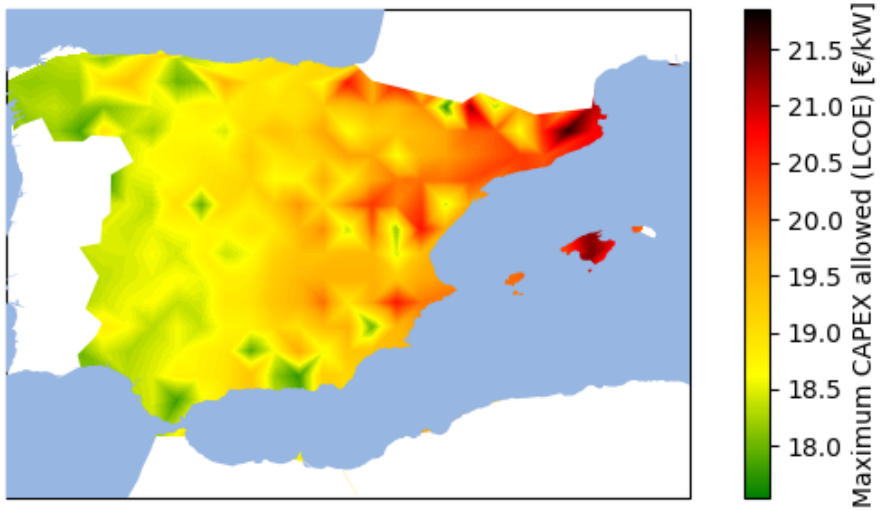


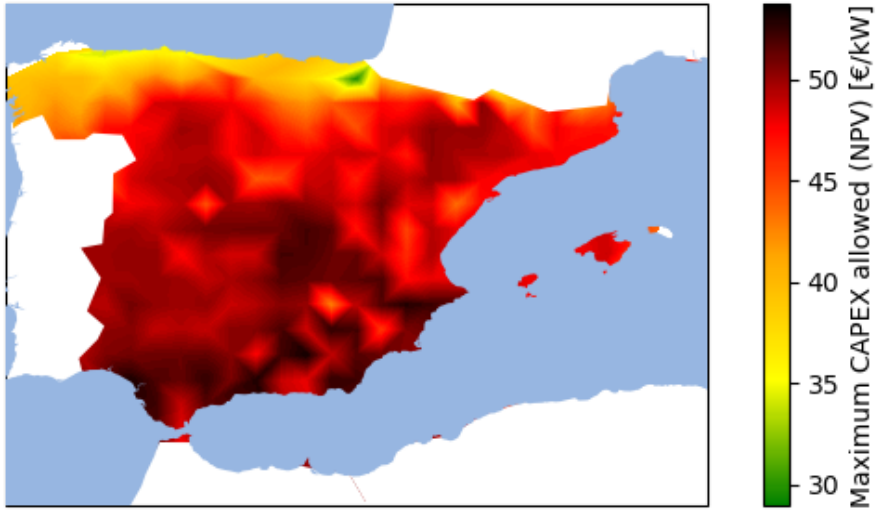
LCOE increases by 1.69 % per % of curtailed energy.
NPV lowers by 2.96 % per % of curtailment.

[1] I. Bonilla-Campos, F.J. Sorbet, D. Astrain, Radical change in the Spanish grid: Renewable energy generation profile and electric energy excess, Sustain. Energy, Grids Networks, 2022.

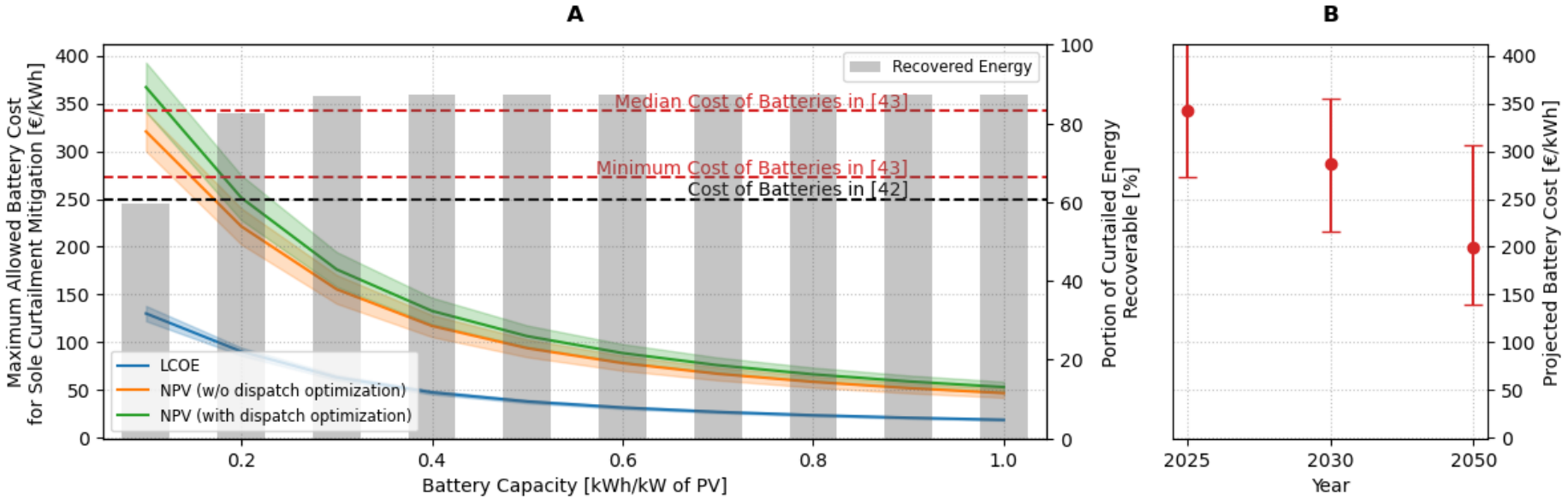
Results: Batteries as mitigation

Maximum additional CAPEX justified by curtailment savings:
19.1 ± 0.8 €/kW (LCOE) vs. **47.0 ± 4.7 €/kW** (NPV)





Results: Economic viability of batteries



Perspective: Impact on soiling

Curtailment masks DC-side losses:
Soiling measurement ≠ Soiling loss

Cleaning ROI ↓

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Soiling estimation is not sufficient: soiling mitigation strategies must now consider grid curtailment.

Introduction of **batteries**

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Reduce curtailed energy

Shift energy dispatch to peak price periods

Conclusions

- Spain lost **~3 %** of PV energy to curtailment (2022–24).
- Losses = **€146 k/day** → +2.5 % LCOE, −7.7 % NPV.
- Every 1 % curtailed → +1.69 % LCOE, −2.96 % NPV.
- **Batteries** can help but not profitable for curtailment alone.
- Need integrated **soiling estimation + market aware** approach for future soiling mitigation planning.

Limitations and future works

- Curtailment considered uniform across the national grid.
- Additional impact related to missed Guarantees of Origin not considered.