Energy MBA • Energy Markets Quantitative Analysis (EMQA)
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Case 6: Probabilistic forecasts and the value of battery arbitrage on the day-ahead market

Based on Andrei, Cepoi, Dumitrescu, Lessmann, Chiriac (Luchian), Pele & Petukhina (2026), *Joint probabilistic forecasting for battery arbitrage in day-ahead power markets*, SSRN 6872381, doi:10.2139/ssrn.6872381

The business question

A Romanian producer with a solar park is offered a battery energy storage system (BESS). The vendor's slide shows the profit a battery *could* have made in 2022. The investment committee must decide: **how much does a battery really earn from buying cheap and selling dear on the day-ahead market (PZU), when it must bid a day ahead without knowing tomorrow's prices — and does that repay the investment?** The trading desk asks a second question: **which hours should the battery bid, and at what prices?**

1 The reference paper

Question. How much arbitrage value can be captured *ex ante* when storage is operated on probabilistic price forecasts, and does it justify the investment, in four interconnected Central and Eastern European (CEE) day-ahead markets (Sections 1 and 3)?

Data. Hourly day-ahead prices of Romania, Bulgaria, Hungary and the Czech Republic, January 2018 – September 2024 (59,160 hours per country), with 37 predictors: load, generation and their forecasts, lagged prices, Brent, TTF and carbon prices, weather and calendar (Section 5.1). Battery: 1 MW / 1 MWh, efficiency 90 %, CAPEX (capital expenditure) 500,000 EUR, 15 years, 7 % discount rate, at most one cycle per day (Section 4).

Method. Distributional Random Forests (DRF) forecast the *joint* distribution of the 96 next-day prices (24 hours × 4 countries), refitted on the last 365 days every 30 days. A quantile-based (QB) rule chooses the buy hour and the sell hour from the forecast medians and places limit bids at forecast quantiles; benchmarks are a fixed pair of hours (NH) and daily perfect foresight (PF-Daily).

Main findings of the paper.

- ⊡ "At $\alpha = 0.8$, QB beats NH in cumulative profit in all four markets, with relative gains of approximately 13 % in Czechia … and 7 % in Romania" (Section 6.2). Romania, January 2019 – September 2024: QB $\alpha = 0.8$ 142,671 EUR, NH 133,230 EUR, PF-Daily 188,249 EUR; payback 20.1 years for QB (Table "single country strategy, RO").
- ⊡ "Under the baseline CAPEX of 500 thousand EUR, none of the strategies is able to cover investment costs" (Section 6.2); break-even CAPEX lies between 48 % and 75 % of the baseline for the QB rule (Section 6.2).
- ⊡ Joint cross-border dispatch adds about 5 % to QB profit (149.9k vs 142.7k EUR for Romania) and 18 % under perfect foresight, "driven by persistent regional price differences" (Abstract; Table "Multi-zone joint-dispatch").
- ⊡ DRF accuracy for Romania: MAE 39.63, RMSE 49.60, CRPS 28.12 EUR/MWh over 70 rolling windows (Table "DRF forecasting performance").

Related work of our group for Lecture 6: Basangova, Bolovăneanu, Conda, Pele et al. (2026), *Day-ahead forecasting*

for redispatch measures using machine learning models, SSRN 7511080, doi:10.2139/ssrn.7511080 — neural networks (NBEATSx, NHiTS, TFT) forecast German redispatch volumes one day ahead better than earlier-generation models (Abstract; Table 4).

2 The method, step by step

Intuition of the method

A battery earns the spread between a cheap hour and an expensive hour, minus the 10 % lost in charging and discharging. Looking back, the best two hours are obvious; looking forward, they are a guess. A probabilistic forecast says not only "the price at 19:00 will be about 150" but "with 80 % probability between 110 and 210" — which tells the trader how aggressively to bid.

Let $p_{d,h}$ be the day-ahead price of hour h on day d and $\eta = 0.9$ the efficiency. Buying 1 MWh in hour h_1 and selling in hour $h_2 > h_1$ earns $\pi_d = \eta\, p_{d,h_2} - p_{d,h_1}/\eta$. *Perfect foresight* takes the best pair each day (an upper bound); *fixed hours* use one pair, chosen *ex ante* as the best pair on average over the previous year (the 365 days before 8 January 2019 for the 2019–2024 window, the year 2024 for 2025–2026), and trade every day. The random forest gives each past day i a weight $w_i(\mathbf{x}_d)$ — the share of trees in which day i falls in the same leaf as tomorrow's conditions $\mathbf{x}_d$ — so the forecast is a whole distribution of 24-hour price vectors, and its quantiles $\hat{Q}_{\tau,d,h}$ are weighted quantiles. The forecast-based rule picks $h_1 < h_2$ maximising $\eta\hat{Q}_{0.5,d,h_2} - \hat{Q}_{0.5,d,h_1}/\eta$, trades only if this is positive, and bids to buy at $\hat{Q}_{1-q,d,h_1}$ and to sell at $\hat{Q}_{q,d,h_2}$, with $q = (1-\alpha)/2$: a larger α means safer bids that clear more often. Investment: annual profit $\bar{\pi}_{ann} = 365\,\bar{\pi}_d$, NPV $= -\text{CAPEX} + \sum_{t=1}^{15} \bar{\pi}_{ann}/1.07^t$, payback $= \text{CAPEX}/\bar{\pi}_{ann}$. Forecast quality: CRPS (continuous ranked probability score) $= \sum_i w_i|y_i - y| - \frac{1}{2}\sum_{i,k} w_i w_k |y_i - y_k|$, in EUR/MWh; lower is better.

In practice

Value the battery on what a forecast-driven strategy earns, never on perfect foresight. Then compare the annual profit with the 54,897 EUR per year needed to repay 500,000 EUR in 15 years at 7 %.

3 Replication on the course data

Notebook `C6_notebook_EN.ipynb`: hourly day-ahead prices of RO, BG and HU (energy-charts.info), CET hours; the paper's test window 8 January 2019 – 30 September 2024 (2,087 days) and an extension to October 2026. Classroom implementation: a standard random forest with leaf weights instead of DRF; only lagged prices and calendar as predictors; no Czech data; a simplified battery state (empty/full) instead of the paper's three-level rule.

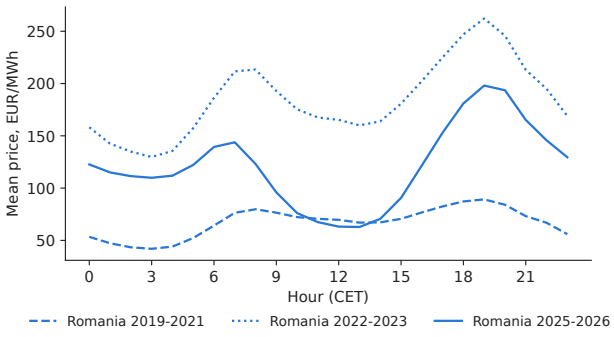


Figure 1: Mean hourly price shape in Romania, three periods.

Source: energy-charts.info; 2019–Oct 2026.

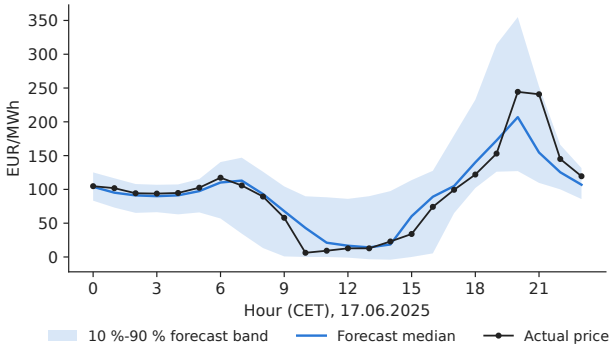


Figure 2: A probabilistic forecast of tomorrow's 24 prices.

Source: our random forest; energy-charts.info.

Forecast quality. Over the paper's window our forest has MAE 26.50, RMSE 48.46 and CRPS 19.71

EUR/MWh (paper's DRF: 39.63, 49.60, 28.12 — different predictors and averaging), and its 10 %–90 % band covers 80.9 % of hours (target 80 %). Note: the naive "same hour yesterday" has MAE 25.59, so our point forecast adds little; its value is in the *distribution*, which sets the bids.

Table 1: Battery strategies in Romania, 1 MW / 1 MWh, 8 Jan 2019 – 30 Sep 2024, and annual profit in 2025–Oct 2026. Best realistic or overall value in bold.

Strategy (1 MW / 1 MWh, Romania)	Profit 2019–2024, EUR	EUR/year	NPV, EUR	Payback, yrs	Both bids, %	EUR/year 2025–2026
Perfect foresight (daily, ex post)	189,816	**33,197**	**−197,642**	**15.1**	–	**52,717**
Fixed hours (chosen on the previous year) 03→19	130,324	22,793	−292,406	21.9	–	39,447
Forecast-based, $\alpha = 0.0$	68,333	11,951	−391,152	41.8	15.4	22,317
Forecast-based, $\alpha = 0.4$	103,163	18,042	−335,672	27.7	43.1	32,757
Forecast-based, $\alpha = 0.8$	126,569	22,136	−298,388	22.6	76.0	40,858

Source: our computation; CAPEX 500,000 EUR, 15 years, 7 %. Paper (RO, same window): PF-Daily 188,249; NH 133,230; QB α=0.8 142,671 EUR.

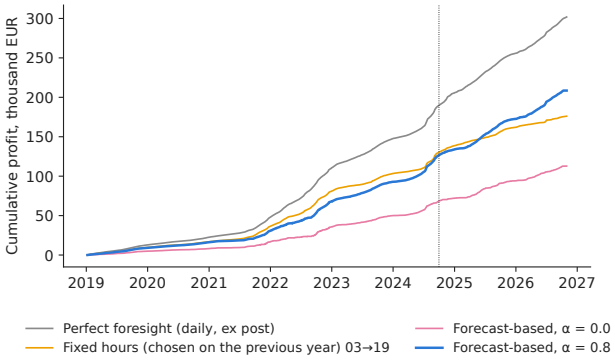


Figure 3: Cumulative profit by strategy; dotted: end of the paper's window.

Source: our computation; energy-charts.info, 2019–Oct 2026.

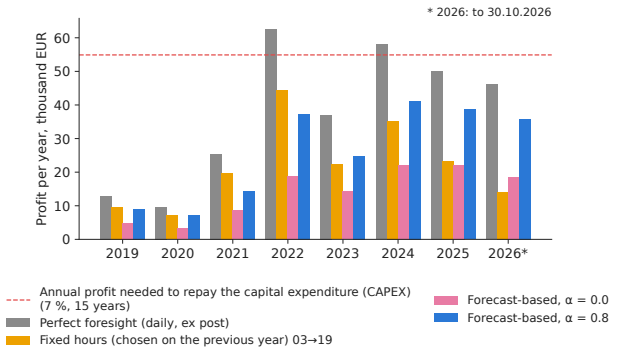


Figure 4: Profit per year vs the annual profit needed to repay the battery.

Source: our computation; 2026 = January–October.

What our data show. Our perfect-foresight profit, 189,816 EUR, and our fixed-hours profit, 130,324 EUR (hours 03:00→19:00 CET), are close to the paper's 188,249 and 133,230 EUR. Our forecast-based rule with $\alpha = 0.8$ earns 126,569 EUR (−2.9 % vs fixed hours), below the paper's 142,671: with only past prices as predictors, our forecasts cannot beat the fixed schedule, whereas the paper's DRF with fundamentals beats it by 7 %. Safe bids matter: $\alpha = 0$ earns only 68,333 EUR, because aggressive bids rarely clear (both bids accepted on 76.0 % of days at $\alpha = 0.8$). Cross-border, the best of the RO/BG/HU routes adds 10.7 % to the perfect-foresight profit; the most frequent cross-border route is BG→RO. **Decision number:** 2019–2024, the realistic strategy earned 22,136 EUR/year against 54,897 needed (NPV −298,388 EUR, payback 22.6 years) — not viable, as in the paper. In 2025–2026, with deeper solar middays (the fixed pair chosen on 2024 is 12:00→19:00), it earns 40,858 EUR/year (payback 12.2 years): closer, but still below the threshold without balancing or capacity revenues.

4 Discussion questions for managers

1. The vendor shows the perfect-foresight profit. By how much would you discount it, and why?
2. The fixed pair chosen on the previous year moved from night→evening to midday→evening. What does that tell you about the value of co-locating a battery with your solar park?
3. Which other revenues (balancing, frequency reserves, capacity payments, grid-fee savings) would you add to close the gap, and how certain are they?
4. Why do safer bids ($\alpha = 0.8$) earn more than aggressive ones? What does this say about trading on point forecasts?
5. At what CAPEX would the battery be viable on 2025–2026 prices? Is that a realistic price trend?

5 Limitations of the classroom replication

(i) We leave out cross-border fees, congestion, intraday and balancing markets, and price impact. (ii) One cycle per day and 1 MWh: real projects use 2–4 hour batteries and several revenue streams. (iii) Perfect foresight is chosen ex post and is an upper bound; the fixed hours (chosen on the previous year) and the forecast-based rule are achievable. (iv) No degradation cost and no grid tariffs (a few lei/MWh in Romania). (v) Our forecasts use no fundamentals; the paper's DRF uses 37 predictors.

Summary of Case 6

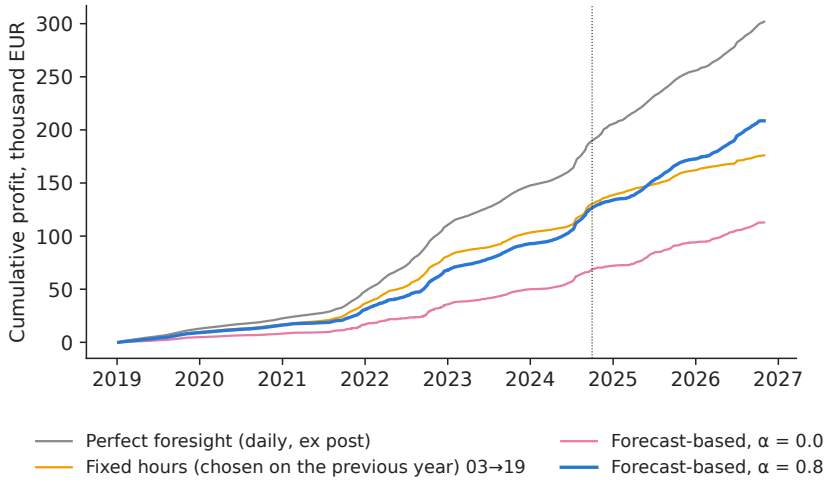
Question
Does day-ahead arbitrage repay a 1 MW / 1 MWh battery when bids are set a day ahead?

Data
Hourly RO, BG, HU prices, 2019–Oct 2026; paper's window 2019–Sep 2024.

Method
Random-forest probabilistic forecasts; quantile bids; fixed hours and perfect foresight as benchmarks; NPV.

Result
Realistic: 22,136 EUR/yr (2019–2024), 40,858 (2025–2026); needed 54,897.

Decision
Not viable on arbitrage alone at 500k EUR CAPEX; stack revenues or wait for cheaper batteries.



Source: our computation on energy-charts.info prices, 2019–Oct 2026.

189,816
EUR, perfect foresight 2019–2024 (paper 188,249)

22.6
years payback, realistic strategy

−298,388
EUR NPV at 500k CAPEX