






Energy Markets Quantitative Analysis

Lecture 6: Renewables and Storage: Cannibalisation, Negative Prices and Batteries




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Learning objectives

- **Merit order**
  - Measure how much zero-cost solar and wind lower the price of the Romanian day-ahead market (PZU)
  - On the real order book and with a regression on hourly data
- **Capture price and capture rate**
  - The price a solar or wind MWh actually earns, compared with the average price
  - Cannibalisation: the more solar, the lower its own price
- **Negative prices and the daily price shape**
  - Count negative prices in hour-equivalents; value switching a park off
  - Read the 15-minute daily profile
- **Batteries**
  - Arbitrage revenue of 1-, 2- and 4-hour batteries from a linear programme (LP)
  - Perfect foresight vs forecast rules, hourly vs 15-minute prices, Romania vs neighbours

Abbreviations

AI	artificial intelligence
BG	Bulgaria (bidding zone)
CET	Central European Time
CP	capture price
CR	capture rate (value factor)
DE-LU	Germany–Luxembourg bidding zone
ENTSO-E	European Network of Transmission System Operators for Electricity
EPEX	EPEX SPOT power exchange
EUR	euro
GW	gigawatt = 1 000 MW
HAC	heteroskedasticity- and autocorrelation-consistent (standard errors)
HU	Hungary (bidding zone)
HUPX	Hungarian Power Exchange
IBEX	Independent Bulgarian Energy Exchange
ISE	Fraunhofer Institute for Solar Energy Systems
kW	kilowatt
kWh	kilowatt-hour
LP	linear programme
MTU	market time unit
MW	megawatt
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory (United States)
OLS	ordinary least squares
OPCOM	Romanian electricity and gas market operator
PPA	power purchase agreement
PZU	Piața pentru Ziua Următoare (day-ahead market)
RO	Romania (bidding zone)
SDAC	Single Day-Ahead Coupling
SE	standard error
TWh	terawatt-hour
XML	Extensible Markup Language (data file format)

Data sources: prices, generation, order books and installed capacity

Series	Frequency	Source
Day-ahead prices: Romania (RO), Bulgaria (BG), Hungary (HU), Germany–Luxembourg (DE-LU)	hourly; 15-min from 1 Oct 2025	Romanian market operator (OPCOM), Independent Bulgarian Energy Exchange (IBEX), Hungarian Power Exchange (HUPX), European Power Exchange (EPEX SPOT); via energy-charts.info (Fraunhofer ISE)
Solar, wind, battery output, load	RO, HU 15-min; BG hourly	European Network of Transmission System Operators for Electricity (ENTSO-E); Transelectrica data for RO
PZU supply and demand curves	2 quarter-hours	OPCOM, Extensible Markup Language (XML) files
Installed capacity	yearly	ENTSO-E via energy-charts.info

- **Period**: 2019 – 31 Oct 2026, the last complete month
  - 2026 = Jan–Oct 2026; "last 12 months" = Nov 2025 – Oct 2026
  - Delivery days in Central European Time (CET)
- **Conventions**
  - Energy = mean MW × duration; a 15-minute market time unit (MTU) counts 0.25 h

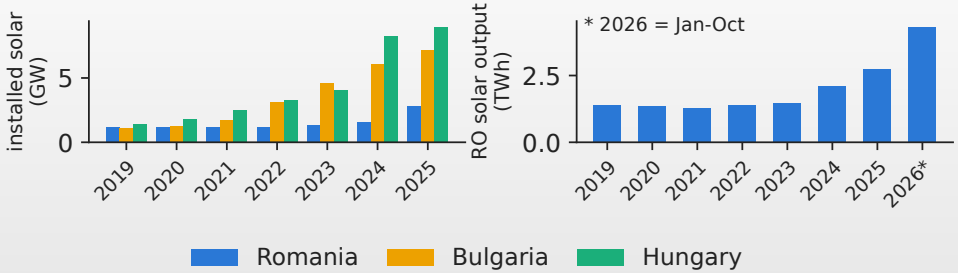
(data/SOURCES.md; data/download_L6.py)

Experiment yourself: notebook §1

Outline

- Renewables and the merit order
  - Growth of solar generation
  - The merit-order effect
  - Renewables and the grid: redispatch
- Capture prices and cannibalisation
- Negative prices
- Intraday shape and price spreads
- The economics of a battery
- Case studies: Apr 2026 and summer 2026

Installed solar in Romania grew 2.4 times from 2019 to 2025



Source: energy-charts.info (Fraunhofer ISE), installed capacity from ENTSO-E; ENTSO-E solar output (Transelectrica data). Data: installed capacity at year end 2019-2025; output 2019 to 2026-10-31.

- **Romanian solar output, Jan–Oct**: 2.53 TWh in 2025, 4.32 TWh in 2026
  - 2.3% of load in 2019, 10.2% in 2026; neighbours: Bulgaria 7.2 GW, Hungary 9.0 GW

- **In practice:** a new solar park sells in the same sunny hours as every park already built, here and next door.

(ENTSO-E; metered output may omit rooftop panels)

EMQA_L6_solar_growth

Zero-cost supply shifts the supply curve right and lowers the clearing price

- **In one sentence:** Solar and wind bid near zero, so dearer offers move right and the crossing with demand slides down.

$$S(p) + X \cdot \mathbf{1}[p \geq 0] = D(p) \;\Rightarrow\; p^*(X)$$

$$\frac{\mathrm{d}p^*}{\mathrm{d}X} = -\frac{1}{S'(p^*) - D'(p^*)}$$

- **where**
  - $S(p)$ = MW offered at prices $\leq p$
  - $D(p)$ = MW bid at prices $\geq p$
  - X = extra MW offered at 0 EUR/MWh
  - S', D' = slopes of the curves (MW per EUR/MWh).

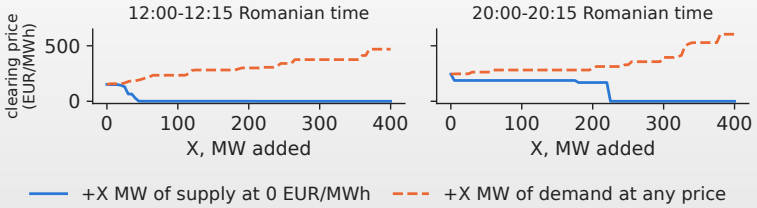
- **Reading the formula**
  - Flat curves around the price: small effect
  - Steep curves: large effect
- **OPCOM, 21 Oct 2026, 12:00–12:15**
  - Price 152.23 EUR/MWh
  - Only 34 MW offered between 1 EUR/MWh and that price

- **In practice:** the steeper the local curve, the more a new park moves its own price.

(Sensfuß, Ragwitz & Genoese, 2008, ENPOL)

Experiment yourself: notebook §2

Romanian order book: 40 MW more at zero price lowers the midday price below 50 EUR/MWh



Source: OPCOM, PZU aggregated curves (XML), own computation. Data: delivery day 2026-10-21; cross-border flows, blocks and hourly orders held at their accepted values.

- **Midday**: +25 MW at zero price, 152.23 → 131.40 EUR/MWh
  - Evening: 1 054 MW of net imports deepen the curve; 225 MW are needed for the same fall
  - Flows held fixed, so this is an upper bound for the coupled market

- **In practice:** for Transelectrica: interconnectors, not local plants, give the midday price its depth.

(OPCOM aggregated curves; own computation)

EMQA_L6_merit_shift

In the coupled market, 1 GW more solar lowers the Romanian price by about 27 EUR/MWh

- **In one sentence:** Within the same month and clock hour, sunnier and windier hours are cheaper; the regression measures by how much.

$$P_t = \underbrace{\alpha_{m(t)} + \gamma_{h(t)} + \delta_{w(t)}}_{\text{fixed effects}} + \beta_L L_t + \beta_W W_t + \beta_S S_t + \varepsilon_t$$

- **where**
  - P_t = hourly price (EUR/MWh), L_t, W_t, S_t = load, wind, solar (GW)
  - α, γ, δ = constants per month (fuel, carbon), clock hour and weekday, estimated by ordinary least squares (OLS).

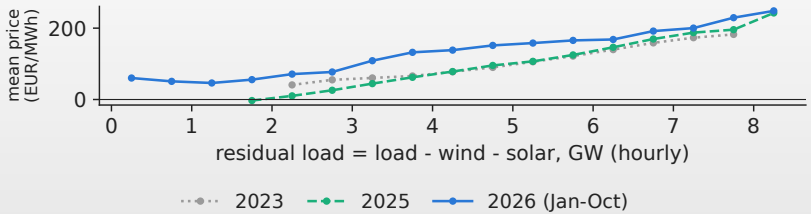
- **Estimates**, 33 600 hours, 2023 – Oct 2026, $R^2 = 0.65$
  - EUR/MWh per GW: solar -26.7, wind -15.3, load $+40.7$
  - Standard error (SE) of solar 2.2, heteroskedasticity- and autocorrelation-consistent (HAC)
- **At midday in 2026**
  - 1.62 GW of solar: -43.3 EUR/MWh, an association, not a causal effect

- **In practice:** a supplier buying midday blocks should expect them cheaper on sunny days, by about this amount.

(Cludius et al., 2014, ENEECO; Würzburg et al., 2013, ENEECO)

Experiment yourself: notebook §3

Price rises with residual load; hours below 2 GW of residual load reached 9.0% in 2026



Source: energy-charts.info (Fraunhofer ISE); OPCOM prices; ENTSO-E solar, wind and load (Transelectrica data for Romania).
Data: hourly, 2023-01-01 to 2026-10-31; bins of 0.5 GW with at least 20 hours.

- **Residual load** = load − wind − solar, the demand left for other plants and imports
  - +1 GW raises the price by 28.3 EUR/MWh (SE 0.9), same fixed effects
  - Hours below 2 GW: 0.1% in 2023, 9.0% in 2026

- **In practice:** a hydro producer saves water for high residual load, where each GW is worth most.

(own computation)

EMQA_L6_resid_price

Research from our group: machine learning forecasts German redispatch one day ahead

- **Why redispatch**: wind in the north, demand in the industrial south of Germany
  - After the day-ahead market, transmission system operators order plants up or down to keep lines within limits
- **What the work did**: forecast the hourly redispatch volume (MW), up and down, of the four German operators
  - 24 h ahead, with what is known on the afternoon of $d - 1$: wind, solar, load, price spreads, scheduled exchanges
  - Data Oct 2021 – Feb 2026; 11 monthly test windows, Mar 2025 – Feb 2026
- **What it found**: deep neural networks are most often among the best models
  - The best of them is in the model confidence set (mean absolute error) for 6 of the 8 series
  - Covariates help only when aligned in time: significantly better forecasts in 40–60% of the dense series

- **In practice:** for Transelectrica: forecast where wind and solar will meet the limits of the grid, a day ahead.

(Basangova, Bolovăneanu, Conda, Erlwein-Sayer, Melzer, Pele, Petukhina & Phan, 2026, talk at AIDA 2026 (AI and Digital Assets in Energy and Finance), Bucharest, 3 June 2026: slides)

Outline

- Renewables and the merit order
- Capture prices and cannibalisation
  - Definitions
  - Capture rates in Romania by year
  - Cannibalisation
- Negative prices
- Intraday shape and price spreads
- The economics of a battery
- Case studies: Apr 2026 and summer 2026

The capture price is the average price weighted by the plant's own output

- **In one sentence:** A solar park is paid the price of the intervals in which it produces, not the average of all intervals.

$$\mathrm{CP} = \frac{\sum_t P_t G_t \Delta_t}{\sum_t G_t \Delta_t}, \qquad B = \frac{\sum_t P_t \Delta_t}{\sum_t \Delta_t}$$

$$\mathrm{CR} = \frac{\mathrm{CP}}{B} = 1 + \frac{\mathrm{Cov}_\Delta(P, G)}{\bar{P}\,\bar{G}}$$

- **where**
  - Capture price (CP), baseload price B, capture rate (CR)
  - P_t = price, G_t = output (MW), Δ_t = 1 h or 0.25 h, Cov_Δ = duration-weighted covariance (Appendix A).

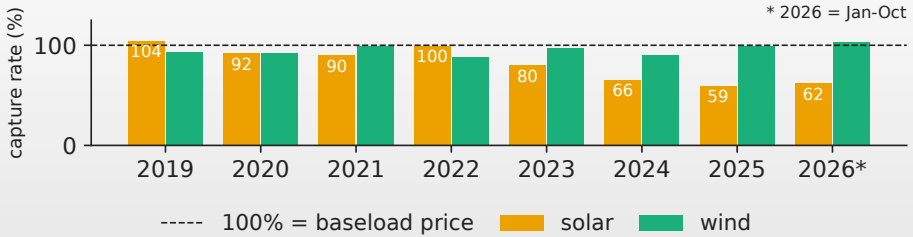
- **Romanian solar, Jan–Oct 2026**
  - CP 85.0, B 137.5 EUR/MWh; CR 61.9%
  - Correlation of price and output −0.43: this pulls CR below 1
- **Romanian wind, same period**
  - CR 103.0%: wind also blows at night and in winter

- **In practice:** price a solar power purchase agreement (PPA) on the capture price, not on the baseload price.

(Hirth, 2013, ENEECO; Hirth, Ueckerdt & Edenhofer, 2016, Energy J.)

Experiment yourself: notebook §4

Solar's capture rate in Romania fell from 104% in 2019 to 59% in 2025



Source: energy-charts.info (Fraunhofer ISE); OPCOM prices; ENTSO-E solar, wind and load (Transelectrica data for Romania).
Data: 2019 to 2026-10-31; hourly to Sep 2025, 15-min from Oct 2025.

- **Solar**: the fall starts in 2023, with the growth of output
  - 2026: 61.9%, while output rose 71% on the same months of 2025
  - Wind: between 88% and 103%, no trend, because wind output did not grow

In practice: a bank lending to a solar project should multiply the baseload price by the capture rate.

(own computation)

EMQA_L6_capture_rates

In 2025 a Romanian solar MWh earned 43.9 EUR less than the baseload price

Year	B	Solar CP	Solar CR, %	$B - \mathrm{CP}$	Wind CP	Wind CR, %	Solar TWh	Wind TWh
2019	50.4	52.7	104.5	−2.3	47.2	93.6	1.37	6.68
2020	39.5	36.4	92.2	+3.1	36.6	92.6	1.34	6.89
2021	111.4	100.6	90.3	+10.8	111.0	99.6	1.29	6.44
2022	265.3	264.0	99.5	+1.3	234.4	88.4	1.37	6.92
2023	103.7	83.2	80.2	+20.6	101.0	97.4	1.46	7.45
2024	103.5	68.0	65.7	+35.5	93.4	90.2	2.09	6.34
2025	108.2	64.2	59.4	+43.9	106.7	98.7	2.72	5.88
2026*	137.5	85.0	61.9	+52.4	141.6	103.0	4.32	5.27

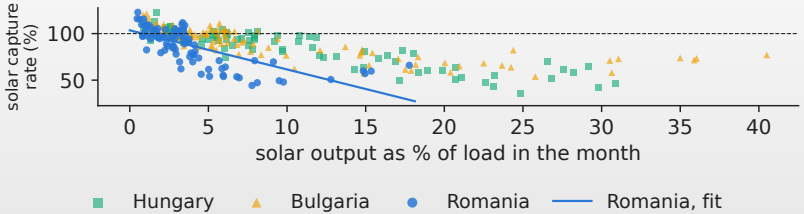
- **Reading the table**: B, CP in EUR/MWh; green = CR close to 100%, red = far below
  - * 2026 = Jan–Oct 2026; 2022 = energy crisis, all prices high

- **In practice:** the gap $B - \mathrm{CP}$ is a cost borne by the solar developer
  - It grew every year since 2022.

(own computation)

Experiment yourself: notebook §4

When solar's share of monthly load rises by one point, the solar capture rate falls by about 4.2 points



Source: energy-charts.info (Fraunhofer ISE); day-ahead prices (OPCOM, IBEX, HUPX); ENTSO-E solar output and load. Data: monthly, 2019-01 to 2026-10; Hungary from Oct 2019.

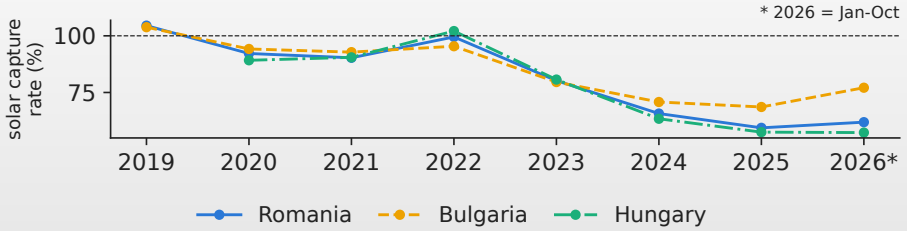
- **Regression** $\mathrm{CR}_m = a + b\,s_m + u_m$, s_m = solar output as % of load in month m
  - Romania: $\hat{b} = -4.20$ (SE 1.03), $R^2 = 0.53$, 94 months
  - Hungary -2.14, Bulgaria -1.32: Romanian prices also fall with the neighbours' solar

- **In practice:** forecast regional solar, not only Romanian solar, to forecast a park's revenue.

(López Prol, Steininger & Zilberman, 2020, ENEECO)

EMQA_L6_cannibal

Regional cannibalisation: Romanian, Bulgarian and Hungarian capture rates fell in step



Source: energy-charts.info (Fraunhofer ISE); day-ahead prices (OPCOM, IBEX, HUPX); ENTSO-E solar output and load. Data: 2019 (Hungary 2020) to 2026-10-31; Bulgaria: hourly solar output.

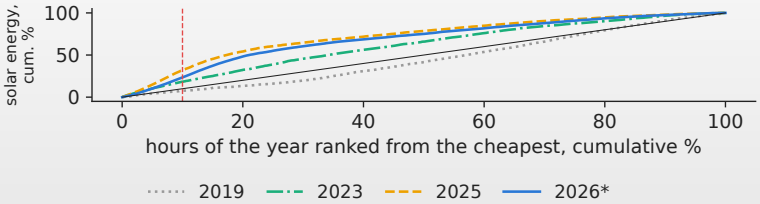
- **2025**: Romania 59.4%, Bulgaria 68.6%, Hungary 57.5%
  - 2026: Bulgaria rises to 77.1% as its battery fleet grows, an association, not a proof

- **In practice:** batteries charging at midday raise the price solar sells at: solar gains from other people's batteries.

(own computation; Bulgarian output is hourly)

EMQA_L6_capture_region

In 2025, 32.1% of Romanian solar output was sold in the cheapest 10% of hours



Source: energy-charts.info (Fraunhofer ISE); OPCOM prices; ENTSO-E solar, wind and load (Transelectrica data for Romania). Data: each calendar year; 2026 to 2026-10-31.

- **Reading**: hours ranked from the cheapest; the curve = share of the year's solar energy produced up to that rank
  - 2019: 7.6%; 2025: 32.1%; 2026: 23.4%; at zero or negative prices: 9.6% of 2025 output

- **In practice:** as announced in Lecture 1: a solar park without storage sells much of its output in the cheapest hours of the year.

(own computation) EMQA_L6_cheap_hours

Outline

- Renewables and the merit order
- Capture prices and cannibalisation
- Negative prices
- Intraday shape and price spreads
- The economics of a battery
- Case studies: Apr 2026 and summer 2026

A producer bids below zero when stopping costs more than paying to produce

- **In one sentence:** The bid is the cost of one more MWh minus what the plant earns or saves only by running.

$$b_i = c_i - s_i - k_i, \qquad h^- = \sum_t \Delta_t \, \mathbf{1}[P_t < 0]$$

- **where**
  - b_i = offer of plant i (EUR/MWh), c_i = marginal cost
  - s_i = support paid per MWh produced, k_i = restart cost per MWh of a stop
  - h^- = negative hours in hour-equivalents.

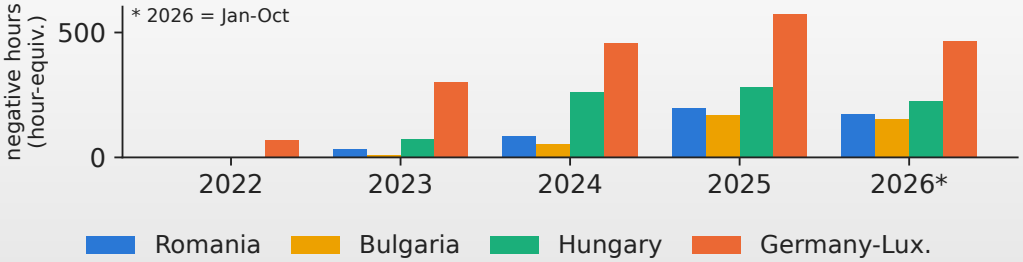
- **Who bids below zero**
  - Output paid per MWh by a support scheme or contract
  - Nuclear and run-of-river hydro, which cannot stop cheaply
- **Romania, 2025**
  - 196 negative hours; mean negative price -10.5 EUR/MWh
  - Lowest 2026 price: -99.75 EUR/MWh

- **In practice:** a merchant solar park has $b_i \approx 0$: it should stop as soon as the price turns negative.

(Fanone, Gamba & Prokopczuk, 2013, ENEECO)

Experiment yourself: notebook §5

Romania had 196 negative hours in 2025, Germany 575



Source: energy-charts.info (Fraunhofer ISE); day-ahead prices of OPCOM (RO), IBEX (BG), HUPX (HU), EPEX SPOT (DE-LU), via ENTSO-E. Data: 2022 to 2026-10-31; a 15-min interval counts 0.25 h.

- **Jan–Oct, 2025 vs 2026**: Romania 196 → 171.75 h, Hungary 281 → 223.5 h
  - Fewer despite more solar; possible reasons: a higher price level, more batteries charging at midday

In practice: a supplier with flexible industrial clients can be paid to consume in these hours.

(own computation; counting rule of Lecture 1)

EMQA_L6_neg_hours

Revenue losses: low positive midday prices cost more than negative prices

- **In one sentence:** A merchant park gains $|P_t|$ for each MWh it does not produce at a negative price; such MWh are few.

$$g = \frac{\sum_t \max(0, -P_t)\, G_t \Delta_t}{\sum_t G_t \Delta_t} \quad \text{vs} \quad B - \mathrm{CP}$$

- **where**
  - G_t = solar output (MW)
  - g = gain per MWh of yearly output if the park stops in every negative interval
  - $B - \mathrm{CP}$ = profile discount.

- **Romanian solar, 2025**
  - 6.2% of output at negative prices, costing 1.71 million EUR
  - $g = 0.63$ against $B - \mathrm{CP} = 43.9$ EUR/MWh
- **2026**
  - 4.0% of output; $g = 0.35$ EUR/MWh

- **In practice:** install remote switch-off because it is cheap, but value a park on its capture price.

(own computation)

Experiment yourself: notebook §5

Quarter-hours reveal 26 negative prices hidden inside hours with a non-negative average

- **Since the 15-minute MTU of the Single Day-Ahead Coupling (SDAC)**, 1 Oct 2025
  - 687 negative quarter-hours in Romania = 171.75 hour-equivalents
  - 26 of them (3.8%) fall in hours whose average is zero or positive
- **Why it matters**
  - Hourly averages show only 195 negative hours
  - A battery or flexible load acting per quarter-hour can use them; a park metered per quarter-hour pays them
- **Counting rule**
  - $h^- = \sum_t \Delta_t \mathbf{1}[P_t < 0]$, $\Delta_t = 0.25$ h: never count a quarter-hour as an hour

In practice: set switch-off and battery logic on the 15-minute grid, as the market now is.

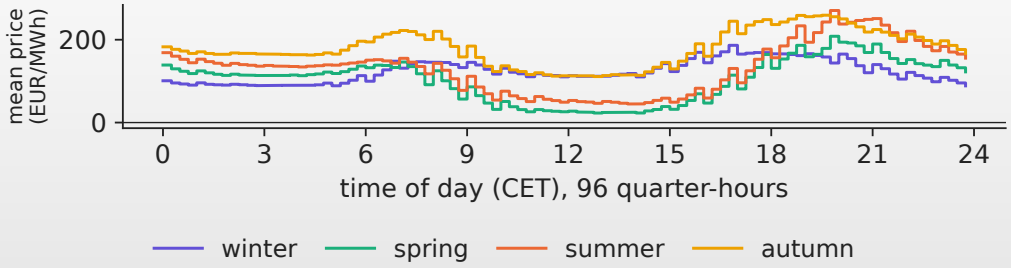
(NEMO Committee, 2025; own computation)

Experiment yourself: notebook §5

Outline

- Renewables and the merit order
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- The economics of a battery
- Case studies: Apr 2026 and summer 2026

Spring quarter-hour prices: 23.0 at midday, 208.3 EUR/MWh in the evening



Source: energy-charts.info (Fraunhofer ISE); OPCOM day-ahead prices for Romania, via ENTSO-E. Data: last 12 months 2025-11-01 to 2026-10-31, 15-min prices, CET; winter = Dec-Feb, spring = Mar-May, summer = Jun-Aug, autumn = Sep-Nov.

- **The solar valley**: spring minimum at 12:45, maximum at 19:45 CET
  - Maximum minus minimum: spring 185, summer 226, winter only 98 EUR/MWh

In practice: a battery charges in the valley and discharges on the evening ramp: the gap is its gross margin.

(own computation, last 12 months (Nov 2025 – Oct 2026))

EMQA_L6_shape15

A battery earns the spread between dear and cheap hours, minus its losses

- **In one sentence:** Buy a MWh when it is cheap; sell what survives the round trip when it is dear.

$$S_d^{(k)} = \bar{P}_d^{\text{top } k} - \bar{P}_d^{\text{bot } k}$$
$$\pi_d \approx k \left(\eta \bar{P}_d^{\text{top } k} - \bar{P}_d^{\text{bot } k} \right)$$

- **where**
  - $\bar{P}_d^{\text{top } k}$, $\bar{P}_d^{\text{bot } k}$ = mean price of the k dearest and cheapest hours of day d, k = hours of storage
  - η = round-trip efficiency (85%), π_d = gross margin of one cycle, 1 MW (EUR).

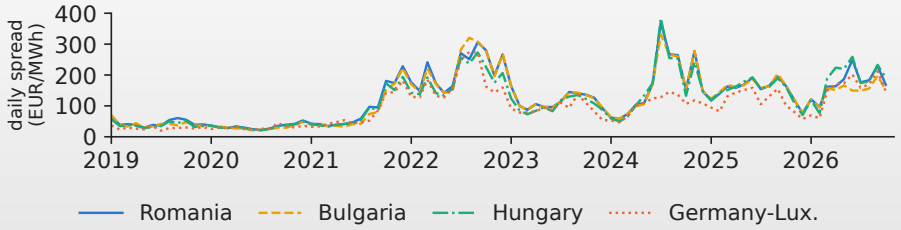
- **Romania, $k = 2$, mean daily spread**
  - 45 EUR/MWh in 2019, 151 in 2025, 174 in 2026
- **Losses set a threshold**
  - Buying at 50 EUR/MWh, it must sell above $50/0.85 \approx 59$ EUR/MWh

- **In practice:** a battery developer reads the business case from the daily spread, before any model.

(Sioshansi et al., 2009, ENEECO)

Experiment yourself: notebook §6

The daily spread is about four times its 2019 level and similar in Romania, Bulgaria and Hungary



Source: energy-charts.info (Fraunhofer ISE); day-ahead prices of OPCOM (RO), IBEX (BG), HUPX (HU), EPEX SPOT (DE-LU), via ENTSO-E. Data: daily, hourly prices (15-min averaged), monthly means, 2019 to 2026-10-31.

- **Dearest 2 minus cheapest 2 hours, 2026**: Romania 174, Bulgaria 150, Hungary 187, Germany 152 EUR/MWh
  - Coupled markets: every battery in the region competes for the same spread

- **In practice:** treat the spread as a regional resource, shared with every new battery next door.

(own computation)

EMQA_L6_spreads

Outline

- Renewables and the merit order
- Capture prices and cannibalisation
- Negative prices
- Intraday shape and price spreads
- The economics of a battery
  - The optimal schedule
  - Probabilistic forecasts for trading
  - 15-minute prices, self-cannibalisation and regional competition
- Case studies: Apr 2026 and summer 2026

The best daily schedule of a battery solves a small linear programme

In one sentence: Choose when to charge and discharge to maximise revenue, within the battery's physical limits.

$$\max_{c,\,x} \sum_t P_t\,(x_t - c_t)\,\Delta_t$$
$$e_t = e_{t-1} + \left(\sqrt{\eta}\,c_t - x_t/\sqrt{\eta}\right)\Delta_t$$
$$0 \le e_t \le E,\ e_0 = e_T = 0,\ 0 \le c_t, x_t \le 1,\ \sum_t x_t \Delta_t \le \sqrt{\eta} E$$

where

- c_t, x_t = charging, discharging power (MW)
- e_t = stored energy (MWh)
- $E = 1$, 2 or 4 MWh
- $\eta = 0.85$
- Last constraint: at most one cycle a day (Appendix B).

Assumptions

- 85% round trip, one cycle a day: National Renewable Energy Laboratory (NREL) reference
- No capacity fade, fees or balancing revenue

Two information sets

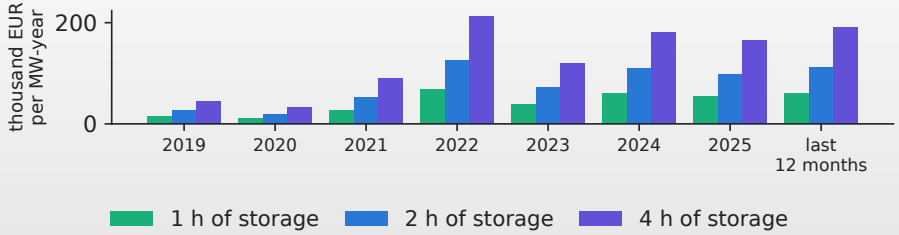
- Perfect foresight: prices known, an upper bound
- Forecast rule: optimise on a forecast, get paid real prices

In practice: this programme, with your own prices and limits, is the core of every battery dispatch tool.

(Cole & Karmakar, 2023, NREL)

Experiment yourself: notebook §7

With perfect foresight, a 2-hour battery earned 111.2 thousand EUR per MW in the last 12 months



Source: energy-charts.info; day-ahead prices via ENTSO-E; ENTSO-E battery output (BG, RO); own optimisation. Data: 1 MW, round trip 85%, max one cycle a day; 2019-2025 and last 12 months 2025-11-01 to 2026-10-31.

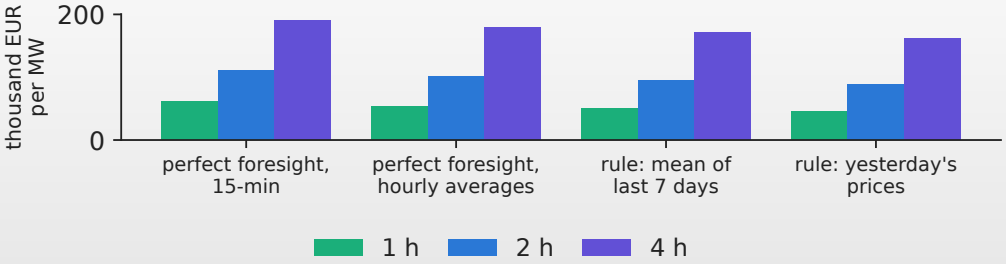
- **2 hours, thousand EUR per MW-year**: 26.3 (2019), 125.0 (2022), 98.7 (2025)
  - 4 hours earn 1.72 times what 2 hours earn: the third and fourth hours trade a smaller spread

- **In practice:** size the battery on the revenue of each extra MWh of storage, not on total revenue.

(own computation; day-ahead prices only)

EMQA_L6_bat_years

A simple 7-day rule earns 85% of the 2-hour perfect-foresight revenue



Source: energy-charts.info; day-ahead prices via ENTSO-E; ENTSO-E battery output (BG, RO); own optimisation. Data: last 12 months 2025-11-01 to 2026-10-31; 1 MW, round trip 85%; forecast rules on 361 common days, scaled to the full period.

- **Rules known at 12:00 CET on** $d-1$: mean profile of the last 7 days, 82%, 85%, 89% (1, 2, 4 h)
  - Yesterday's prices: 75%, 79%, 84%; longer batteries forgive timing errors

- **In practice:** budget on a rule you can actually run: a better forecast (Lecture 2) closes part of the gap.

(own computation, last 12 months (Nov 2025 – Oct 2026))

EMQA_L6_bat_rules

Forecasting the whole price distribution helps a battery bid

- **What the work did**: forecast the joint next-day distribution of 96 hourly prices (24 h × Romania, Bulgaria, Hungary, Czechia)
  - Distributional random forest, 37 predictors, Jan 2018 – Sep 2024; 70 rolling windows: 365 days to train, the next 30 to test
  - The median picks the charge hour and the later discharge hour; quantiles set the buy and sell limit prices
- **What it found**: forecast errors peak at 17:00–18:00, usually the discharge hours
  - Romania, cumulative profit of a 1 MW / 1 MWh battery: 143.0 thousand EUR with the quantile rule, 133.2 with fixed hours, 188.2 with perfect foresight
  - The quantile rule beats the fixed-hour rule in all four markets; trading across markets adds value (150.3 thousand EUR)
- **Investment**: with 500 000 EUR upfront, 90% efficiency, 15 years and 7%, day-ahead arbitrage alone does not cover it

- **In practice:** bid from forecast quantiles, not from a single price forecast: the hours that pay are in the tails.

(Andrei, Cepoi, Dumitrescu, Lessmann, Luchian, Pele & Petukhina, 2026, doi:10.2139/ssrn.6872381; talk by C. O. Cepoi at AIDA 2026, Bucharest, 3 June 2026: slides)

15-minute prices raised a 1-hour battery's revenue by 14.5% on the same days

⊡ **In one sentence:** Any hourly schedule can be run on quarter-hours, so finer prices can only add revenue.

$$R^{15} = \max_{c,x} \sum_t P_t^{15}(x_t - c_t)\tfrac{1}{4} \;\geq\; R^{60}$$

⊡ **where**

- R^{15} = optimal revenue on the 96 quarter-hour prices P_t^{15}
- R^{60} = optimal revenue when each hour is paid the mean of its quarters
- Same days, so the difference is the value of granularity alone.

⊡ **Last 12 months, thousand EUR per MW**

- 1 h: 53.2 → 61.0 (+14.5%)
- 2 h: 100.8 → 111.2 (+10.3%)
- 4 h: 178.4 → 190.9 (+7.0%)

⊡ A comparison with the hourly year before would mix in price-level changes.

⊡ **In practice:** short batteries gain most from 15-minute prices.

(NEMO Committee, 2025; own computation)

Experiment yourself: notebook §8

Batteries cannibalise their own spread: on the local order book, 50 MW would have closed it on 21 Oct 2026

- **In one sentence:** Charging adds demand at midday and discharging adds supply in the evening: both pull the two prices together.

$$\Delta P(X) = p^*_{\text{eve}}(+X \text{ supply}) - p^*_{\text{mid}}(+X \text{ demand})$$

- **where**
  - X = MW of batteries
  - p^* = clearing price recomputed on the OPCOM curves of 12:00–12:15 and 20:00–20:15 (Romanian time)
  - Flows fixed (Appendix C).

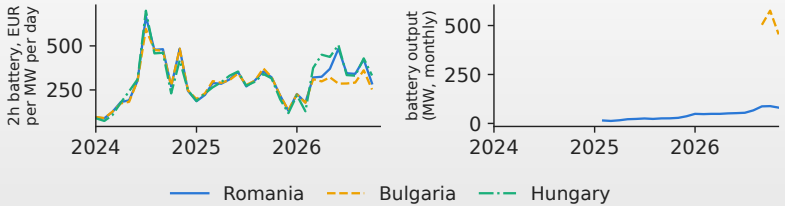
- **Evening minus midday price**
  - Actual 91.77 EUR/MWh
  - 50 MW: −13.15; 100 MW: −47.12
- **Fleets already running**
  - Romania: battery output up to 766 MW in 2026
  - Bulgaria, reported since 9 Sep 2026: up to 2 795 MW

- **In practice:** model the spread after the fleet is built, not the spread seen before it.

(OPCOM aggregated curves; own computation)

Experiment yourself: notebook §2

A Romanian battery competes for the same regional spread as the Bulgarian and Hungarian ones



Source: energy-charts.info; day-ahead prices via ENTSO-E; ENTSO-E battery output (BG, RO); own optimisation. Data: 2h battery, perfect foresight, 2024-01 to 2026-10; battery output as reported to ENTSO-E.

- **2 hours, last 12 months, thousand EUR per MW**: Hungary 117.6, Romania 111.2, Bulgaria 96.4, Germany 90.6
  - Daily revenue correlation with Romania: Bulgaria 0.80, Hungary 0.87

- **In practice:** as announced in Lecture 1: a Romanian battery developer competes for the same regional evening spread.

(own computation; battery output as reported to ENTSO-E)

EMQA_L6_bat_region

At 8% over 15 years, the 2-hour revenue supports at most 808 EUR per kW

In one sentence: The largest investment a yearly revenue can repay is that revenue times the annuity factor.

$$I^{\max} = R \cdot a(r, n)$$

$$a(r, n) = \sum_{j=1}^{n} (1 + r)^{-j} = \frac{1 - (1 + r)^{-n}}{r}$$

where

- R = yearly revenue per MW (EUR), $r = 8\%$ (assumption), $n = 15$ years (NREL), so $a = 8.56$
- $I^{\max}/1\,000$ = EUR per kilowatt (kW), Appendix D.

2 hours, last 12 months

- Perfect foresight: 952 EUR/kW
- 7-day rule: 808 EUR/kW = 404 EUR per kilowatt-hour (kWh)

Not included

- Operating costs, grid tariffs, fade: lower $I^{\max}$
- Balancing revenue raises it; new fleets shrink the spread

In practice: compare 404 EUR/kWh with the turnkey quote before anything else.

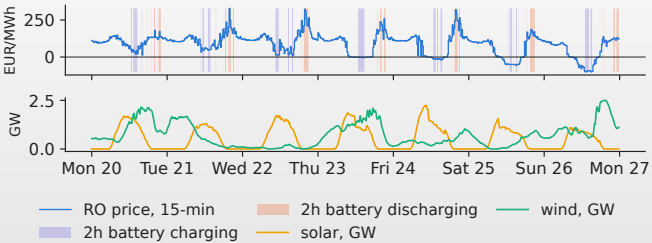
(Cole & Karmakar, 2023, NREL; Schmidt et al., 2019, Joule)

Experiment yourself: notebook §8

Outline

- Renewables and the merit order
- Capture prices and cannibalisation
- Negative prices
- Intraday shape and price spreads
- The economics of a battery
- Case studies: Apr 2026 and summer 2026
  - Month with the most negative-price hours: Apr 2026
  - Summer 2026: Romania and Bulgaria

Case study: in the week of 20 Apr 2026, Romania had 24 negative hours and solar captured 42%



Source: energy-charts.info (Fraunhofer ISE); OPCOM prices; ENTSO-E solar, wind and load (Transelectrica data for Romania).
Data: week 2026-04-20 to 2026-04-26, 15-min, CET.

- **Prices from −99.75 to 328.00 EUR/MWh**; solar CP 37.0 vs B 87.0
  - 2-hour battery: 391 EUR per MW a day, against 305 on an average day of the last 12 months

- **In practice:** the same sunny week is the worst for a solar park and among the best for a battery.

(own computation; schedule with perfect foresight)

EMQA_L6_case_week

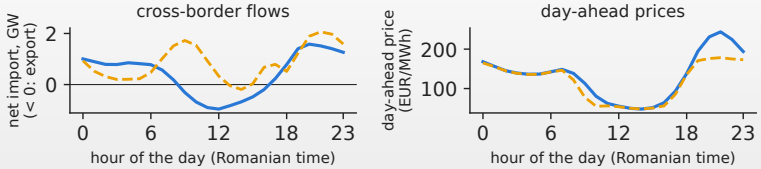
Case study: implications of Apr 2026 for each participant in the Romanian market

- **Solar developer**: capture rate 49.4% (47.2 vs 95.6 EUR/MWh)
  - 17.9% of output at negative prices; decision: storage on site, or a PPA that prices the solar profile
- **Wind developer**: capture rate 97.8%
  - In Romania, wind is not the cannibalised technology
- **Battery developer**: 2 hours, 325 EUR per MW a day
  - Against 305 on average over the last 12 months
- **Supplier and industrial consumer**: 67 negative hours
  - Moving consumption to spring middays is paid
- **Transelectrica**
  - After sunset the evening ramp and the interconnectors set the price

(own computation)

Experiment yourself: notebook §9

Case study: midday exports and evening imports from Bulgaria, summer 2026



Source: energy-charts.info (Fraunhofer ISE): cross-border physical flows of Romania (ENTSO-E); day-ahead prices of OPCOM (RO) and IBEX (BG). Data: hourly means, 2026-06-01 to 2026-08-31; Moldova and Ukraine borders only partly reported.

- **Midday: Romania exports**, 960 MW net at 12:00 on all borders
  - Mostly to Hungary (857 MW) and Serbia (367 MW); to Bulgaria on only 43 of 92 days (12:00–15:00)
- **Evening: Romania imports from Bulgaria**, 2 064 MW at 21:00, on all 92 days
  - Price at 21:00: Romania 243.9, Bulgaria 178.3 EUR/MWh; the full border separates the two prices

In practice: the evening gap of 65.6 EUR/MWh is the value of evening storage and interconnection.

(own computation; + = import into Romania)

EMQA_L6_rogb_summer

Quiz 1: capture rate

- A solar PPA is offered at the 2025 baseload forward of 108 EUR/MWh
  - What does the solar profile really earn?

Answer

- About 64 EUR/MWh in 2025 (capture rate 59%)
  - The buyer at the baseload price pays a large premium for the profile.

Quiz 2: counting negative prices

- Since 1 October 2025, Romania has had 687 negative quarter-hours
  - How many negative hours do you report?

Answer

- 171.75 hour-equivalents ($\times 0.25$ h), not 687 hours.

Quiz 3: battery duration

- Doubling storage from 2 h to 4 h doubles the cost of the cells
  - Does it double revenue?

Answer

- No: in the last 12 months a 4-hour battery earned 1.72 times what a 2-hour one earned, because the extra hours trade a smaller spread.

Quiz 4: the merit-order effect

- On the OPCOM curves of 21 Oct 2026, 25 MW more at zero price lowers the midday price to 131.4 EUR/MWh
  - Is this what a new 25 MW park does?

Answer

- No: the curves hold cross-border flows fixed
  - In the coupled market part of the extra output is exported, so the true effect is smaller (the regression gives a fall of about 27 EUR/MWh per GW).

Wrap-up

- Renewables and the merit order
  - Growth of solar generation
  - The merit-order effect
  - Renewables and the grid: redispatch
- Capture prices and cannibalisation
  - Definitions
  - Capture rates in Romania by year
  - Cannibalisation
- Negative prices
- Intraday shape and price spreads
- The economics of a battery
  - The optimal schedule
  - Probabilistic forecasts for trading
  - 15-minute prices, self-cannibalisation and regional competition
- Case studies: Apr 2026 and summer 2026
  - Month with the most negative-price hours: Apr 2026
  - Summer 2026: Romania and Bulgaria

- Solar lowers the price it is paid: Romanian capture rate 104% (2019) $\rightarrow$ 59% (2025)
  - Wind near 100%.
- Batteries live on the same regional spread: 111 thousand EUR per MW for 2 h with perfect foresight, about 85% of it with a simple rule
  - Next: Lecture 7.

Research from our group on renewables and Romanian prices

- **Explaining price drops and spikes** (Andrei & Pele, 2025, Preprints)
  - What the paper did: detected unusual hourly Romanian prices with an isolation forest and explained them with Shapley values
  - Result: wind and solar output drive the price drops; load forecast errors and conventional generation drive the spikes
- **Price drivers by horizon and regime** (Andrei, Pele & Cramer, 2026, PICBE)
  - What the paper did: forecast Romanian hourly prices 2018–2024 with tree ensembles and measured which drivers matter at each horizon and in low-, normal- and high-price regimes
  - Use here: the renewable drivers behind the low-price regime of this lecture
- **Early warning of spikes** (Andrei, Pele, Cramer, Amza & Diaconu, 2026, PICBE)
  - What the paper did: built an explainable artificial intelligence (AI) early-warning system for Romanian price spikes
  - Result: the residual-load forecast is the main driver, the variable of our regression
- **Price elasticity of demand** (Proșcanu, Proșcanu & Pele, 2025, JSES)
  - What the paper did: tested Granger causality between Romanian consumption and price
  - Result: consumption does not react to price, hence the almost vertical demand curve of the merit order
- Findings as stated in the papers; numbers on the other slides come from our own data.

(Bucharest University of Economic Studies; Romanian Academy, Institute for Economic Forecasting)

Further reading and resources

- **Hirth (2013)**: the reference paper on the value factor of wind and solar: doi:10.1016/j.eneco.2013.02.004.
- **Cole & Karmakar (2023)**: battery costs, efficiency and lifetime used in this lecture: doi:10.2172/1984976.
- **energy-charts.info**: live prices, generation and installed capacity for Romania and its neighbours: energy-charts.info.
- **This course**: code, data, notebooks — github.com/danpele/EMQA.
- **OPCOM aggregated curves**: download another day and repeat the merit-order computation: opcom.ro.
- **Experiment yourself**: the notebook reproduces every chart and number of this lecture.

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Appendix A: the capture rate is one plus a scaled covariance

- **Notation**
  - Weights $w_t = \Delta_t / \sum_s \Delta_s$; $\bar{P} = \sum_t w_t P_t = B$; $\bar{G} = \sum_t w_t G_t$; $\mathrm{Cov}_\Delta(P, G) = \sum_t w_t (P_t - \bar{P})(G_t - \bar{G})$
- **Step 1**
  - Divide numerator and denominator of CP by $\sum_s \Delta_s$: $\mathrm{CP} = \sum_t w_t P_t G_t \,/\, \bar{G}$
- **Step 2**
  - $\sum_t w_t P_t G_t = \mathrm{Cov}_\Delta(P, G) + \bar{P}\bar{G}$ (definition of the covariance)
- **Step 3**
  - $\mathrm{CR} = \mathrm{CP}/\bar{P} = 1 + \mathrm{Cov}_\Delta(P, G)/(\bar{P}\bar{G})$
  - Romanian solar, Jan–Oct 2026: $\bar{P} = 137.4$, $\bar{G} = 593$ MW, covariance $-31\,069$, so CR $= 0.619$
- **Reading**
  - CR < 1 exactly when output is high in cheap intervals; CR is undefined if $\bar{P} \leq 0$

(Hirth, 2013, ENEECO)

Appendix B: the battery programme in matrix form

- **Variables**
  - $z = (c_1..c_T,\ x_1..x_T,\ e_1..e_T)$, $3T$ variables, $T = 92$, 96 or 100 quarter-hours (24 hours before October 2025)
- **Objective**
  - Minimise $\sum_t P_t \Delta_t c_t - \sum_t P_t \Delta_t x_t$ (the negative of revenue)
- **Equalities**
  - $e_t - e_{t-1} - \sqrt{\eta}\Delta_t c_t + \Delta_t x_t/\sqrt{\eta} = 0$ for $t = 1..T$, with $e_0 = 0$; and $e_T = 0$
- **Inequality and bounds**
  - $\sum_t \Delta_t x_t/\sqrt{\eta} \le E$; $0 \le c_t, x_t \le 1$; $0 \le e_t \le E$; solved with the HiGHS solver (scipy)
- **Forecast rules**
  - The programme is solved on $\hat{P}_t$ (mean of the last 7 days, or day $d-1$), then revenue is $\sum_t P_t(x_t - c_t)\Delta_t$ with the real P_t
  - Days whose length differs from the forecast's (clock changes) are dropped: 361 of 365 days kept

(Sioshansi et al., 2009, ENEECO)

Appendix C: recomputing the clearing price on the OPCOM curves

- **Curves**
  - OPCOM publishes, per quarter-hour, the aggregated supply and demand points (price, cumulative MW) in XML
  - Blocks, hourly orders and net cross-border flows are added at the price limits (-600 and $+4\,000$ EUR/MWh), as in OPCOM's own chart
- **Algorithm**
  - $S(p)$, $D(p)$ = linear interpolation between published points; new price = lowest p with $S(p) + X\mathbf{1}[p \geq 0] - D(p) \geq 0$, by bisection on $[-600, 4000]$
  - For battery charging, X MW of demand at any price are added to D
- **Check**
  - With $X = 0$ the curves cross on a flat segment: midday prices from 152.16 upwards, evening from 206.49; the official prices 152.23 and 244.00 lie on these segments
  - The official price, not the curve, is used at $X = 0$

(OPCOM; data/clean/opcom_pzu_curves_meta.json)

Appendix D: the annuity factor

- **Present value of a constant revenue**
  - $V = \sum_{j=1}^{n} R(1+r)^{-j} = R\,q\,\frac{1-q^n}{1-q}$ with $q = (1+r)^{-1}$
- **Simplify**
  - $q/(1-q) = 1/r$, hence $V = R\,\frac{1-(1+r)^{-n}}{r} = R\,a(r,n)$
- **Break-even**
  - The project pays back if investment $I \leq V$; with $r = 8\%$, $n = 15$: $a = 8.56$
- **Per kWh of storage**
  - $I^{\max}/E$: for 1, 2, 4 h with the 7-day rule, 428, 404, 365 EUR/kWh

(Cole & Karmakar, 2023, NREL)