

# Energy Markets Quantitative Analysis

## Lecture 1: Energy Markets and Their Data





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# Learning objectives

- Explain how one day-ahead auction sets a price for every hour (now every quarter-hour) and how European market coupling links Romania with its neighbours.
- Compute and read the Romanian generation mix from metered data, with its coverage.
- Recognise the stylized facts of power prices on real data and choose a transformation that works when prices are zero or negative.
- Use the core time-series toolkit and the naive benchmark that every forecast must beat.
- Read six current episodes quantitatively, from the dry year 2025 to Bulgaria's new batteries in 2026.

# Abbreviations (1/2)

| | |
|---|---|
| **ACER** | EU Agency for the Cooperation of Energy Regulators |
| **ACF** | autocorrelation function |
| **ADF** | augmented Dickey–Fuller test |
| **AIC** | Akaike information criterion |
| **ANRE** | Romanian Energy Regulatory Authority |
| **AR** | autoregressive model |
| **ARX** | autoregressive model with exogenous variables |
| **bbl** | barrel (159 litres) |
| **BG** | Bulgaria (bidding zone) |
| **CEST** | Central European Summer Time |
| **CET** | Central European Time |
| **CNCAN** | National Commission for Nuclear Activities Control (Romania) |
| **DE-LU** | Germany–Luxembourg bidding zone |
| **DST** | daylight saving time |
| **ECB** | European Central Bank |
| **EET** | Eastern European Time (Romania) |
| **ENTSO-E** | European Network of Transmission System Operators for Electricity |
| **EPEX** | EPEX SPOT power exchange |
| **EU** | European Union |
| **EUPHEMIA** | Pan-European Hybrid Electricity Market Integration Algorithm |
| **EUR** | euro |
| **EWMA** | exponentially weighted moving average |
| **GW** | gigawatt |
| **HAC** | heteroskedasticity- and autocorrelation-consistent |
| **HU** | Hungary (bidding zone) |
| **HUPX** | Hungarian Power Exchange |
| **IBEX** | Independent Bulgarian Energy Exchange |
| **IDA** | intraday auction |
| **IQR** | interquartile range |
| **ISE** | Fraunhofer Institute for Solar Energy Systems |
| **JAO** | Joint Allocation Office |

# Abbreviations (2/2)

| | |
|---|---|
| **JB** | Jarque–Bera test |
| **KPSS** | Kwiatkowski–Phillips–Schmidt–Shin test |
| **MA** | moving average |
| **MAD** | median absolute deviation |
| **MAE** | mean absolute error |
| **MMBtu** | million British thermal units |
| **MTU** | market time unit |
| **MW** | megawatt |
| **MWh** | megawatt-hour |
| **NEMO** | Nominated Electricity Market Operator |
| **OLS** | ordinary least squares |
| **OPCOM** | Romanian electricity and gas market operator |
| **OTC** | over the counter (bilateral) |
| **PACF** | partial autocorrelation function |
| **PPA** | power purchase agreement |
| **PZU** | Piața pentru Ziua Următoare (day-ahead market) |
| **REMIT** | EU Regulation 1227/2011 on wholesale energy market integrity and transparency |
| **RO** | Romania (bidding zone) |
| **RON** | Romanian leu |
| **RoR** | run-of-river hydro |
| **SDAC** | Single Day-Ahead Coupling |
| **SES** | simple exponential smoothing |
| **SIDC** | Single Intraday Coupling |
| **SMA** | simple moving average |
| **STL** | Seasonal–Trend decomposition using Loess |
| **TSO** | transmission system operator |
| **TTF** | Title Transfer Facility (Dutch gas hub) |
| **TWh** | terawatt-hour |
| **USD** | US dollar |
| **UTC** | Coordinated Universal Time |
| **YTD** | year to date |

# Data sources and sample period

- Exchanges: Romanian electricity and gas market operator (OPCOM), Independent Bulgarian Energy Exchange (IBEX), Hungarian Power Exchange (HUPX), European Power Exchange (EPEX SPOT); European Network of Transmission System Operators for Electricity (ENTSO-E).

| Series | Frequency | Source | From |
|---|---|---|---|
| Day-ahead prices: Romania (RO), Bulgaria (BG), Hungary (HU), Germany–Luxembourg (DE-LU) | 15/60 min | energy-charts.info (Fraunhofer ISE); prices of the exchanges above | 2015-01-01 |
| Generation by source and consumption, Romania and Bulgaria | hourly | energy-charts.info, ENTSO-E actual generation | 2015-01 |
| Romanian cross-border physical flows | hourly | energy-charts.info, ENTSO-E | 2015-01-01 |
| Brent crude oil, front-month futures | daily | Yahoo Finance (BZ=F) | 2015-01-02 |
| Title Transfer Facility (TTF) gas, monthly | monthly | World Bank; European Central Bank (ECB) exchange rates | 2015-01 |

- **Cut-off: 31 Oct 2026** (last complete month), downloaded 4 Nov 2026
  - "2026 year to date (YTD)" always means Jan–Oct 2026.
- Missing values stay missing: never interpolated, never counted as zero, and coverage is always reported.

**Experiment yourself:** notebook §1

# Outline


- Power markets in Romania and Europe
  - How the day-ahead auction works
  - Market coupling and the 15-minute market time unit
  - Electricity generation in Romania
- Energy data and stylized facts
- Time-series methods
- Case studies on current data

# The day-ahead auction: a clearing price for each quarter-hour

- **In one sentence:** Sellers and buyers send price–quantity bids; the exchange finds the price at which energy offered equals energy demanded, and every accepted trade is paid that single price.

$$p_t^* = \min\left\{ p : \underbrace{S_t(p)}_{\text{supply curve}} \geq \underbrace{D_t(p)}_{\text{demand curve}} \right\}$$

- **where**
  - $t$ = delivery quarter-hour (hour before Oct 2025)
  - $S_t(p)$ = energy offered at prices $\leq p$, plants sorted by cost (the *merit order*: renewables and nuclear at the bottom, gas near the top)
  - $D_t(p)$ = energy bought at prices $\geq p$
  - $p_t^*$ = clearing price, in euro per megawatt-hour (EUR/MWh).

- **On our data**: Romania's day-ahead market, Piața pentru Ziua Următoare (PZU), run by the Romanian market operator (OPCOM), cleared on average at 137.45 EUR/MWh in Jan–Oct 2026.
- Reservoir hydro bids its "water value" (opportunity cost) and often sets the Romanian price.
- **Two extremes**
  - Demand on the steep part: **spikes**
  - Inflexible output and sun above demand: **negative prices**

- **In practice:** on PZU a supplier pays the price of the most expensive plant needed, not the average cost.

(Weron, 2014, IJF; Maciejowska, Uniejewski & Weron, 2023, Oxford Res. Enc.)

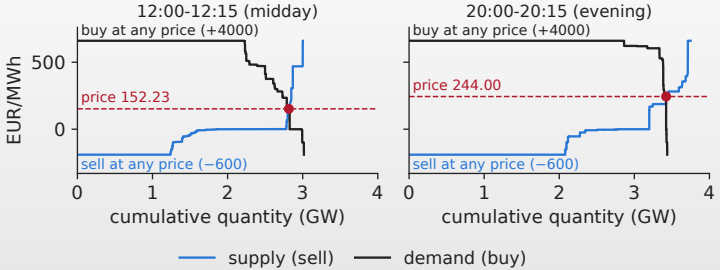
# The merit order: how the price is formed

- **Supply**: sell offers sorted from cheapest to dearest
  - Each producer offers near its marginal cost, the cost of one more MWh
  - Usual order: wind, solar and nuclear (marginal cost near zero), run-of-river hydro, lignite, gas
  - Reservoir hydro offers at its water value, the price it expects to get later for the same water
- **Demand**: buy bids sorted from highest to lowest price
  - Most consumption is bought at any price, so the demand curve is almost vertical
- **Price**: set by the last accepted offer, the marginal one
  - Every accepted seller receives it, also those with lower costs
  - Their difference between price and cost pays for capacity (inframarginal rent)
- **Why prices move**
  - Sun and wind shift the supply to the right: lower price
  - Evening demand or a missing reactor moves the crossing to the steep, gas-fired part: higher price

- **In practice:** the price of a quarter-hour is the cost of its most expensive accepted offer, not the average cost of the system.

(Weron, 2014, IJF; Maciejowska, Uniejewski & Weron, 2023, Oxford Res. Enc.)

# The merit order on real OPCOM curves, 21 Oct 2026




Source: OPCOM, PZU aggregated curves. Data: 2026-10-21, Romanian time; quantities include blocks, hourly orders and net flows.

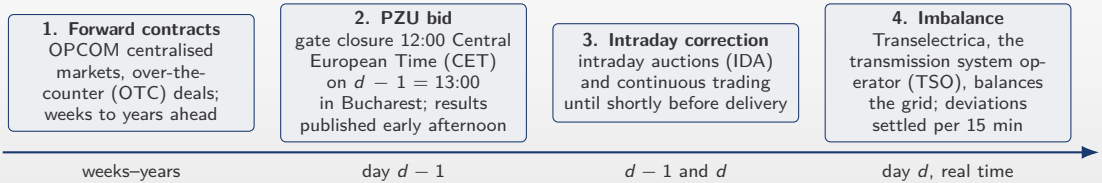
- Same day, two prices: the supply curve changes with the sun
  - Midday: 2 333 MW offered at zero or negative prices, price 152.23 EUR/MWh
  - Evening: no sun, 1 054 MW of net imports in the supply, price 244.00 EUR/MWh

- **In practice:** a buyer who can shift consumption from evening to midday pays the lower clearing price.

(OPCOM, PZU aggregated curves)

EMQA_L1_merit_opcom

# Trading stages for one delivery day




- **Clocks and money**: Romania runs on Eastern European Time (EET), one hour ahead of CET
  - The Single Day-Ahead Coupling (SDAC) clears in EUR, and OPCOM also publishes prices in Romanian lei (RON).
- **Why the order matters**: each step corrects the previous one
  - What is not covered forward is bought on PZU, and what is still wrong after intraday trading is settled as imbalance.

- **In practice:** a trader hedges forward, bids on PZU before 13:00 Bucharest time, fixes forecast errors intraday and pays what is left as imbalance.

(Maciejowska, Uniejewski & Weron, 2023, Oxford Res. Enc.; OPCOM; Transelectrica)

# Market institutions: operators, regulators, price limits, disclosure

- **Who is who**
  - OPCOM: the Nominated Electricity Market Operator (NEMO); it runs PZU and the intraday market
  - Transelectrica (TSO): runs the grid in real time and settles imbalances
  - The Romanian Energy Regulatory Authority (ANRE): sets the national rules and licenses market participants
- **Disclosure**
  - The European Union (EU) Regulation on wholesale energy market integrity and transparency (REMIT): inside information must be published promptly
  - For example, unplanned outages of large plants; such messages move PZU prices
  - The EU Agency for the Cooperation of Energy Regulators (ACER) monitors the market for abuse
- **Price limits**
  - SDAC harmonised minimum: $-500$ EUR/MWh; $-600$ for delivery from 29 May 2026 (OPCOM)
  - A series that touches the floor is censored there: the true willingness to pay was even lower

- **In practice:** read REMIT messages before bidding
  - An unplanned outage announced in time changes the PZU price.

(OPCOM; ANRE; ACER; Regulation (EU) 1227/2011)

# Coupling lets power flow to the higher price until the network limit binds

- **In one sentence:** Europe runs one joint day-ahead auction; cheap zones export to expensive ones until a network limit binds, and only then do prices differ.

$$\max \sum_z \left[ \underbrace{\int_0^{d_z} D_z^{-1}}_{\text{buyers' value}} - \underbrace{\int_0^{s_z} S_z^{-1}}_{\text{sellers' cost}} \right] \text{ s.t. } \underbrace{\text{flows} \in \mathcal{F}}_{\text{network limits}}$$

- **where**
  - $z$ = bidding zone
  - $d_z, s_z$ = energy bought and sold in $z$
  - $\mathcal{F}$ = feasible exchanges
  - If no limit binds, $p_z = p_{z'}$, otherwise prices separate.

- *Simplified picture*: one capacity per border
  - Since 8 Jun 2022 Romania–Hungary is in the Core region's *flow-based* allocation (limits on critical network elements)
  - Romania–Bulgaria keeps a per-border limit.
- Equal prices do not prove an uncongested border
  - A gap does not say which line is full.
- Scheduled exchanges differ from physical flows
  - Long-term rights are sold by the Joint Allocation Office (JAO).

- **In practice:** a trader on RO–HU flows earns the price spread only when cross-border capacity binds.

(Weron, 2014, IJF; JAO; Core flow-based market coupling)

# Milestones of market coupling for Romania, 2014–2025




- Prices are computed by the Pan-European Hybrid Electricity Market Integration Algorithm (EUPHEMIA).
- Each step changed the data: new neighbours, new products, a finer resolution
  - Check the date before comparing periods.

(OPCOM press releases 2019–2025; IBEX/OPCOM, 27 Oct 2021; JAO)

# The 15-minute market time unit since 1 October 2025

- **In one sentence:** The market time unit (MTU) shrank from one hour to 15 minutes, so every count of hours must be converted.

$$\bar{p}_d = \frac{1}{M_d}\sum_{m=1}^{M_d} p_{d,m}, \qquad H_y = \sum_{t\in y} \underbrace{\mathbb{1}\{p_t < 0\}}_{\text{1 if negative}} \cdot \underbrace{\Delta_t/60}_{\text{length in hours}}$$

- **where**
  - $p_{d,m}$ = price of MTU $m$ on day $d$
  - $M_d$ = MTUs that day: 96 since Oct 2025, 24 before ($\pm 1$ hour on the daylight saving time (DST) days)
  - $\bar{p}_d$ = *daily base price*
  - $\Delta_t \in \{60, 15\}$ = MTU length in minutes
  - $H_y$ = hour-equivalents in year $y$.

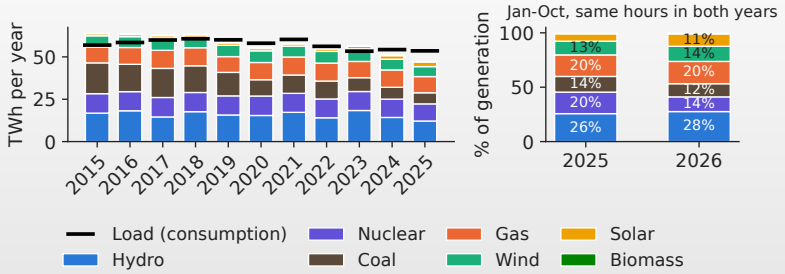
- **On our data**
  - 94 222 hourly MTUs until Sep 2025, 38 020 quarter-hours since
  - Jan–Oct 2026: 687 negative quarter-hours in Romania = 171.75 h
  - Counting them as hours would overstate the duration by a factor of 4

- **In practice:** always ask "hours or quarter-hours?" before comparing years.

(OPCOM, 1 Oct 2025)

**Experiment yourself:** notebook §1

# Romania's generation mix: hydro, nuclear, gas, coal and growing solar



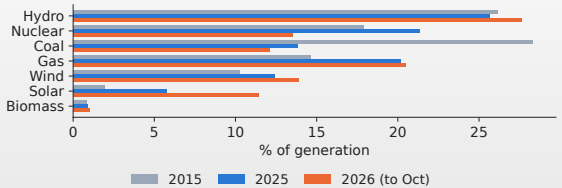

Source: energy-charts.info (Fraunhofer ISE); ENTSO-E (Transelectrica data for Romania). Data: 2015-2025 full years (left); Jan-Oct 2025 and 2026, hours reported in both years (right); cut-off 2026-10-31.

- Hydro = run-of-river (RoR) + reservoir, coal = lignite + hard coal
  - Black bar = consumption, above the stack it means net imports
  - Energy summed over reported hours (coverage $\geq$ 98.1% in full years)
  - Metered solar may miss rooftop output.

(energy-charts.info; data source: ENTSO-E)

EMQA_L1_mix_ro_annual

# Generation by source in Romania: less coal, more solar, lower nuclear output in 2026




Source: energy-charts.info (Fraunhofer ISE); ENTSO-E (Transelectrica data for Romania). Data: 2015, 2025 full years; Jan-Oct 2026, hours reported in both 2025 and 2026.

- Coal output: −63.9% from 2015 to 2025
  - Metered solar 2.2× over the same years.
- Nuclear, Jan–Oct 2026 vs 2025: −31.3% on hours reported in both years
  - A lower bound: the 29 unreported September days are left out.

**In practice:** when water or a reactor is missing, another plant sets the price.

(Romania; energy-charts.info; data source: ENTSO-E)

EMQA_L1_mix_shares

# Course structure and models covered

## Course roadmap

1. **Energy markets and their data** (today)
2. Forecasting: classical and expert autoregressive models with exogenous variables (ARX)
3. Volatility
4. Risk in energy companies: price–volume, cash flow at risk, imbalance, basis
5. Derivatives and hedging, including power purchase agreements
6. Renewables, storage, flexibility: cannibalisation, negative prices, batteries
7. Machine learning and foundation models for forecasting

- **Model families**
  - Fundamental: supply stack, fuel and carbon cost
  - Reduced-form (mean reversion, jumps) and statistical
  - Machine learning and hybrids
- **Two views of the same data**
  - Univariate: one long series of prices
  - Multivariate: 24 (now 96) daily series, one per period
- Every model must beat the **naive benchmark** of Section 3.

- **In practice:** ask any forecast vendor which family the model belongs to and by how much it beats the naive benchmark.

(Weron, 2014, IJF; Ziel & Weron, 2018, ENEECO)

# Outline


- Power markets in Romania and Europe
- Energy data and stylized facts
  - Units, clocks and clean data
  - Price level and seasonality
  - Spikes and negative prices
  - Distribution and volatility
- Time-series methods
- Case studies on current data

# Power (MW) and energy (MWh)

- **In one sentence:** A megawatt (MW) is how fast energy flows; a megawatt-hour (MWh) is how much flowed, e.g. 1 MW for one hour.

$$E = \frac{1}{10^6} \sum_{t \text{ reported}} \underbrace{P_t \, \Delta_t}_{\text{MWh}} \text{ [TWh]}$$

$$\text{coverage} = \frac{\text{reported hours}}{\text{hours in the period}}$$

- **where**
  - $P_t$ = mean power in interval $t$ (MW)
  - $\Delta_t$ = its length (h)
  - $E$ = energy in terawatt-hours (TWh), 1 TWh = $10^6$ MWh.

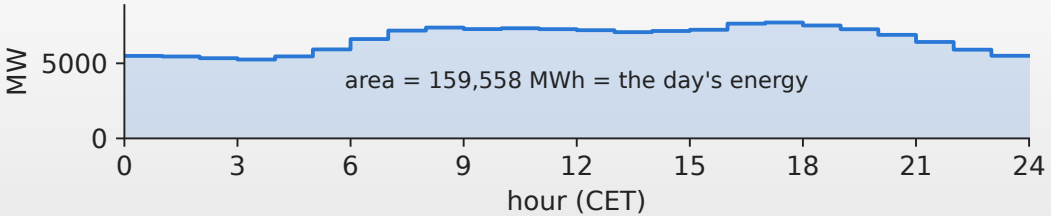
- **On our data**: Romania consumed 53.56 TWh in 2025, a mean load of 6.1 gigawatts (GW).
- Missing hours are not filled, and every total comes with its coverage.
- **Reference prices**
  - Base: mean of the delivery day
  - Peak: mean of 08:00–20:00, Monday to Friday
- Gas and oil are quoted in US dollars (USD) per million British thermal units (MMBtu) and per barrel (bbl)
  - Conversion to EUR/MWh: Appendix G.

- **In practice:** a 10 MW baseload contract delivers 240 MWh a day.

(energy-charts.info; World Bank Commodity Price Data)

**Experiment yourself:** notebook §1

# One day of Romanian consumption: power in MW, energy in MWh




Source: energy-charts.info (Fraunhofer ISE); ENTSO-E (Transelectrica data for Romania). Data: Romania, load on 2026-10-28 (CET day, 24 hourly values).

- **The curve** shows power: how much the country draws at each hour (MW)
  - Minimum 5 253 MW at 3:00, maximum 7 719 MW at 17:00 (CET)
- **The shaded area** is energy: 159 558 MWh on 28 Oct 2026
  - 24 hours × a mean of 6 648 MW

**In practice:** a supplier buys energy (MWh), while the grid must cover the peak power (MW).

(Romania; energy-charts.info; data source: ENTSO-E) EMQA_L1_day_load

# Clean data (1): delivery day, clock changes, zone changes

- **Clocks**: raw time stamps are in Coordinated Universal Time (UTC)
  - Daily statistics use the SDAC delivery day, in Central European Time (CET) or, in summer, Central European Summer Time (CEST)
  - A UTC day would put one or two hours into the wrong day.
- **Clock changes**: the last Sunday of March has 23 hours, the last Sunday of October 25
  - Daily means use the intervals that exist.
- **Zone change**: Germany–Austria–Luxembourg was one zone until 30 Sep 2018
  - Our series is spliced there.
- Every chart and number is reproduced in the student notebook (notebooks/L1_notebook.ipynb)
  - One simulated figure, clearly labelled, illustrates white noise and the random walk.

(Lago, Marcjasz, De Schutter & Weron, 2021, APEN)

**Experiment yourself:** notebook §1

# Clean data (2): missing days and series breaks

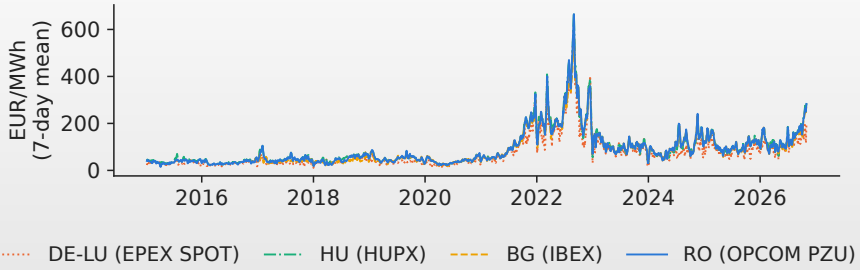
- **Missing days**: the source (energy-charts.info, which republishes the prices of OPCOM and of the Independent Bulgarian Energy Exchange (IBEX) reported to ENTSO-E) has no price for some days, and gives no reason
  - Romania: 5 days (21 Sep 2015, 20 Dec 2015, 21 Dec 2015, 31 Dec 2017, 17 Aug 2018)
  - Bulgaria: the series starts 31 Oct 2016, although IBEX has run its day-ahead market since 19 Jan 2016, and 15 more days are missing up to 31 Dec 2016
  - We do not fill these days, and no daily change is computed across a gap.
- **Futures rolls**: the Brent front-month series jumps when the contract rolls
  - Those days are dropped from return statistics.

- **In practice:** most forecasting errors at a supplier start in data handling (wrong clock, filled gaps), not in the model.

(Lago, Marcjasz, De Schutter & Weron, 2021, APEN)

**Experiment yourself:** notebook §1

# Prices jumped in 2021–2022 and never returned to the old level




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: 2015-01-01 to 2026-10-31 (BG from 2016-10-31).

- Romanian daily maximum 738.28 EUR/MWh on 30 Aug 2022
  - RO, BG and HU move together (coupled), while Germany has been cheaper since 2023.

- **In practice:** an industrial consumer budgeting with pre-2021 prices is off by a factor of two to three.

(energy-charts.info; prices: OPCOM, IBEX, HUPX, EPEX SPOT) EMQA_L1_prices_daily_4zones

# Volatility moves with the price level

| Mean, EUR/MWh | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 YTD |
|---|---|---|---|---|---|---|---|---|---|
| RO | 46.4 | 50.4 | 39.5 | 111.4 | 265.3 | 103.7 | 103.5 | 108.2 | 137.4 |
| BG | 39.9 | 47.5 | 39.3 | 108.7 | 252.8 | 103.8 | 102.5 | 106.9 | 129.9 |
| HU | 51.0 | 50.4 | 39.0 | 113.8 | 271.7 | 106.8 | 100.8 | 108.5 | 141.0 |
| DE-LU | 44.5 | 37.7 | 30.5 | 96.8 | 235.5 | 95.2 | 78.5 | 89.3 | 114.0 |
| *Volatility: standard deviation of daily price changes* | | | | | | | | | |
| RO | 10.9 | 11.5 | 8.6 | 25.2 | 58.9 | 26.3 | 32.4 | 24.4 | 31.6 |
| BG | 13.6 | 12.8 | 9.8 | 23.6 | 56.6 | 26.2 | 31.5 | 23.9 | 28.2 |
| HU | 9.2 | 9.2 | 8.5 | 24.8 | 56.6 | 25.0 | 34.7 | 25.3 | 32.6 |
| DE-LU | 11.5 | 11.9 | 11.5 | 34.4 | 65.3 | 30.3 | 31.4 | 28.3 | 36.0 |

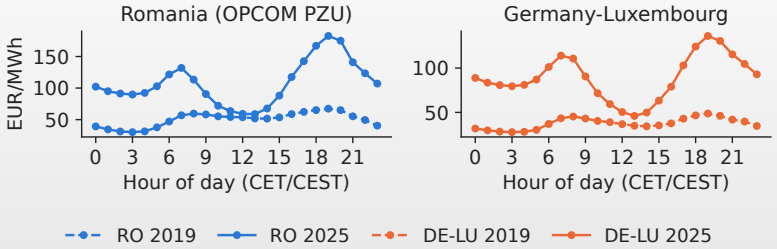
- Colour within each row: green = lowest, red = highest (2026 YTD = Jan–Oct).

- 2026 YTD: Romania 137.45 vs 105.88 EUR/MWh in Jan–Oct 2025 (+29.8%).

- **In practice:** collateral for PZU purchases must scale with the price, since a 200 EUR/MWh market moves far more than a 50 one.

(energy-charts.info; own computation)

# Solar moved the cheapest hour of the day to midday




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: calendar years 2019 and 2025, hourly.

- From 2019 to 2025 the cheapest hour moved from night to midday
  - 2025: cheapest at 13:00 (58.8 EUR/MWh in Romania), evening peak 182.5
  - Evening/midday ratio 1.30 → 3.11, the "duck curve".

- **In practice:** a battery developer's revenue is this midday-to-evening spread, captured once or twice a day.

(energy-charts.info; hourly day-ahead prices)

EMQA_L1_profile_intraday

# Weekly seasonality: lower prices at weekends

- **In one sentence:** Factories and offices consume less on weekends, so fewer plants are needed and the price drops.

$$\hat{s}_j = \frac{1}{W}\sum_{w=1}^{W}\Bigg(\underbrace{p_{w,j}}_{\text{day } j \text{ of week } w} - \underbrace{\tfrac{1}{7}\textstyle\sum_{i=1}^{7} p_{w,i}}_{\text{mean of week } w}\Bigg)$$

- **where**
  - $j$ = weekday
  - $W$ = number of complete weeks
  - $\hat{s}_j$ = average distance of weekday $j$ from its own week's mean (EUR/MWh)
  - Subtracting each week's mean removes level shifts such as 2022.

- **On our data**: 199 weeks, 2 Jan 2023 – 25 Oct 2026.

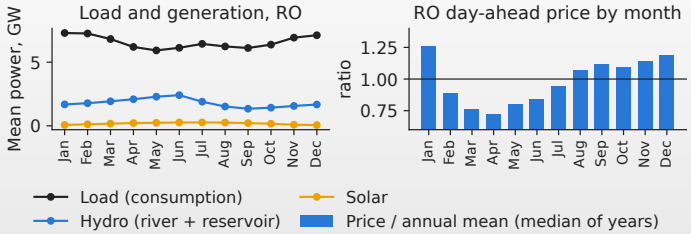
| | Mon | Tue | Wed | Thu | Fri | Sat | Sun |
|---|---|---|---|---|---|---|---|
| RO | 9.1 | 12.7 | 12.6 | 10.4 | 3.4 | −17.5 | −30.7 |
| DE-LU | 7.0 | 11.0 | 11.6 | 7.9 | 3.3 | −15.8 | −25.1 |

- Sunday in Romania: $\hat{s}_{\text{Sun}} = -30.7$ EUR/MWh relative to its week's mean.

- **In practice:** an industrial consumer can move flexible load (maintenance, pumping, charging) to Sunday and save that difference.

**Experiment yourself:** notebook §3

# Seasonal profile of prices, consumption and hydro output




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: monthly means 2016-2025.

- Price relative to the annual mean: highest in January (1.26), lowest in April (0.72)
  - Consumption is highest in January–February and lowest in May
  - Hydro peaks in June (snow melt).

- **In practice:** a hydro producer saves reservoir water in spring, when power is cheap, to sell it in winter and late summer.

(energy-charts.info; monthly means 2016–2025)

EMQA_L1_profile_annual

# Price spikes: definition and number of hours per year

- **In one sentence:** A spike is an interval whose price is far above what is normal for that year.

$$p_t > \underbrace{Q_{3,y}}_{\text{75th percentile}} + 3 \cdot \underbrace{(Q_{3,y} - Q_{1,y})}_{\text{interquartile range (IQR)}}$$

- **where**
  - $Q_{1,y}, Q_{3,y}$ = 25th and 75th percentiles of all prices of year $y$, weighted by interval length (15-min intervals count a quarter)
  - Percentiles are robust, so spikes barely move the threshold.

| Year | RO thr. | RO h | DE-LU h |
|---|---|---|---|
| 2020 | 109 | 54.00 | 30.00 |
| 2021 | 394 | 69.00 | 280.00 |
| 2022 | 873 | 4.00 | 4.00 |
| 2023 | 292 | 38.00 | 13.00 |
| 2024 | 274 | 276.00 | 72.00 |
| 2025 | 285 | 120.00 | 88.75 |
| 2026 | 427 | 39.25 | 32.25 |

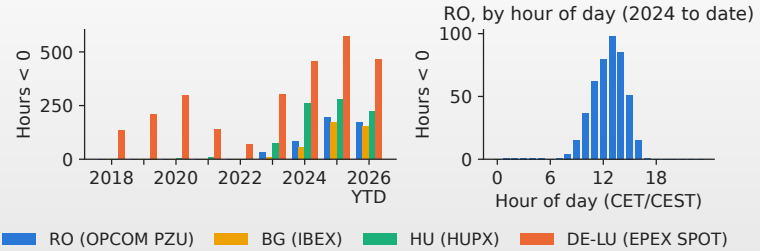
- Highest Romanian price in our data: 1021.61 EUR/MWh on 3 Sep 2024, 19:00 CEST.

- **In practice:** a supplier with fixed-price retail contracts loses most of the year's margin in a few dozen spike hours, which is why it hedges.

(Janczura, Trück, Weron & Wolff, 2013, ENEECO)

**Experiment yourself:** notebook §4

# Negative prices reached Romania in 2023 and are now routine




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: 2018 to 2026-10-31; a 15-min MTU counts 0.25 h.

- First negative Romanian price: 21 May 2023
  - Since 2024, 91.1% of negative hours fall between 10:00 and 16:00 and 83.9% on weekends
  - Bars in hour-equivalents.

- **In practice:** a solar park without storage sells much of its output in the cheapest hours of the year (Lecture 6).

(energy-charts.info; own count, a 15-min MTU = 0.25 h)

EMQA_L1_negative_prices

# Counting negative prices correctly: hour-equivalents

| Zone | 2022 | 2023 | 2024 | 2025 | 2026 YTD | Jan–Oct 2025 | 2026: 15-min MTUs |
|---|---|---|---|---|---|---|---|
| RO | 0 | 32 | 85 | 196 | 171.75 | 196 | 687 |
| BG | 0 | 11 | 55 | 170 | 152.25 | 170 | 609 |
| HU | 0 | 74 | 262 | 281 | 223.50 | 281 | 894 |
| DE-LU | 69 | 301 | 457 | 574.75 | 465 | 574.75 | 1 860 |

- Hours with a negative day-ahead price; darker = more hours; last column: negative quarter-hours (= 4 × hour-equivalents).

- Romania had none before 2023
  - Germany had them every year (inflexible plants plus wind).
- RO, BG and HU move together (coupled), but Hungary has had more negative hours since 2023.
- Jan–Oct 2026: Romania 171.75 h vs 196.00 h a year earlier
  - Growth is not automatic (Case study d).

- **In practice:** in reports to the board, write "687 quarter-hours (171.75 h)"
  - Never a bare number.

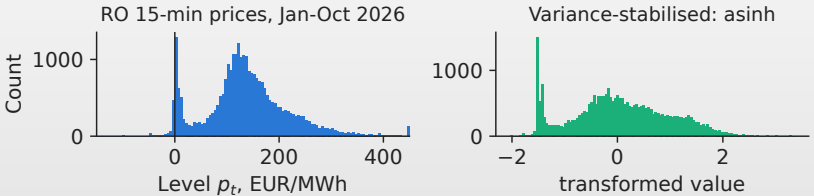
(energy-charts.info; own computation)

**Experiment yourself:** notebook §4

# Transformations for zero and negative prices: differences and asinh

- **In one sentence:** Percentage changes need a positive price, but asinh is defined for any sign.

$$y_t = \operatorname{asinh}(x_t) = \ln\left(x_t + \sqrt{x_t^2 + 1}\right), \quad x_t = \frac{p_t - \tilde{p}}{\widehat{\mathrm{MAD}}}, \quad \operatorname{asinh}(x) \approx \operatorname{sign}(x)\ln(2|x|) \text{ for large } |x|$$




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: all 15-min MTUs, 2026-01-01 to 2026-10-31.

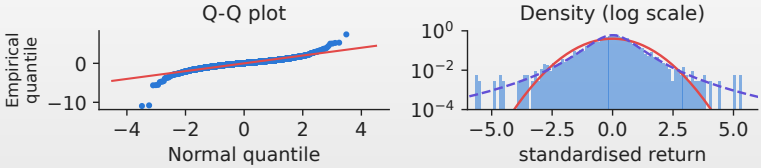
- $\tilde{p}$ = median, $\widehat{\mathrm{MAD}}$ = median absolute deviation (MAD) $\times 1.4826$.
- Jan–Oct 2026: 1 189 of 29 184 quarter-hours $\leq 0$ (502 exactly 0)
  - Skewness 1.19 $\rightarrow$ 0.13, excess kurtosis 6.73 $\rightarrow$ −0.55.

(Uniejewski, Weron & Ziel, 2018, IEEE TPWRS)

EMQA_L1_asinh_ro

# Extreme oil moves are far more frequent than a normal curve allows

⊡ **In one sentence:** "Fat tails": very large up or down days come far more often than a bell curve allows.




Source: Yahoo Finance (BZ=F). Data: 2015-01-05 to 2026-10-30.

⊡ Brent daily log returns without the 141 contract-roll days

- Moves beyond 4 standard deviations: 16 observed vs 0.18 expected under normality, excess kurtosis 13.98 (Jarque–Bera (JB) test: Appendix F).

⊡ **In practice:** a fuel budget built on the normal curve understates crisis days (Lecture 4).

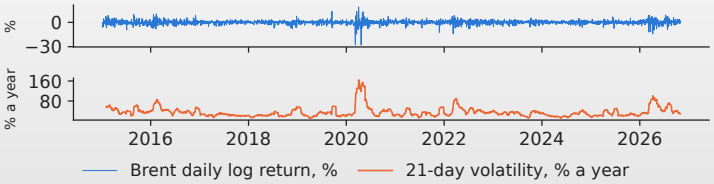
(Jarque & Bera, 1980, Econ. Letters; Yahoo Finance BZ=F)

EMQA_L1_tails_brent

# Calm and turbulent periods come in clusters

- **In one sentence:** A big move today makes another big move more likely, whatever its direction.

$$Q(m) = T(T+2)\sum_{k=1}^{m}\frac{\hat{\rho}_k^2}{T-k} \sim \chi^2_m \quad \text{(Ljung–Box)}$$




Source: Yahoo Finance (BZ=F). Data: 2015-01-05 to 2026-10-30.

- Brent: $Q_{10}(r) = 28.1$ but $Q_{10}(r^2) = 506.9$ (5% critical value 18.31)
  - Little memory in the direction of moves, a lot in their size.

- **In practice:** after a shock, a risk desk keeps wider limits for weeks, not days (Lecture 3).

(Ljung & Box, 1978, Biometrika)

EMQA_L1_volclust_brent

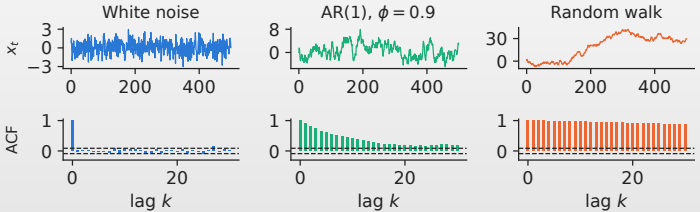
# Outline


- Power markets in Romania and Europe
- Energy data and stylized facts
- Time-series methods
  - Stationarity and autocorrelation
  - Unit-root tests, decomposition, smoothing
- Case studies on current data

# Weak stationarity: constant mean, variance and autocovariances

⊡ **In one sentence:** Weakly stationary: mean, spread and lag-$k$ memory are the same in every period.

$$\mathbb{E}X_t = \mu, \quad \text{Var}\, X_t = \gamma_0, \quad \text{Cov}(X_t, X_{t-k}) = \gamma_k \quad \text{for every } t$$




**SIMULATED DATA (teaching illustration)** Source: simulation, numpy, seed 20261104. Data: T = 500, N(0,1) shocks.

⊡ White noise, a first-order autoregressive (AR) model AR(1) with $\phi = 0.9$, a random walk
- AR(1) reverts to its mean; random-walk shocks are permanent: autocorrelation 0.96 at lag 10

⊡ **In practice:** a historical average price is a forecast only if the series is stationary.

(Hyndman & Athanasopoulos, 2021, OTexts)

EMQA_L1_sim_wn_ar_rw

# Autocorrelation: dependence of today's price on past prices

- **In one sentence:** The autocorrelation at lag $k$ is the correlation between the series and itself shifted by $k$ periods.

$$\hat{\rho}_k = \frac{\sum_{t=k+1}^{T}(x_t - \bar{x})(x_{t-k} - \bar{x})}{\sum_{t=1}^{T}(x_t - \bar{x})^2}$$

- White-noise band: $\pm 1.96/\sqrt{T}$.
- Bartlett band at lag $k$: $\pm 1.96\sqrt{(1 + 2\sum_{j<k}\hat{\rho}_j^2)/T}$, valid if the true autocorrelation is zero beyond lag $k-1$.
- Partial autocorrelation function (PACF): memory at lag $k$ net of shorter lags.

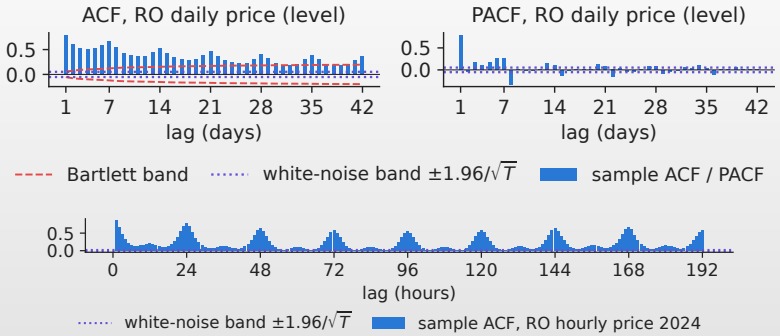
- **Four reading rules**
  - Slow decay from near 1: persistence or a unit root; test it
  - Geometric decay, PACF cut after $p$ lags: an AR($p$) model
  - Peaks at lags 7, 14 (days) or 24, 168 (hours): seasonality
  - All inside the band: no linear memory (check $x_t^2$ too)

- **In practice:** a supplier's forecast for tomorrow starts from "same weekday last week": $\hat{\rho}_7 = 0.672$ in Romania since 2023.

(Hyndman & Athanasopoulos, 2021; Ljung & Box, 1978)

**Experiment yourself:** notebook §6

# Autocorrelation of prices at daily and weekly lags




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: top: 2023-01-01 to 2026-10-31, T = 1400; bottom: 2024, hourly, T = 8784.

- Daily, 1 Jan 2023 – 31 Oct 2026: $\hat{\rho}_1 = 0.789$, $\hat{\rho}_7 = 0.672$, PACF $\hat{\alpha}_7 = 0.257$
  - Hourly, 2024: $\hat{\rho}_{24} = 0.776$, $\hat{\rho}_{168} = 0.681$.

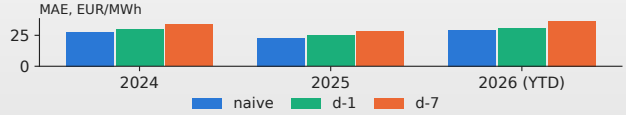
(Ziel & Weron, 2018, ENEECO)

EMQA_L1_acf_pacf_ro_daily EMQA_L1_acf_ro_hourly

# The naive forecast as a benchmark

- **In one sentence:** Tomorrow, each hour costs what it cost today (after weekends: the same day last week).

$$\hat{p}_{d,h} = \begin{cases} p_{d-1,h} & d = \text{Tue–Fri} \\ p_{d-7,h} & d = \text{Mon, Sat, Sun} \end{cases}, \qquad \text{MAE} = \frac{1}{n}\sum_{d,h} |p_{d,h} - \hat{p}_{d,h}|$$




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: hourly day-ahead prices, 2024-01 to 2026-10.

- Mean absolute error (MAE), EUR/MWh: Romania 2025, 22.9 at a mean price of 108.2
  - The weekday/weekend rule beats both pure lags in 7 of 8 years (Appendix E).

- **In practice:** before paying for a forecasting service, ask for its MAE next to this benchmark.

(Nogales et al., 2002, IEEE TPWRS; Weron, 2014, IJF; Lago et al., 2021, APEN)

EMQA_L1_naive_bar

# Shock persistence: two tests with opposite null hypotheses

- **In one sentence:** One test starts from "shocks are permanent" and looks for a pull back to a mean; the other starts from "the series is stable" and looks for a slow drift.

$$\Delta x_t = \alpha + \underbrace{\gamma\, x_{t-1}}_{\text{pull to the mean}} + \underbrace{\sum_j \delta_j \Delta x_{t-j}}_{\text{extra lags}} + u_t$$

| | KPSS: keep | KPSS: reject |
|---|---|---|
| ADF: reject | stationary | conflict |
| ADF: keep | inconclusive | unit root* |

- **where**
  - Augmented Dickey–Fuller (ADF): $H_0 : \gamma = 0$ (unit root), $\hat{\gamma}/\mathrm{se}$ against Dickey–Fuller critical values (about $-2.86$ at 5%), lags $p$ chosen by the Akaike information criterion (AIC)
  - Kwiatkowski–Phillips–Schmidt–Shin (KPSS): $H_0 =$ stationary, large values reject (0.463 at 5%)
  - Full formulas: Appendix A.

- *Consistent with a unit root, not a proof: ADF has low power against slow mean reversion, and level breaks (2022) push it towards "unit root".

- **In practice:** if a supplier's price can carry permanent shocks, "prices will come back to normal" is not a safe budget assumption.

(Dickey & Fuller, 1979, JASA; Kwiatkowski et al., 1992, J. Econometrics)

**Experiment yourself:** notebook §7

# ADF and KPSS results by series: levels and changes

| Series | Sample | $T$ | ADF | $p$ | KPSS | $p$ | Verdict |
|---|---|---|---|---|---|---|---|
| RO price, level | 2015–2026 | 4 317 | −2.71 | 0.073 | 3.645 | <0.01 | unit root* |
| RO price, daily change | 2015–2026 | 4 312 | −14.81 | <0.001 | 0.045 | >0.10 | stationary |
| DE-LU price, level | 2015–2026 | 4 322 | −3.54 | 0.007 | 3.441 | <0.01 | conflict |
| Brent, log price | 2015–2026 | 2 976 | −2.19 | 0.212 | 3.820 | <0.01 | unit root* |
| Brent, log return | 2015–2026 | 2 975 | −10.79 | <0.001 | 0.049 | >0.10 | stationary |
| RO hydro, deseasonalised | 2015–2025 | 132 | −4.19 | <0.001 | 0.354 | 0.097 | stationary |

- *Consistent with a unit root (not rejected); not a proof.

- Romanian and Brent **levels** are consistent with a unit root, while their **changes** are stationary.
- Germany: both tests reject (conflict): mean reversion plus the 2021–2022 level shift.
- Hydro is tested without its monthly means (a seasonal series)
  - Romanian price since 2023 only: ADF $p = 0.361$, KPSS 1.039.

- **In practice:** model price *changes* (or transformed prices) and put seasonality in explicitly.

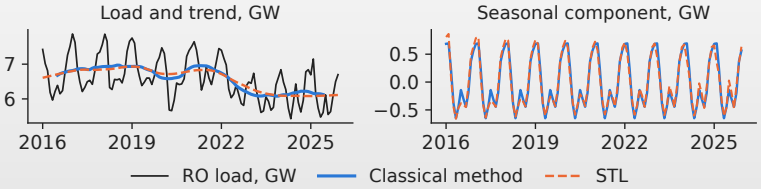
(own computation; constant only; ADF lags by AIC; 5% level)

**Experiment yourself:** notebook §7

# Decomposition: trend, seasonal and remainder components

⊡ **In one sentence:** Seasonal–Trend decomposition using Loess (STL) lets the season evolve.

$$x_t = T_t + S_t + R_t \qquad \text{(trend + season + remainder)}$$




Source: energy-charts.info (Fraunhofer ISE); ENTSO-E (Transelectrica data for Romania). Data: 2016-01 to 2025-12, monthly mean load.

⊡ Romanian load vs trend: Jan +0.69, Feb +0.69, May −0.65 GW
- ▶ STL amplitude 1.52 → 1.27 GW, moving-average (MA) weights: Appendix B.

⊡ **In practice:** Transelectrica and suppliers plan monthly capacity with seasonal indices.

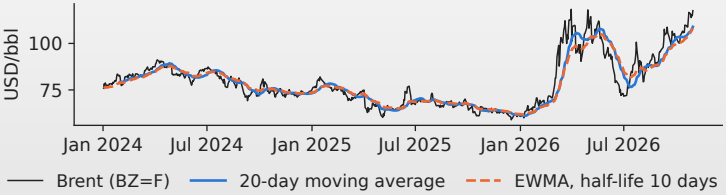
(Cleveland et al., 1990, JOS; Hyndman & Athanasopoulos, 2021)

EMQA_L1_decomp_load

# Exponential smoothing: higher weights on recent observations

⊡ **In one sentence:** The smoothed level averages all past values, with weights shrinking geometrically.

$$\ell_t = \underbrace{\alpha x_t}_{\text{news}} + \underbrace{(1-\alpha)\ell_{t-1}}_{\text{memory}}, \qquad \alpha = 1 - 2^{-1/h}$$




Source: Yahoo Finance (BZ=F). Data: 2024-01-02 to 2026-10-30.

⊡ $h$ = half-life (days), so the exponentially weighted moving average (EWMA) has $\alpha = 0.067$
- Best simple exponential smoothing (SES) weight: 0.948, almost the last price.

⊡ **In practice:** an EWMA is a good contract reference price, but a weak forecast.

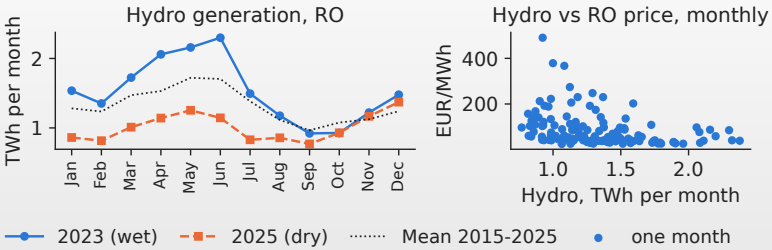
(Hyndman & Athanasopoulos, 2021, OTexts, ch. 8)

EMQA_L1_smooth_brent

# Outline

- Power markets in Romania and Europe
- Energy data and stylized facts
- Time-series methods
- Case studies on current data
  (a) Hydro output in 2023 and 2025
  (b) The June 2025 oil shock
  (c) Regional price separation, summer 2024
  (d) Negative prices and solar
  (e) Market developments in 2026
  (f) Romania, Bulgaria and batteries

# Case study (a): 2025 hydro output was a third below wet 2023




Source: energy-charts.info (Fraunhofer ISE); ENTSO-E (Transelectrica data for Romania). Data: monthly, 2015-01 to 2025-12.

- Hydro: 18.34 TWh in 2023 (highest since 2015) vs 12.15 TWh in 2025 (lowest), $-$**33.8%**
  - 2025 vs the 2015–2025 mean of 15.85 TWh: $-23.3\%$.
- Romania went from net exporter ($-3.06$ TWh) to net importer ($+3.76$ TWh)
  - Consistent with less water, but nuclear, demand and prices abroad also moved.

- **In practice:** a hydro producer's output and a net importer's bill depend on rain.

(energy-charts.info; data source: ENTSO-E)

EMQA_L1_hydro_case

# Case study (a): wetter months go with lower Romanian prices

- **In one sentence:** Holding the gas price fixed, months with more hydro output have had lower Romanian prices — an association, not a measured effect.

$$p_m = \beta_0 + \underbrace{\beta_1 \,\mathrm{Hydro}_m}_{\text{water}} + \underbrace{\beta_2 \,\mathrm{TTF}_m}_{\text{gas cost}} + u_m$$

- **where**
  - $p_m$ = mean RO day-ahead price, month $m$ (EUR/MWh)
  - $\mathrm{Hydro}_m$ = hydro output (TWh)
  - $\mathrm{TTF}_m$ = Dutch gas price (EUR/MWh)
  - Estimated by ordinary least squares (OLS) with heteroskedasticity- and autocorrelation-consistent (HAC) standard errors, 6 lags.

| 2015–2025 | $\hat{\beta}$ | s.e. | $t$ |
|---|---|---|---|
| Constant | 44.80 | 10.21 | 4.39 |
| Hydro | −19.55 | 7.02 | −2.78 |
| TTF | 1.89 | 0.06 | 34.16 |

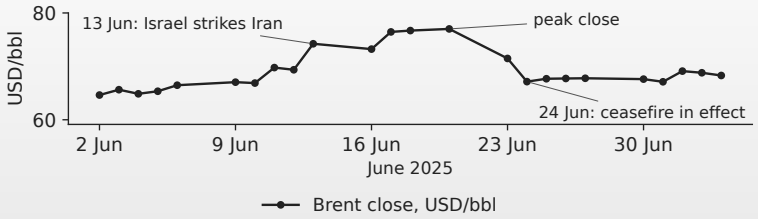
- One TWh more hydro in a month: −19.55 EUR/MWh on average, gas held fixed.
- Caveat: price and gas levels trend (Section 3): spurious regression unless cointegrated
  - $R^2 = 0.941$ is not evidence
  - Lecture 2 tests cointegration.

- **In practice:** hydro producers and traders watch reservoir levels as a leading indicator of the PZU price.

(own estimation; Newey–West standard errors)

**Experiment yourself:** notebook §10a

# Case study (b): one-day 7% rise in Brent and its reversal




Source: Yahoo Finance (BZ=F). Data: 2025-06-02 to 2025-07-04, trading days.

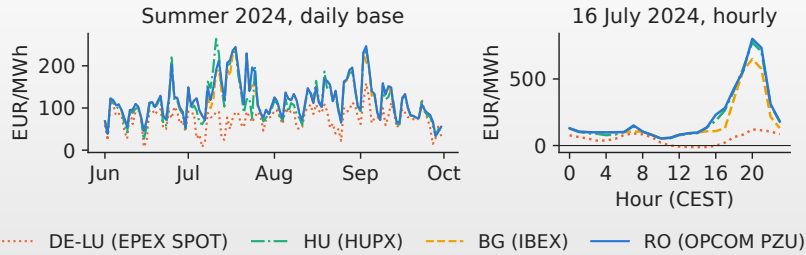
- Close 12 Jun 2025 69.36 → 13 Jun (Israel strikes Iran) 74.23: +**7.0%** (4.3 standard deviations of 2024 daily returns)
  - Peak 77.01 on 20 Jun 2025
  - 24 Jun (ceasefire in effect) 67.14, i.e. −**12.8%** from the peak and −3.2% vs 12 Jun.

- **In practice:** a fuel buyer hedged at the 20 June peak
  - Four days later the market was far below that price.

(Yahoo Finance, Brent BZ=F)

EMQA_L1_iran_brent

# Case study (c): in July 2024 Romania paid twice the German price




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: 2024-06-01 to 2024-09-30 daily (left); 2024-07-16 hourly (right).

- July 2024 averages: RO 145.14, BG 136.47, HU 135.54, DE-LU 67.70 EUR/MWh
  - 16 Jul: RO–DE-LU gap 162.87
  - RO hourly peak 801.62 at 20:00 while DE-LU was −11.48 at 14:00.

**In practice:** for South-East European buyers, the evening hours of hot, dry summers are the main price risk.

(energy-charts.info; daily and hourly day-ahead prices)

# Case study (c): evening hours, heat and network congestion

- Equal prices (within 0.01 EUR/MWh) in July hours: RO–BG 86.8%, RO–HU 6.3%, RO–DE-LU 3.1%
  - The network towards Central Europe was binding
  - Which element was binding cannot be read from prices alone.
- After sunset solar disappears while air conditioning keeps demand high
  - The region must import exactly then.
- Romanian hydro in July–August: 1.94 TWh in 2024 vs 2.67 in 2023
  - Net imports averaged 737 MW vs 66 MW.
- Summer peak: RO daily 246.89 EUR/MWh on 3 Sep 2024 (DE-LU 158.39)
  - Hourly 1021.61 at 19:00 CEST, the highest Romanian hourly price in our data.

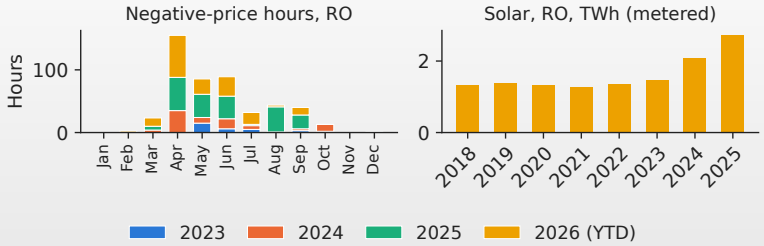
(energy-charts.info; ENTSO-E physical flows)

**Lesson for modelling**

- Coupled prices are equal only while the network is not binding.
- Model Romania with regional drivers: hydro, solar, load in South-East Europe.
- Treat the spread to Germany as its own, regime-dependent variable.

**Experiment yourself:** notebook §10c

# Case study (d): negative hours cluster in spring, as solar grows year after year




Source: energy-charts.info (Fraunhofer ISE); exchange prices (OPCOM, IBEX, HUPX, EPEX SPOT) via ENTSO-E. Data: Jan 2023 to 2026-10-31 (left); 2018-2025 (right).

- April–May hold 49.6% of Romanian negative hours since 2023 (June–August 34.0%)
  - Metered solar: 1.46 TWh (2023) → 2.72 TWh (2025), 4.33 TWh in Jan–Oct 2026.

- **In practice:** the cheapest hours are spring weekend middays
  - A battery charges and flexible industry consumes then.

(energy-charts.info; data source: ENTSO-E)

EMQA_L1_negative_solar

# Case study (d): factors associated with negative-price days

- **In one sentence:** We describe the realised conditions on days with at least one negative quarter-hour; this describes, it does not forecast for bidding.

$$\Pr(\text{negative day}) = \Lambda\Big(\beta_0 + \underbrace{\beta_1 R_d}_{\text{residual load}} + \beta_2 \mathrm{Hyd}_d + \underbrace{\beta_3 \mathrm{Wkd}_d + \gamma_y}_{\text{calendar}}\Big)$$

- **where**
  - $\Lambda(u) = 1/(1+e^{-u})$ (logit)
  - Residual load $R_d$ = load − solar − wind (daily means, GW), the demand left for other plants
  - $\gamma_y$ = year effects
  - Sample 1 Jan 2024 – 31 Oct 2026, $n = 1\,035$ days, 108 negative
  - Full table: Appendix F.

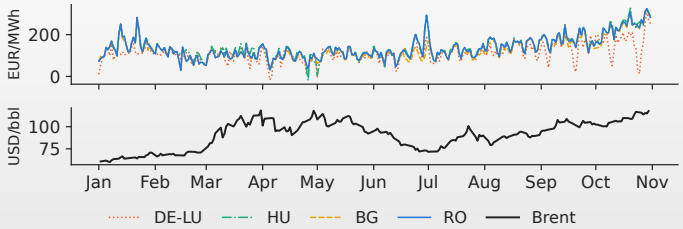
- **In plain words**
  - Each extra GW of residual load multiplies the odds of a negative day by 0.24
  - Each extra GW of hydro multiplies the odds by 4.52
  - A weekend day multiplies the odds by 16.13
  - McFadden pseudo-$R^2 = 0.369$

- **In practice:** curtailment of renewables is most likely on spring weekends with full reservoirs.

(own estimation, logit; energy-charts.info)

**Experiment yourself:** notebook §10d

# Case study (e): rising prices in 2026 and the oil price jump in March




Source: energy-charts.info (exchange prices via ENTSO-E); Yahoo Finance (BZ=F). Data: 2026-01-01 to 2026-10-31, daily.

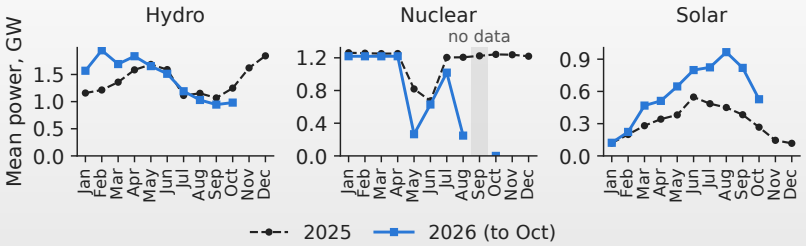
- Jan–Oct 2026: Romania 137.45 EUR/MWh (+29.8%)
  - October 239.3 vs 121.9 a year earlier.
- Brent monthly average 64.77 → 108.34 USD/bbl
  - Within March the May contract rose +52.2% (press: Iran conflict, Strait of Hormuz)
  - The −14.5% on 1 April is a contract roll.

**In practice:** budgets set in January were far too low.

(energy-charts.info; Yahoo Finance BZ=F; cut-off 31 Oct 2026)

EMQA_L1_cy_prices

# Case study (e): two Cernavodă outages and lower hydro output than in 2025




Source: energy-charts.info (Fraunhofer ISE); ENTSO-E (Transelectrica data for Romania). Data: monthly means of reported hours, 2025-01 to 2026-10.

- Nuclear 0 MW on 19 days in May and from August (low Danube)
  - Jan–Oct −31.3% on hours reported in both years (lower bound).
- Hydro −14.7% in Aug–Oct, solar +71.2% year to date.

**In practice:** one plant can move the national price: read REMIT messages like the weather forecast.

(Nuclearelectrica, 29 Jul 2026; World Nuclear News, 30 Jul 2026; CNCAN, 9 Sep 2026)

EMQA_L1_cy_generation

# Case study (e): prices about 30% higher and lower supply in 2026

| Jan–Oct | 2025 | 2026 | % chg |
|---|---|---|---|
| RO price, EUR/MWh | 105.88 | 137.45 | +29.8 |
| DE-LU price, EUR/MWh | 87.66 | 114.01 | +30.1 |
| RO − DE-LU, EUR/MWh | 18.2 | 23.4 | |
| RO negative hours | 196 | 171.75 | |
| RO hydro, TWh | 9.61 | 10.44 | +8.6 |
| RO nuclear, TWh* | 7.42 | 5.10 | −31.3 |
| RO solar, TWh | 2.53 | 4.33 | +71.2 |
| RO net imports, TWh | 3.67 | 2.51 | |

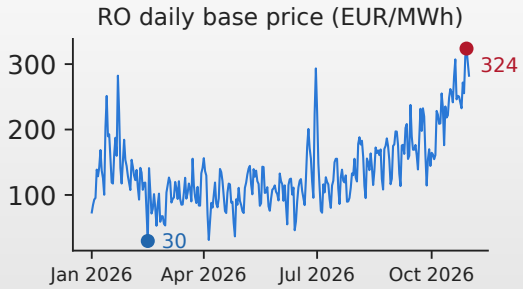
- Green = favourable for a consumer, red = unfavourable; cut-off 31 Oct 2026.
- *Hours reported in both years (lower bound).

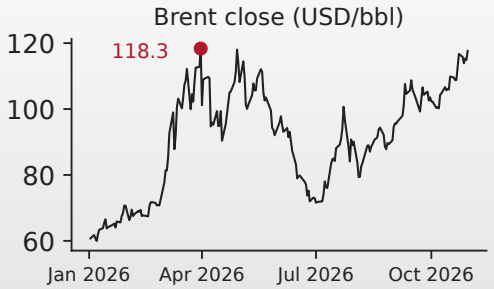
- **In practice:** price up by about 30%, with nuclear, hydro and oil all pointing the same way, and a hedge paid for itself.

(own computation; energy-charts.info)

**Experiment yourself:** notebook §10e

# Case study (e): 2026 extremes in Romania and on Brent




Source: energy-charts.info (OPCOM prices); Yahoo Finance (BZ=F). Data: 2026-01-01 to 2026-10-31, daily.

**Romania**

- Daily base price: high 323.76 EUR/MWh on 29 Oct 2026, low 29.63 on 15 Feb 2026
- Quarter-hour: high 1015.65 on 30 Jun 2026, 18:45, low −99.75 on 26 Apr 2026, 13:00 (CET/CEST)

(own computation; energy-charts.info; Yahoo Finance)

EMQA_L1_cy_extremes

# Case study (e): 2026 extremes in Germany and on Brent

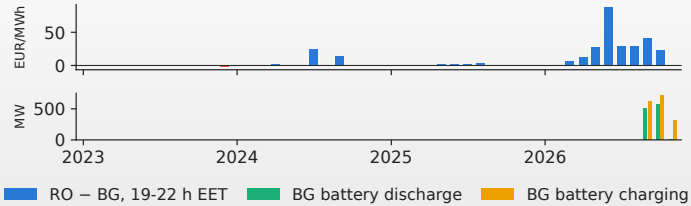
- **Germany**
  - Lowest quarter-hour −499.99 on 1 May 2026, 13:15, at the −500 floor then in force
  - After such prices on 26 April and 1 May, the floor became −600 for delivery from 29 May 2026
- **Brent**
  - Highest close 118.35 USD/bbl on 31 Mar 2026
  - Largest daily change excluding contract rolls: −13.29% on 8 Apr 2026

- **In practice:** set risk limits on the extremes, not on the averages.

(own computation; OPCOM SDAC note, 7 May 2026)

**Experiment yourself:** notebook §10e

# Case study (f): lower evening prices in Bulgaria since spring 2026




Source: energy-charts.info (Fraunhofer ISE); ENTSO-E (Transelectrica data for Romania). Data: 2023-01 to 2026-10, local time; BG battery series reported from 2026-09-10.

- Evenings 19:00–22:00 local time (EET), Apr–Sep, RO vs BG
  - 171.1 vs 169.7 EUR/MWh (2025), 215.5 vs 178.0 (2026)
  - Middays 11:00–15:00 close in 2026 (48.1 vs 46.0).
- Battery data start only 10 Sep 2026, after the gap opened (May 2026)
  - An association, not proof.

- **In practice:** a Romanian battery developer competes for the same evening spread (Lecture 6).

(energy-charts.info; data source: ENTSO-E; own computation, local time EET)

EMQA_L1_bg_battery

## Quiz 1: counting negative prices

- In a month after 1 October 2025, 48 of Romania's quarter-hour prices were negative
  - A board member asks how many negative hours there were
  - What do you answer?

**Answer**

- $48 \times 15/60 = 12$ hour-equivalents
  - Saying 48 "hours" overstates by a factor of 4 against earlier, hourly years
  - Best answer: "48 quarter-hours (12 hours)".

## Quiz 2: reading an autocorrelation

- Your analyst says: "the PZU price autocorrelation is 0.98 at lag 1 and 0.90 at lag 30, so prices are white noise and last month tells us nothing"
  - Is this right?

**Answer**

- No: white noise has autocorrelations near 0
  - Values near 1 mean strong persistence, i.e. a unit root or a very slow mean reversion
  - Run ADF and KPSS and look at the autocorrelation of daily changes.

# Wrap-up

- Power markets in Romania and Europe
  - How the day-ahead auction works
  - Market coupling and the 15-minute market time unit
  - Electricity generation in Romania
- Energy data and stylized facts
  - Units, clocks and clean data
  - Price level and seasonality
  - Spikes and negative prices
  - Distribution and volatility
- Time-series methods
  - Stationarity and autocorrelation
  - Unit-root tests, decomposition, smoothing
- Case studies on current data
  - (a) Hydro output in 2023 and 2025
  - (b) The June 2025 oil shock
  - (c) Regional price separation, summer 2024
  - (d) Negative prices and solar
  - (e) Market developments in 2026
  - (f) Romania, Bulgaria and batteries

- One auction per day, coupled across Europe, with 96 quarter-hours since Oct 2025
  - Count in hour-equivalents.
- Benchmark to beat: the naive forecast (Romania 2025: MAE 22.92 EUR/MWh)
  - Next: forecasting (Lecture 2).

# Research from our group on the Romanian market

- **The summer-2024 crisis** (Case c): a counterfactual analysis of Romania's June–July 2024 price crisis on ENTSO-E hourly data
  - A 10% demand reduction is the robust first-tier intervention, and the peak fell in hours with almost no solar (Andrei, Pele & Cramer, 2026, PICBE).
- **Explaining price forecasts**: which drivers matter at which horizon (0–6 h up to two weeks) and in which price regime, for Romanian hourly prices 2018–2024 (Andrei, Pele & Cramer, 2026, PICBE) — preview of Lecture 7.
- **Forecasting national consumption**: classical seasonal models against neural networks on Romanian load (Proșcanu, Proșcanu, Pele & Costea, 2025, Romanian J. Economic Forecasting) — preview of Lecture 2.
- **Demand barely reacts to price**: Romanian consumption is price-inelastic
  - Granger causality runs from consumption to price, not back (Proșcanu, Proșcanu & Pele, 2025, J. Social and Economic Statistics) — why the demand curve is steep.
- **Does liberalisation lower prices?** Causal machine learning on US market liberalisation finds a short-term price decrease of about 7% (Shahar, Lessmann & Pele, 2025, arXiv 2507.12331).
- Findings as stated in the papers' abstracts; 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

- **R. Weron, IIF Distinguished Lectures on electricity price forecasting** (2025): slides part I, part II, notebooks, videos.
- **epftoolbox**, the open benchmark of Lago et al. (2021): github.com/jeslago/epftoolbox.
- **Forecasting: Principles and Practice**, 3rd ed.: otexts.com/fpp3.
- **This course**: code, data, notebooks — github.com/danpele/EMQA.
- **Data and rules**: energy-charts.info, ENTSO-E Transparency Platform, opcom.ro, transelectrica.ro, jao.eu.
- **Experiment yourself**: the notebook reproduces every chart and number of this lecture — notebooks/.

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# Appendix A: ADF and KPSS in full

## ADF (Said & Dickey, 1984)

$$\Delta x_t = \alpha + \beta t + \gamma x_{t-1} + \sum_{j=1}^{p} \delta_j \Delta x_{t-j} + u_t$$

- $H_0 : \gamma = 0$ vs $H_1 : \gamma < 0$
  - $\tau = \hat{\gamma}/\mathrm{se}(\hat{\gamma})$ follows the Dickey–Fuller distribution
  - $p$-values from MacKinnon (1996).
- Lag order: minimise AIC starting from $p_{\max} = 12(T/100)^{1/4}$.
- Deterministic terms must match the alternative
  - Constant: level-stationary
  - Trend: trend-stationary.

## KPSS (Kwiatkowski et al., 1992)

$$\mathrm{KPSS} = \frac{1}{T^2 \hat{\sigma}^2_{\mathrm{LR}}} \sum_{t=1}^{T} S_t^2, \quad S_t = \sum_{s \le t} e_s$$

$$\hat{\sigma}^2_{\mathrm{LR}} = \hat{\gamma}_0 + 2 \sum_{k=1}^{\ell} \left(1 - \frac{k}{\ell + 1}\right) \hat{\gamma}_k$$

- $e_s$ = residuals from a regression on a constant (and trend).
- Bartlett kernel with bandwidth $\ell$ (Hobijn et al. rule in statsmodels)
  - Critical value 0.463 (5%, level).

# Appendix B: classical decomposition, worked example

$$\hat{T}_t = \tfrac{1}{24}x_{t-6} + \tfrac{1}{12}\sum_{j=-5}^{5} x_{t+j} + \tfrac{1}{24}x_{t+6}$$

- First trend value, Jul 2016: $\hat{T} = \frac{1}{24}(7.424 + 7.870) + \frac{1}{12}\cdot 72.503 = 6.679$ GW (Jan 2016 and Jan 2017 at half weight; Feb–Dec 2016 summed).
- Observed 6.389 GW $\Rightarrow$ deviation $-0.290$.
- Seasonal index: $\hat{S}_j = \bar{d}_j - \frac{1}{12}\sum_i \bar{d}_i$ (raw means summed to 0.0005).

| Month | $\hat{S}_j$ | Month | $\hat{S}_j$ |
|---|---|---|---|
| Jan | 0.686 | Jul | −0.143 |
| Feb | 0.694 | Aug | −0.302 |
| Mar | 0.237 | Sep | −0.444 |
| Apr | −0.381 | Oct | −0.194 |
| May | −0.650 | Nov | 0.374 |
| Jun | −0.442 | Dec | 0.565 |

- Romanian load (GW), Jan 2016 – Dec 2025; checked against statsmodels.

# Appendix C: the STL algorithm

- **Inner loop** (repeated): (1) detrend, $x_t - \hat{T}_t$
  - (2) smooth each month's sub-series (all Januaries, all Februaries, ...) by loess with span $n_s$
  - (3) remove its low-frequency part $\Rightarrow \hat{S}_t$
  - (4) smooth $x_t - \hat{S}_t$ by loess with span $n_t \Rightarrow \hat{T}_t$.
- **Outer loop**: robustness weights $\rho_t = B\big(|\hat{R}_t|/(6\,\mathrm{median}|\hat{R}|)\big)$, $B(u) = (1-u^2)^2$ for $|u| < 1$, else 0, so outliers count less in the next inner loop.
- Here: period 12, $n_s = 13$, robust
  - Strength of seasonality $1 - \mathrm{Var}(R)/\mathrm{Var}(S+R) = 0.848$.
- Additive only: for multiplicative seasonality apply STL to $\ln x_t$ (or asinh for prices).

(Cleveland, Cleveland, McRae & Terpenning, 1990, JOS)

# Appendix D: generation mix in numbers

| Share, % | 2015 | 2020 | 2023 | 2024 | 2025 | Jan–Oct 2025 | Jan–Oct 2026 |
|---|---|---|---|---|---|---|---|
| Hydro | 26.2 | 27.8 | 32.4 | 27.9 | 25.6 | 25.7 | 27.6 |
| Nuclear | 17.9 | 20.7 | 19.8 | 21.1 | 21.3 | 19.8 | 13.5 |
| Coal | 28.3 | 17.4 | 14.4 | 13.6 | 13.8 | 14.4 | 12.1 |
| Gas | 14.6 | 18.4 | 16.9 | 20.1 | 20.2 | 19.8 | 20.5 |
| Wind | 10.3 | 12.4 | 13.2 | 12.4 | 12.4 | 12.6 | 13.9 |
| Solar | 1.9 | 2.4 | 2.6 | 4.1 | 5.7 | 6.8 | 11.4 |
| Biomass | 0.8 | 0.9 | 0.7 | 0.9 | 0.9 | 0.9 | 1.0 |
| **Total TWh** | 64.2 | 55.4 | 56.6 | 51.2 | 47.4 | 37.4 | 37.9 |
| Load TWh | 57.0 | 58.1 | 53.4 | 54.3 | 53.6 | 43.9 | 42.3 |
| Net imp. TWh | −6.9 | 1.9 | −3.1 | 3.0 | 3.8 | 3.7 | 2.5 |

- Last two columns: hours reported in both years.
- Net imports $> 0$: into Romania.

(energy-charts.info; data source: ENTSO-E)

# Appendix E: naive benchmark, all years

| MAE | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|---|---|---|
| RO naive | 9.7 | 7.4 | 19.9 | 59.7 | 26.0 | 27.7 | 22.9 | 29.4 |
| RO $d-1$ | 10.7 | 8.1 | 22.2 | 58.5 | 27.3 | 29.7 | 24.9 | 31.1 |
| RO $d-7$ | 11.2 | 8.6 | 25.1 | 75.4 | 31.0 | 33.9 | 28.2 | 36.6 |
| DE-LU naive | 9.8 | 9.3 | 24.3 | 66.2 | 28.6 | 27.3 | 27.5 | 36.1 |
| DE-LU $d-1$ | 9.5 | 10.0 | 25.3 | 58.2 | 27.2 | 27.8 | 26.0 | 32.8 |
| DE-LU $d-7$ | 10.3 | 10.3 | 31.5 | 87.1 | 33.6 | 32.8 | 32.8 | 42.2 |

- MAE in EUR/MWh on hourly prices (from Oct 2025: hourly mean of the 15-min prices).
- Green = best of the three in that year and zone.

(Nogales et al., 2002, IEEE TPWRS; Weron, 2014, IJF)

# Appendix F: fat tails and the negative-day logit in full

$$\hat{S} = \frac{\frac{1}{T}\sum_t (r_t - \bar{r})^3}{\hat{\sigma}^3}, \quad \hat{K} = \frac{\frac{1}{T}\sum_t (r_t - \bar{r})^4}{\hat{\sigma}^4}$$

$$\mathrm{JB} = \frac{T}{6}\left(\hat{S}^2 + \frac{(\hat{K}-3)^2}{4}\right) \sim \chi^2_2$$

- Brent daily log returns (roll days removed): skewness $-0.94$, excess kurtosis 13.98, JB 23 500 (5% critical value 5.99)
  - Student-$t$ fit: 3.21 degrees of freedom.

(Jarque & Bera, 1980; own estimation)

| | $\hat{\beta}$ | odds ratio | $z$ |
|---|---|---|---|
| Constant | $-0.023$ | 0.98 | $-0.02$ |
| Residual load, GW | $-1.445$ | 0.24 | $-7.67$ |
| Hydro, GW | 1.508 | 4.52 | 4.37 |
| Weekend | 2.780 | 16.13 | 9.24 |
| Year 2025 | 1.337 | 3.81 | 3.98 |
| Year 2026 | 0.534 | 1.71 | 1.54 |

- Logit for a day with at least one negative RO quarter-hour; base year 2024.

# Appendix G: converting gas and oil prices to EUR/MWh

$$P^{\text{EUR/MWh}} = P^{\text{USD/MMBtu}} \times 3.412142 \,/\, e_m$$

- **where**
  - 1 MMBtu = 0.293071 MWh, so $1/0.293071 = 3.412142$ MMBtu per MWh
  - $e_m$ = monthly USD per EUR rate of the ECB
  - Brent: 1 bbl = 159 litres, quoted in USD/bbl

(World Bank Commodity Price Data; ECB reference rates)

- World Bank TTF is a monthly average in USD/MMBtu converted with the ECB rate
  - It is not a traded EUR quote.
- Compare fuels and power only in the same unit and currency
  - A gas price in USD/MMBtu and a power price in EUR/MWh differ by a factor of about 3.4 before any exchange rate.