



Energy Markets Quantitative Analysis

Lecture 5: Energy Derivatives and Hedging



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Learning objectives

- **Contracts**
  - Forwards and futures on power and gas, physical or cash-settled; the forward curve
- **Plant margins**
  - Spark and dark spreads, clean of the price of the European Union (EU) emission allowance (EUA)
- **Hedging**
  - The minimum-variance hedge ratio and its uncertainty; basis risk; shape risk
- **Options**
  - Caps, floors and collars; the Black-76 formula with a volatility estimated on real data
- **Decisions**
  - What a Romanian supplier and a producer gained or lost by hedging in 2022, 2025 and 2026

Abbreviations (1/2)

ACER	European Union Agency for the Cooperation of Energy Regulators
CDS	clean dark spread
CET	Central European Time
CSS	clean spark spread
DE-LU	Germany–Luxembourg bidding zone
ECB	European Central Bank
EEX	European Energy Exchange
ENTSO-E	European Network of Transmission System Operators for Electricity
EPEX	European Power Exchange (EPEX SPOT)
ETC	exchange-traded commodity
EU	European Union
EUA	EU emission allowance (1 t CO_2)
EUR	euro
GARCH	generalised autoregressive conditional heteroskedasticity
HAC	heteroskedasticity- and autocorrelation-consistent
HE	hedge effectiveness
HU	Hungary (bidding zone)
HUDEX	Hungarian Derivative Energy Exchange
HUPX	Hungarian Power Exchange
IPCC	Intergovernmental Panel on Climate Change
ISE	Fraunhofer Institute for Solar Energy Systems
LASSO	least absolute shrinkage and selection operator
LD	Monday to Sunday (luni–duminică), OPCOM product code

Abbreviations (2/2)

MACEE	Centralised Electricity Purchase Mechanism (Romania, 2023–2024)
MW	megawatt
MWh	megawatt-hour
NYMEX	New York Mercantile Exchange
OLS	ordinary least squares
OPCOM	Romanian electricity and gas market operator
OUG	Government Emergency Ordinance (Romania)
PC-OTC	OPCOM continuous market for standardised bilateral contracts
PCCB-LE	OPCOM centralised market for bilateral contracts, extended auctions
PPA	power purchase agreement
PZU	Piața pentru Ziua Următoare (day-ahead market)
RO	Romania (bidding zone)
RON	Romanian leu
SS	spark spread
€STR	euro short-term rate
TJ	terajoule
TTF	Title Transfer Facility (Dutch gas hub)
TWh	terawatt-hour
USD	United States dollar
VaR	value at risk
VM	variation margin
VWAP	volume-weighted average price

Data sources: Romanian forwards, spot prices, gas and carbon

Series	Frequency	Source
Romanian forward contracts: 2 298 auctions, 83.7 TWh	per auction	Romanian electricity and gas market operator (OPCOM): centralised market for bilateral contracts, extended auctions (PCCB-LE)
Day-ahead prices, Piața pentru Ziua Următoare (PZU): Romania (RO), Hungary (HU), Germany–Luxembourg (DE-LU)	hourly	OPCOM, Hungarian Power Exchange (HUPX), European Power Exchange (EPEX SPOT); energy-charts.info (Fraunhofer ISE), from the European Network of Transmission System Operators for Electricity (ENTSO-E)
Gas: Title Transfer Facility (TTF); coal	monthly, daily	World Bank Pink Sheet; New York Mercantile Exchange (NYMEX) futures, via Yahoo Finance
Carbon (EUA); EUR/RON; euro short-term rate (€STR)	daily	European Energy Exchange (EEX) auctions; exchange-traded commodity (ETC); European Central Bank (ECB)

- **Cut-off** 31 Oct 2026 (last complete month)
  - Forward auctions 12 May 2020 – 28 Oct 2026.
- **Not free**: EEX or Hungarian Derivative Energy Exchange (HUDEX) power futures, option prices
  - We do not invent them.

Experiment yourself: notebook §1

Outline

- Reasons for hedging: price exposures and the 2021–2022 crisis
- Forwards, futures and the forward curve
- Spreads: the margins of power plants
- Hedge ratio, basis risk and shape risk
- Options on energy
- Case study: a Romanian supplier and a producer

Every firm in the power chain holds a price position

- **In one sentence:** A supplier with fixed retail prices loses when the wholesale price rises; a producer loses when it falls.

$$\Pi^{\text{sup}} = Q(\underbrace{R}_{\text{retail}} - \underbrace{S}_{\text{spot}}), \quad \Pi^{\text{prod}} = Q(S - \underbrace{c}_{\text{cost}})$$

$$\Pi^{\text{sup}}_{\text{hedged}} = Q(R - S) + Q(S - F) = Q(R - F)$$

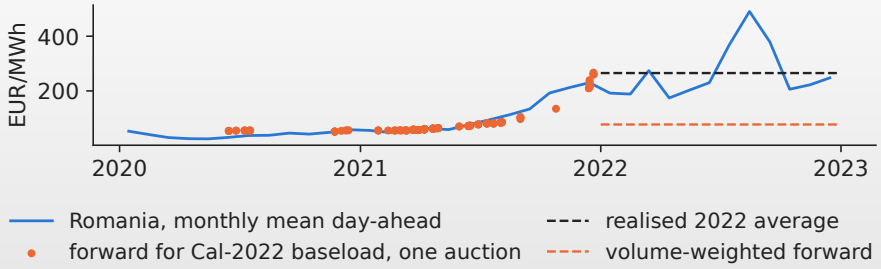
- **where**
  - Q = energy, MWh
  - S = spot price at delivery
  - F = forward price fixed today, EUR/MWh
  - A bought forward pays $S - F$ per MWh.

- **Short power**
  - Supplier at fixed prices, industrial consumer
  - Hedge: buy forward or a cap
- **Long power**
  - Hydro, nuclear, lignite and solar producers
  - Hedge: sell forward or buy a floor
- **Long the spread**
  - Gas plant: power minus gas and carbon

- **In practice:** fix the sign of your exposure first: a long firm that buys forward doubles its risk.

(Hull, 2022; Eydeland & Wolyniec, 2003)

In 2022 the spot cost 3.4 times the forward bought earlier



Source: OPCOM (PCCB-LE-flex results; day-ahead prices via energy-charts.info); ECB. Data: 150 auctions for 2022 baseload; spot 2020-2022.

- 2022 baseload: 150 auctions, volume-weighted average price (VWAP) 77.4 EUR/MWh; spot 265.3
  - 2020: 54.4; first half of 2021: 61.5; second half: 136.7; saving 1.65 million EUR per MW

- **In practice:** when you hedge matters: contracts bought late in 2021 cost twice as much.

(own computation; OPCOM)

EMQA_L5_crisis_cal22

The crisis reduced forward trading and led to regulated prices

- **A transfer, not a gain**
  - Each MWh sold forward for 2022 went 187.9 EUR/MWh below spot: producers lost what hedged suppliers saved
- **Then forwards overshot**
  - Calendar 2023 traded up to 509.2 on 17 Aug 2022; 2023 averaged 103.7 EUR/MWh
- **Romania**
  - Government Emergency Ordinance (OUG) 27/2022: capped final prices
  - OUG 153/2022: Centralised Electricity Purchase Mechanism (MACEE), OPCOM single buyer at 450 lei/MWh for 2023–2024
  - OPCOM forward volume: 27.3 TWh in 2021, 1.6 TWh in 2023
- **In the EU**
  - The EU Agency for the Cooperation of Energy Regulators (ACER) kept the market design and flagged thin forward markets beyond three years

- **In practice:** write the hedging policy before the crisis
  - During it, nobody can agree on one.

(OUG 27/2022; OUG 153/2022; ACER, 2022; OPCOM)

Experiment yourself: notebook §2

Outline

- Reasons for hedging: price exposures and the 2021–2022 crisis
- Forwards, futures and the forward curve
  - Contracts
  - The forward curve
- Spreads: the margins of power plants
- Hedge ratio, basis risk and shape risk
- Options on energy
- Case study: a Romanian supplier and a producer

A power forward delivers constant MW over a whole period

- **In one sentence:** A baseload forward fixes today the price of every hour of a month, quarter or year.

$$\bar{S} = \frac{1}{H}\sum_{h=1}^{H} S_h, \qquad \underbrace{V_T = q\,H\,(\bar{S} - F)}_{\text{value to the buyer}}$$

- **where**
  - H = hours of the delivery period (744 in a 31-day month, 8 760 in a year)
  - S_h = day-ahead price of hour h
  - q = power, MW
  - F = forward price.

- **Profiles**
  - Band: all hours, Monday to Sunday (LD), 94% of volume
  - Peak: the peak hours of working days only
- **OPCOM, 31 Oct 2026**
  - Year 2027: 148.1 EUR/MWh $\times$ 8 760 MWh per MW
  - Next month: 215.3 EUR/MWh

- **In practice:** price a customer's contract on the forward of its delivery period, not on today's spot.

(OPCOM; Benth et al., 2008)

Experiment yourself: notebook §3

Physical delivery and cash settlement

- **In one sentence:** A physical forward delivers MWh at F; a cash-settled future pays the gap to a reference average.

$$\underbrace{F \cdot Q}_{\text{physical}} = \underbrace{\bar{S} Q}_{\text{spot}} - \underbrace{(\bar{S}^{\text{ref}} - F) Q}_{\text{cash settlement}} \text{ only if } \bar{S}^{\text{ref}} = \bar{S}$$

- **where**
  - $\bar{S}^{\text{ref}}$ = settlement index of the future (e.g. the German average)
  - Otherwise the gap is basis risk (section 4).

- **Physical, Romania**
  - OPCOM PCCB-LE auctions and continuous trading of standard contracts (PC-OTC)
  - No basis risk
- **Cash-settled, abroad**
  - EEX and HUDEX futures, cleared
  - Margin calls replace counterparty risk

- **In practice:** physical when you need MWh in Romania
  - Cash-settled when you need liquidity and can carry the basis.

(OPCOM; Hull, 2022)

Daily settlement of futures and the liquidity needs of a hedge

⊡ **In one sentence:** A forward settles once at delivery; a future pays or collects every day's price change.

$$\underbrace{VM_t = Q(F_t - F_{t-1})}_{\text{variation margin}}, \qquad \sum_{t=1}^{T} VM_t = Q(F_T - F_0)$$

⊡ **where**

- F_t = settlement price of day t
- Q = MWh
- Initial margin from a value-at-risk (VaR) model (Lecture 4).

⊡ **NYMEX TTF, December 2026**

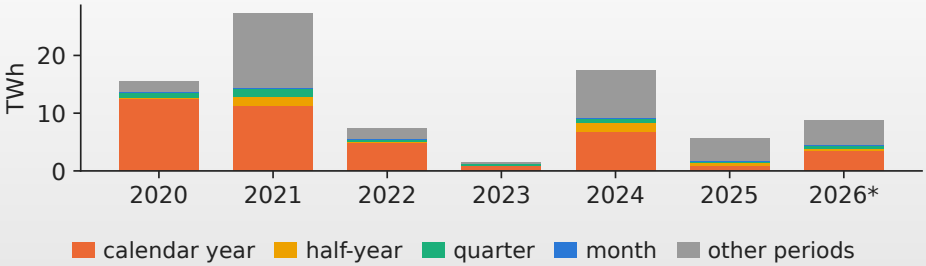
- 1 487 daily prices, 15.1 – 103.9 EUR/MWh
- Largest daily move 11.83 EUR/MWh, 29 Aug 2022
- 10 MW × 744 h: margin call 88 015 EUR in a day

⊡ **In practice:** size a credit line for the worst daily move before hedging on an exchange.

(own computation; Hull, 2022)

Experiment yourself: notebook §3

Romanian forward volume collapsed in 2022–2023



Source: OPCOM, PCCB-LE-flex results; ECB (EUR/RON). Data: 2,298 traded auctions, 2020-05-12 to 2026-10-31; *2026 to the cut-off.

- Three producers sell 83% of the volume: lignite 32%, nuclear 30%, hydro 21%
  - Calendar-year products: 80% of baseload volume

- **In practice:** liquidity is thin: spread purchases over many auctions.

(own computation; OPCOM)

EMQA_L5_fw_volume

Forward prices and the cost of carry: gas and power

- **In one sentence:** Gas can be stored, which ties forward to spot; power cannot, so its forward is an expectation plus a risk premium.

$$\underbrace{F_{t,T} = S_t e^{(r+u-y)(T-t)}}_{\text{storable}}, \qquad \underbrace{F_{t,T} = \mathbb{E}_t[\bar{S}_T] + \pi_{t,T}}_{\text{power}}$$

- **where**
  - r = interest rate
  - u = storage cost
  - y = convenience yield
  - π = risk premium
  - Contango $F > S$, backwardation $F < S$.

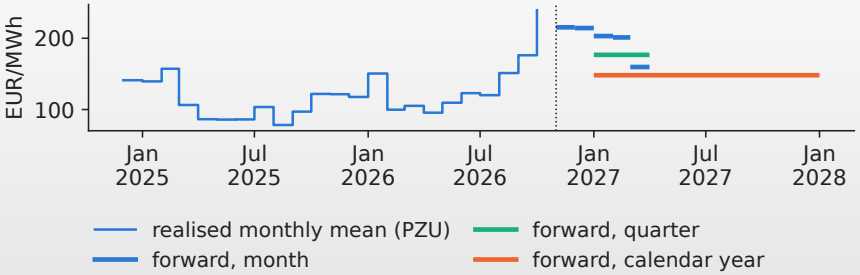
- **Gas**, NYMEX TTF, 30 Oct 2026
  - Dec 2026 103.9, May 2027 78.1 EUR/MWh
  - Winter above summer pays for storage
- **Power**, OPCOM
  - October spot 239.3; Q1 2027 176.7; year 148.1
  - Backwardation: the spike is expected to fade

- **In practice:** never put today's spot into next year's budget
  - Use the curve.

(Fama & French, 1987; Bessembinder & Lemmon, 2002)

Experiment yourself: notebook §3

The Romanian forward curve slopes down from a high spot



Source: OPCOM (PCCB-LE-flex results; day-ahead prices via energy-charts.info); ECB. Data: 85 auctions 2026-09-01 to 2026-10-31.

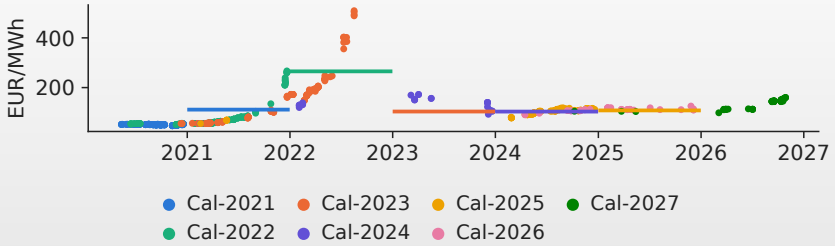
- 7 baseload products, VWAP per delivery period: next month 215.3, Q1 176.7, year 2027 148.1 EUR/MWh.

- **In practice:** a 2027 offer starts from 148 EUR/MWh, not from the October spot.

(own computation; OPCOM)

EMQA_L5_fwd_curve

Yearly forward prices by trade date and realised spot prices



Source: OPCOM (PCCB-LE-flex results; day-ahead prices via energy-charts.info); ECB. Data: calendar-year baseload auctions to 2026-10-31; thick line = realised mean.

- 2021: VWAP 51.3, realised 111.4
  - 2023: 172.5 vs 103.7
  - 2025: 102.1 vs 108.2 EUR/MWh.

In practice: the forward is the price of certainty, not a forecast to rely on in a crisis.

(own computation; OPCOM)

EMQA_L5_cal_by_trade

The ex-post forward premium has no stable sign in Romania

- **In one sentence:** If buyers fear spikes more than sellers fear slumps, forwards trade above the expected spot.

$$\hat{\pi}_i = F_i - \bar{S}_i, \qquad t = \frac{\bar{\pi}}{\widehat{\mathrm{se}}_{\mathrm{HAC}}(\bar{\pi})}$$

- **where**
  - i = delivery month
  - F_i = VWAP of the monthly band bought the month before
  - $\bar{S}_i$ = realised mean
  - Standard error heteroskedasticity- and autocorrelation-consistent (HAC), Newey–West, 3 lags.

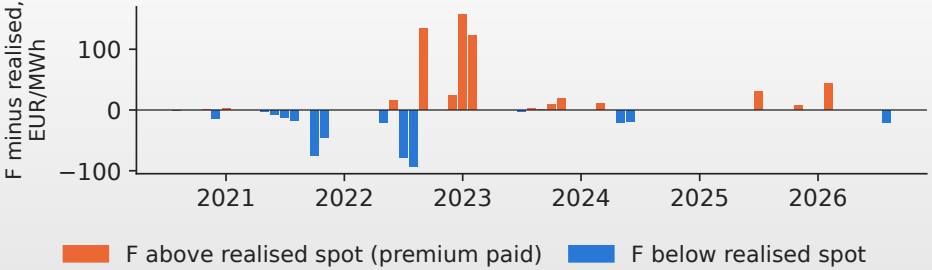
- **One month ahead**, 30 months
  - Mean +5.2 EUR/MWh, $t = 0.42$, $p = 0.68$
  - Since 2023: +24.5, $t = 1.51$
- **All products**, volume-weighted
  - Delivered to 2021: −55.8
  - 2022: −166.5; from 2023: +29.7 EUR/MWh

- **In practice:** hedging is cheap on average
  - Its real cost is the upside you give up.

(Bessembinder & Lemmon, 2002; Redl et al., 2009)

Experiment yourself: notebook §3

Monthly difference between forward and spot prices



Source: OPCOM (PCCB-LE-flex results; day-ahead prices via energy-charts.info); ECB. Data: 30 delivery months, 2020-08 to 2026-08.

- Median −0.2 EUR/MWh
  - The deep negative bars are 2021–2022 surprises, not a stable discount.

- **In practice:** judge a hedge by the risk it removed, not by its ex-post profit.

(own computation; OPCOM)

EMQA_L5_premium

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Clean spark spread: power minus gas minus carbon

- **In one sentence:** A gas plant sells 1 MWh of power, burns $1/\eta$ MWh of gas and pays for its CO_2.

$$SS = P - \frac{G}{\eta_g}, \qquad CSS = P - \frac{G}{\eta_g} - \frac{e_g}{\eta_g} A$$

- **where**
  - Spark spread (SS), clean spark spread (CSS)
  - P = power, EUR/MWh
  - G = gas, EUR/MWh thermal
  - η_g = efficiency of the gas plant, 0.50 (assumed)
  - e_g = emission factor of gas, 0.202 t CO_2/MWh thermal, Intergovernmental Panel on Climate Change (IPCC)
  - A = EUA, EUR/t.

- **Romania, Oct 2026**
  - Power 239.3; gas cost per MWh of power 173.6 (= 86.8/0.5); carbon 33.3
  - SS +65.7, CSS +32.4 EUR/MWh
- **Yearly mean CSS**
  - Romania: 2022 −32.2, 2025 +5.8
  - Germany: 2022 −62.2, 2025 −13.1

- **In practice:** a gas producer hedges the spread: sell power, buy gas and EUA forward together.

(IPCC, 2006; Deng et al., 2001)

Experiment yourself: notebook §4

Dark spreads and the carbon price that favours gas over coal

In one sentence: Coal emits more CO_2 per MWh, so a high EUA price pushes coal behind gas in the merit order.

$$CDS = P - \frac{C}{\eta_c} - \frac{e_c}{\eta_c} A, \qquad A^* = \frac{G/\eta_g - C/\eta_c}{e_c/\eta_c - e_g/\eta_g}$$

where

- Clean dark spread (CDS)
- C = coal price, EUR/MWh thermal (USD/t ÷ EUR/USD ÷ 6.978)
- η_c = coal plant efficiency, 0.38 (assumed)
- e_c = emission factor, 0.341 t CO_2/MWh thermal
- A^* = EUA price at which CSS = CDS.

Month: Oct 2026

- Coal 12.8 EUR/MWh thermal; CDS Romania +131.7
- A^* = 283.7 EUR/t vs EUA 82.4

Caveats

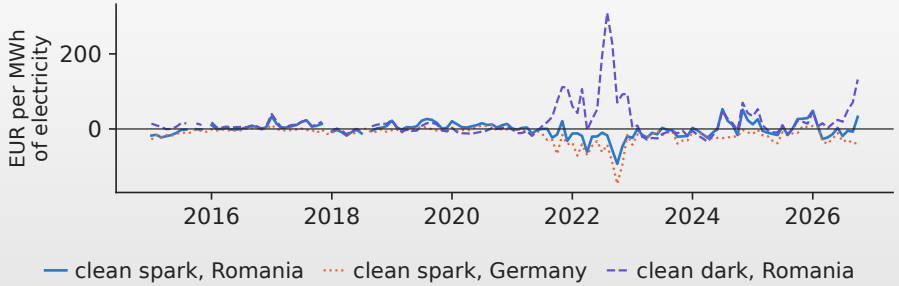
- Lignite has no market price; coal = South African export price
- EUA = EEX auctions, then the ETC from Jan 2026

In practice: a coal producer selling power forward should buy EUA forward with it.

(IPCC, 2006; World Bank)

Experiment yourself: notebook §4

Monthly clean spark and clean dark spreads



Source: energy-charts.info; World Bank (TTF, coal); EEX and SparkChange ETC (EUA); ECB. Data: monthly, 2015-01 to 2026-10.

- CSS negative in 67 of 138 months in Romania, 121 in Germany
  - Romania higher by 13.9 EUR/MWh on average.

- **In practice:** a mean spread near zero does not make a plant worthless: it runs only in good hours.

(own computation; IPCC, 2006)

EMQA_L5_spreads

A flexible gas plant is a strip of hourly call options

- **In one sentence:** The plant runs only when the spread is positive, so it earns the positive part of each hourly spread.

$$\underbrace{\sum_h \max(CSS_h, 0)}_{\text{flexible}} \;\geq\; \max\Bigg(\underbrace{\sum_h CSS_h}_{\text{must-run}}, 0\Bigg)$$

- **where**
  - CSS_h = clean spark spread of hour h, 1 MW, gas and EUA at monthly means
  - No start-up costs, so an upper bound.

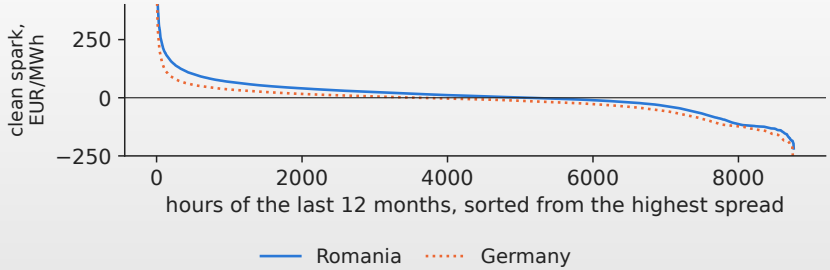
- **Romania**, last 12 months
  - Positive in 58% of hours
  - Must-run 38 095, flexible 235 494 EUR per MW
- **Germany**
  - Positive in 41% of hours
  - Must-run −165 206, flexible 112 724 EUR per MW

- **In practice:** value a gas plant or a battery as options, never as a mean spread times 8 760 h.

(Deng et al., 2001; Eydeland & Wolyniec, 2003)

Experiment yourself: notebook §4

Sorted hourly spreads: value concentrated in the best hours



Source: energy-charts.info; World Bank (TTF, coal); EEX and SparkChange ETC (EUA); ECB. Data: 2025-11-01 to 2026-10-31, hourly.

- The area above zero is the option value
  - At equal gas and carbon prices Romania has more profitable hours than Germany.

- **In practice:** hedge a flexible plant with peak products, not with a band.

(own computation) EMQA_L5_spark_hourly

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- Reasons for hedging: price exposures and the 2021–2022 crisis
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The minimum-variance hedge ratio is a regression slope

In one sentence: Choose the contracts per MWh of exposure that make the hedged cost vary least.

$$h^* = \arg\min_h \mathrm{Var}(\Delta S - h\Delta F) = \rho\frac{\sigma_S}{\sigma_F} = \frac{\mathrm{Cov}(\Delta S, \Delta F)}{\mathrm{Var}(\Delta F)}$$

$$\Delta S_t = a + h\,\Delta F_t + \varepsilon_t, \qquad HE = \rho^2$$

where

- ΔS, ΔF = monthly changes of the exposure and of the hedge
- ρ = their correlation
- Hedge effectiveness (HE) = variance removed
- h^* by ordinary least squares (OLS)
- Derivation in Appendix A.

Instrument

- A cash-settled future ends at its zone's monthly mean: we use HU and DE-LU means
- 133 months, Feb 2015 – Oct 2026

Uncertainty

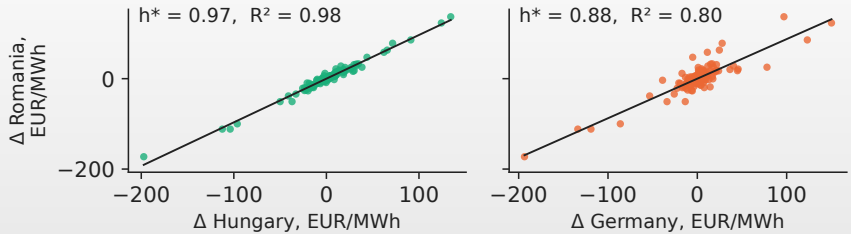
- HAC standard error, 3 lags
- Block bootstrap, 6-month blocks, 2 000 draws

In practice: a hedge ratio without a confidence interval is a guess.

(Johnson, 1960; Ederington, 1979)

Experiment yourself: notebook §5

Cross-border hedges: Hungarian contracts are more effective than German ones



Source: energy-charts.info: day-ahead prices of OPCOM, HUPX, EPEX SPOT. Data: monthly changes, 2015-02 to 2026-10.

Hedge	h^*	HAC s.e.	bootstrap 95%	R^2	h^* 2015–20	variance cut from 2021
Hungary	0.966	0.023	[0.93; 1.03]	0.98	0.92	97.9%
Germany	0.875	0.049	[0.73; 1.01]	0.80	0.91	81.1%

⊡ **In practice:** hedge with Hungarian futures before German ones.

(own computation; out of sample: h^* of 2015–2020 applied from 2021)

EMQA_L5_hedge_scatter

Basis risk of a cross-border hedge

- **In one sentence:** Hedged with a German future, a Romanian supplier pays the German forward plus the Romania–Germany gap at delivery.

$$\bar{S}^{\mathrm{RO}} - h(\bar{S}^{X} - F_0^{X}) = hF_0^{X} + \underbrace{(\bar{S}^{\mathrm{RO}} - h\bar{S}^{X})}_{\text{basis } b}$$

- **where**
  - X = zone of the future (HU, DE-LU)
  - F_0^X = its price today
  - With $h = 1$, b = monthly price gap Romania minus X.

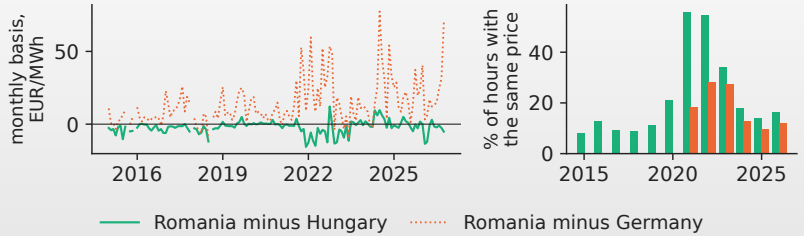
- **Romania – Hungary**
  - Mean -2.1, st. dev. 4.5 EUR/MWh
  - Equal prices in 56% of hours in 2021
- **Romania – Germany**
  - Mean $+13.9$, st. dev. 15.2
  - Since 2023 mean $+18.7$ EUR/MWh

- **In practice:** a German hedge costs the German forward plus about 19 EUR/MWh: price it in.

(Hull, 2022; own computation)

Experiment yourself: notebook §5

The basis became more volatile after 2021, though RO and HU often share a price



Source: energy-charts.info: day-ahead prices of OPCOM, HUPX, EPEX SPOT. Data: 2015-01 to 2026-10; right: |difference| < 0.01 EUR/MWh.

- Basis to Germany, st. dev. 7.6 before 2021 and 18.2 after
  - Coupling steps: 17 June 2021 (Interim Coupling), 8 June 2022 (Core flow-based).

- **In practice:** prices converge only without congestion: basis risk is congestion risk.

(own computation; ENTSO-E, 2021)

EMQA_L5_basis

Shape risk: customers do not consume a flat band

In one sentence: A band covers the same MW every hour; load is higher in dear hours, solar output in cheap ones.

$$f^{\text{load}} = \frac{\sum_h L_h P_h}{\bar{P} \sum_h L_h}, \qquad f^{\text{solar}} = \frac{\sum_h Q_h P_h}{\bar{P} \sum_h Q_h}$$

where

- L_h = Romanian load, Q_h = solar output in hour h
- $\bar{P}$ = simple mean price of the year
- $f > 1$: the profile costs more than the band.

Supplier, national load

- f^{load}: 1.039 (2019), 1.066 (2025)
- +7.1 EUR/MWh over the band in 2025

Solar producer

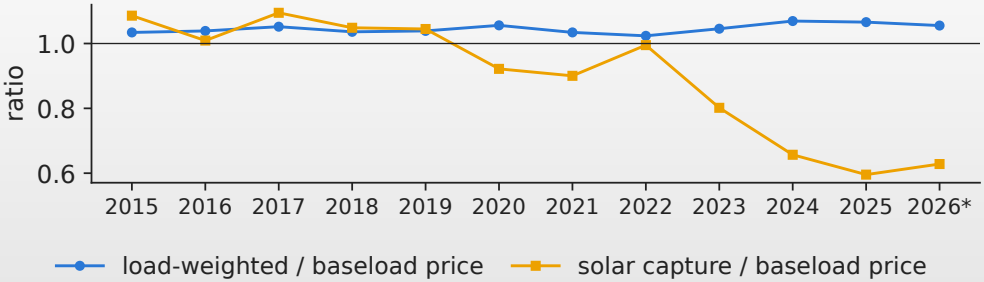
- f^{solar}: 1.045 (2019), 0.596 (2025)
- −43.7 EUR/MWh under the band in 2025

In practice: price a solar power purchase agreement (PPA) at the capture factor, not at the band forward.

(own computation)

Experiment yourself: notebook §5

Value of the solar and load profiles relative to baseload



Source: energy-charts.info: OPCOM prices; ENTSO-E load and solar output. Data: hourly, 2015 to 2026-10-31; *to the cut-off.

- Solar capture factor down to 0.596 in 2025
  - Load-weighted price 7.1 EUR/MWh above the band in 2025.

- **In practice:** buy band for the base of the portfolio, peak and hourly products for the shape.

(own computation)

EMQA_L5_shape

Outline

- Reasons for hedging: price exposures and the 2021–2022 crisis
- Forwards, futures and the forward curve
- Spreads: the margins of power plants
- Hedge ratio, basis risk and shape risk
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Caps, floors and collars

⊡ **In one sentence:** A call caps the purchase price and keeps the gain if prices fall; it costs a premium today.

$$\underbrace{(F_T - K)^+}_{\text{call}}, \quad \underbrace{(K - F_T)^+}_{\text{put}}, \quad \underbrace{\min(F_T, K_c) + c}_{\text{price with a cap}}$$

$$\text{collar: } \max\left(K_p, \min(F_T, K_c)\right) + c - p$$

⊡ **where**

- F_T = forward price at expiry T
- K = strike
- c, p = call and put premiums
- Collar = buy a call at K_c, sell a put at $K_p < K_c$.

⊡ **Who uses what**

- Supplier: a cap (call)
- Producer: a floor (put)
- Both: a low-cost collar (the supplier buys a call and sells a put; the producer the reverse)

⊡ **In Romania**

- No listed power options
- Caps sit inside bilateral and PPA contracts

⊡ **In practice:** buy a cap when a spike would break the firm, not when it would merely hurt.

(Hull, 2022)

Experiment yourself: notebook §6

Black-76 prices an option on a forward from five inputs

- **In one sentence:** Under the pricing measure a forward has no drift, so the option depends only on F, K, T, r and σ.

$$C = e^{-rT}[F\Phi(d_1) - K\Phi(d_2)], \quad P = e^{-rT}[K\Phi(-d_2) - F\Phi(-d_1)]$$

$$d_1 = \frac{\ln(F/K) + \sigma^2 T/2}{\sigma\sqrt{T}}, \qquad d_2 = d_1 - \sigma\sqrt{T}$$

- **where**
  - Φ = standard normal distribution function
  - σ = annual volatility of $\ln F$
  - T in years
  - r = continuous rate (Appendix B).

- **Inputs**, 2027 band
  - $F = 148.12$ EUR/MWh (OPCOM VWAP)
  - $T = 45$ days; $r = 2.44\%$ (€STR)
  - $\sigma = 0.220$ (next slide)
- **Prices**, EUR/MWh
  - $K = F$: call = put = 4.55
  - Cap at 1.1 F: 0.63
  - Floor at 0.9 F: 0.43

- **In practice:** ask the bank which volatility it used
  - The premium grows almost linearly with σ.

(Black, 1976; Hull, 2022)

Experiment yourself: notebook §6

Estimating volatility for option pricing: estimates differ across data sources

- **1. Romanian yearly forwards**
  - Irregular auctions: $\hat{\sigma}^2 = \sum_k (\Delta \ln F_k)^2 / \sum_k \Delta t_k$, gaps ≤ 30 days
  - $\hat{\sigma} = 0.220$ on 49 pairs of auction days
- **2. TTF future, January 2027**
  - Last 60 trading days: $\hat{\sigma} = 0.499$; call 10.30
- **3. Month average vs forward**
  - $\mathrm{sd}(\ln(\bar{S}/F)/\sqrt{T}) = 0.668$, 153 auctions

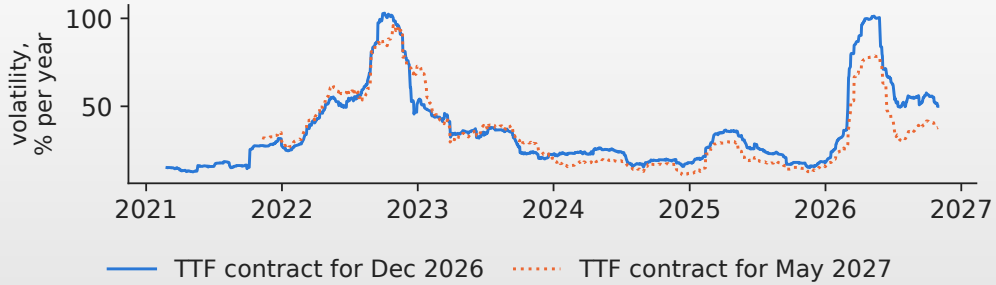
- **Why they differ**
  - A year averages 8 760 hours, far calmer than a month
  - Gas has its own crisis in 2026
  - No free implied volatility for Romania
- **Better**
  - Generalised autoregressive conditional heteroskedasticity (GARCH) models of Lecture 3

In practice: match the volatility to the underlying: year, quarter or month.

(own computation; OPCOM; Yahoo Finance)

Experiment yourself: notebook §6

The Samuelson effect in TTF: higher volatility of near contracts



Source: Yahoo Finance, NYMEX TTF futures. Data: daily closes to 2026-10-31, rolling 60 trading days.

- 1 Nov 2025 – 31 Oct 2026: December 2026 63%, May 2027 48% a year
  - In 2022 both near 66%.

- **In practice:** an option close to delivery needs a higher volatility.

(own computation; Samuelson, 1965)

EMQA_L5_samuelson

Delta and vega: the option in MWh, and its volatility risk

⊡ **In one sentence:** Delta is the forward quantity that offsets the option; vega is the premium change per volatility point.

$$\Delta_C = e^{-rT}\Phi(d_1), \quad \Delta_P = -e^{-rT}\Phi(-d_1)$$
$$\mathcal{V} = e^{-rT}F\varphi(d_1)\sqrt{T}, \qquad C - P = e^{-rT}(F - K)$$

⊡ **where**

- φ = standard normal density
- $\mathcal{V}$ per volatility point (0.01)
- The last identity is put–call parity.

⊡ $K = F$, $\sigma = 0.220$

- $d_1 = 0.039$; $\Delta_C = 0.514$, $\Delta_P = -0.483$
- Vega 0.207 EUR/MWh
- $C = P$, as parity requires

⊡ **Cap at 1.1** F

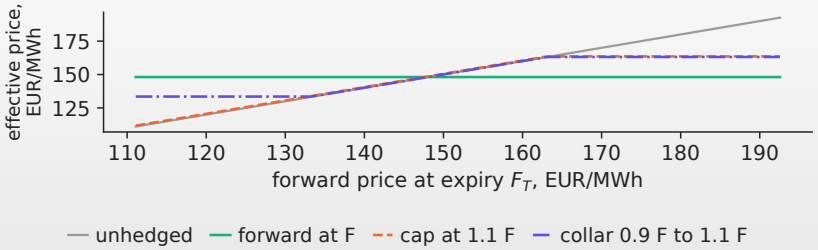
- Delta 0.116
- Cap premium for 1 MW over a year: 5 519 EUR

⊡ **In practice:** the seller of a cap hedges by holding delta MWh forward and rebalancing.

(Black, 1976; Hull, 2022)

Experiment yourself: notebook §6

Effective price of the 2027 band by instrument



Source: OPCOM PCCB-LE-flex; ECB (€STR); Black-76. Data: F = Cal-2027 baseload, auctions 2026-09-01 to 2026-10-31.

- Forward 148.1
  - Cap at 162.9 costs 0.63
  - Collar 133.3 – 162.9 costs 0.20 EUR/MWh
  - Spikes and monthly averages (Asian options) break Black-76.

In practice: a near-zero-cost collar lets a supplier sell a capped retail price.

(Black, 1976; Weron, 2008)

EMQA_L5_collar

Outline

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Case study: a supplier with a 1 MW fixed-price customer in 2026

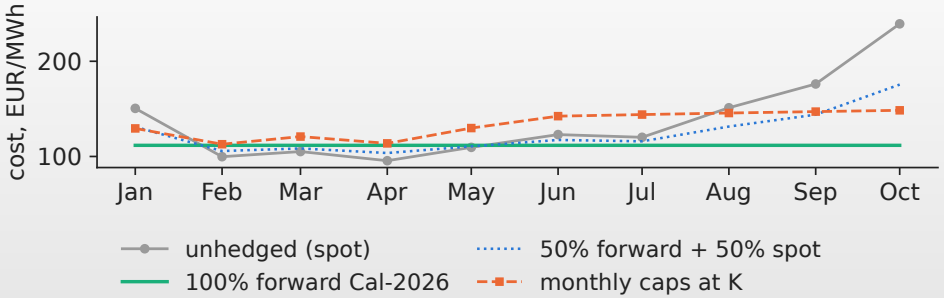
- **The position**
  - 1 MW flat for all of 2026 sold at a fixed price; energy still to be bought
  - Measured on 10 delivered months, to Oct 2026
- **Four strategies, real prices**
  - Unhedged: buy each month at the realised spot mean
  - 100% forward: OPCOM band 2026, VWAP 111.70 EUR/MWh, 31 auctions
  - 50% forward, 50% spot
  - Monthly caps bought 15 Dec 2025, $K = 120.16$ (VWAP of the last 5 auctions), Black-76, $\sigma = 0.668$
- **What we report**
  - Mean cost, its month-to-month standard deviation, the worst month, total cost per MW

In practice: a supplier's risk committee should see exactly this table every month.

(own computation; OPCOM)

Experiment yourself: notebook §7

Case study: in 2026 the forward was cheaper than spot in 6 of 10 months



Source: OPCOM (PCCB-LE-flex results; day-ahead prices via energy-charts.info); ECB. Data: 2026-01 to 2026-10; 1 MW baseload.

- Spot peak 239.3 EUR/MWh in Oct 2026
  - The caps paid out in 5 of 10 months.

- **In practice:** a cap costs its premium every month, also when it pays nothing.

(own computation; OPCOM)

Case study: effect of the forward and the cap on cost and risk

EUR/MWh	mean	st. dev.	worst	EUR/MW
spot	137.5	44.4	239.3	1 002 956
100% forward	111.7	0.0	111.7	814 946
50% forward	124.6	22.2	175.5	908 951
caps	133.6	13.9	148.5	975 020

⊡ Weighted by the hours of each month.

⊡ **Reading**

- Forward: 188 010 EUR per MW saved, zero variation
- Caps: premium 20.4 EUR/MWh a month; net 27 936 EUR per MW

⊡ **Not a general verdict**

- Prices rose after the hedge; in a falling year the forward costs more than spot

⊡ **In practice:** set the hedged share by policy (e.g. 60–80% bought in layers), not by a price view.

(own computation)

Experiment yourself: notebook §7

The producer's perspective and the summer 2024 price spike

- **Producer, 2025**
  - 101 auctions, VWAP 102.1 vs realised 108.2 EUR/MWh
  - Selling forward earned 6.0 EUR/MWh less than spot (52 797 EUR per MW-year), the price of a fixed revenue
  - In 2022 the same decision cost 187.9 EUR/MWh
- **Summer 2024**
  - Third quarter bought at 90.0, delivered at 127.4 EUR/MWh; July alone 145.1
  - Peak hour 916.7 EUR/MWh on 18 Jul 2024, 20:00, Central European Time (CET)
- **The lesson**
  - A hedge transfers value between the two sides; it makes cash flows predictable, which lenders pay for

In practice: a producer with debt should sell forward even when it expects higher prices.

(own computation; OPCOM; Andrei, Pele & Cramer, 2026, PICBE)

Experiment yourself: notebook §7

Elements of a hedging policy

- **Exposure**
  - Net position per month and profile (band, peak, solar)
  - Volume risk: demand hardly reacts to price
- **Instruments**
  - OPCOM forwards first, then Hungarian, then German futures
  - Caps for the tail, not for all the volume
- **Execution**
  - Buy in layers over 12–24 months
  - Keep a liquidity buffer for margin calls
- **Control**
  - Limits on open position and VaR (Lecture 4)
  - Report hedged cost and its variance

In practice: the board approves the policy, traders execute it, risk management measures it.

(Hull, 2022; Proșcanu, Proșcanu & Pele, 2025, JSES; Lecture 4)

Quiz 1: basis risk

- A Romanian supplier hedged July 2024 with German baseload futures bought at F
  - July averaged 67.7 in Germany and 145.1 EUR/MWh in Romania
  - What did it pay per MWh?

Answer

- It bought at 145.1 in Romania and received from the future the difference between 67.7 and F: net cost $F + 77.4$ EUR/MWh, the largest monthly basis in our data.

Quiz 2: the hedge ratio

- Our estimate for Hungary is $h^* = 0.966$ with a bootstrap interval $[0.93; 1.03]$
  - A 20 MW exposure needs how many MW of Hungarian futures?

Answer

- $20 \times 0.966 = 19.3$ MW
  - Since 1 lies inside the interval, a one-for-one hedge of 20 MW is statistically as good.

Quiz 3: spark spread

- In Oct 2026: power 239.3, gas 86.8 EUR/MWh, EUA 82.4 EUR/t
  - Efficiency 50%, 0.202 t CO_2 per MWh thermal
  - Did a gas plant earn money on average?

Answer

- Fuel $86.8/0.5 = 173.6$
  - Carbon $0.404 \times 82.4 = 33.3$
  - Clean spark $+32.4$ EUR/MWh: yes, even before choosing the best hours.

Quiz 4: a cap for a supplier

- The 2027 band trades at 148.1
  - A cap at 162.9 costs 0.63 EUR/MWh
  - What does the supplier pay if the forward ends at 1.3 F, and at 0.9 F?

Answer

- At 1.3 F: the strike 162.9 plus the premium
  - At 0.9 F: the market price plus the premium, since the cap is not exercised.

Wrap-up

- Reasons for hedging: price exposures and the 2021–2022 crisis
- Forwards, futures and the forward curve
  - Contracts
  - The forward curve
- Spreads: the margins of power plants
- Hedge ratio, basis risk and shape risk
- Options on energy
- Case study: a Romanian supplier and a producer

- A forward turns an unknown spot into a known price
  - In 2022 it saved a Romanian supplier 1.65 million EUR per MW, and cost producers the same.
- Hedge Romania with Hungary before Germany, price the shape, and match the volatility to the underlying
  - Next: Lecture 6.

Research from our group on Romanian power risk

- **The summer 2024 price spike** (Andrei, Pele & Cramer, 2026, PICBE)
  - Question: which intervention would have lowered Romanian prices most in June–July 2024
  - Method: a random forest on hourly ENTSO-E data, 147 counterfactual scenarios, checked against ridge regression
  - Result: a 10% load reduction was the most effective measure; the peak came at night, so solar could not help and storage is the enabling asset
- **Systemic risk in the EU energy sector** (Toma, Dima, Grecu, Pele & Lessmann, 2026, SSRN)
  - Method: the Energy Financial Risk Meter, a least absolute shrinkage and selection operator (LASSO) quantile regression on daily returns of 100 European energy companies
  - Result: the index captures the 2020 pandemic and the 2022 war; a geopolitical-to-energy risk channel switched on
- **Demand barely reacts to price** (Proșcanu, Proșcanu & Pele, 2025, JSES)
  - Method: Granger causality and vector autoregressions on Romanian consumption and prices
  - Result: consumption is inelastic and drives price, not the reverse, so volume cannot hedge price risk

- 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

- **J. Hull, Options, Futures, and Other Derivatives**, chapters on hedging, futures and Black's model.
- **Benth, Šaltytė Benth & Koekebakker (2008)**: forward curves and options in electricity markets.
- **OPCOM reports**: forward auction results, the source of this lecture — opcom.ro.
- **This course**: code, data, notebooks — github.com/danpele/EMQA.
- **ACER (2022)**: the final assessment of the EU wholesale electricity market design.
- **Experiment yourself**: the notebook reproduces every chart and number of this lecture — notebooks/.

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Appendix A: the minimum-variance hedge ratio and its estimation

$$\frac{\partial}{\partial h}\operatorname{Var}(\Delta S - h\Delta F) = -2\operatorname{Cov}(\Delta S, \Delta F) + 2h\operatorname{Var}(\Delta F) = 0$$

$$\Rightarrow\; h^* = \frac{\operatorname{Cov}(\Delta S, \Delta F)}{\operatorname{Var}(\Delta F)}$$

$$\operatorname{Var}(\Delta S - h^*\Delta F) = \sigma_S^2(1-\rho^2)$$

- The second derivative $2\operatorname{Var}(\Delta F) > 0$, so h^* is a minimum.
- h^* is the OLS slope of ΔS on ΔF
  - HAC variance (Newey–West, Bartlett kernel, 3 lags).

(Johnson, 1960; Ederington, 1979; Kroner & Sultan, 1993)

- **Moving-block bootstrap**
  - Draw blocks of 6 consecutive months with replacement until n months; recompute h^*; repeat 2 000 times
  - 95% interval = 2.5% and 97.5% percentiles; blocks keep the autocorrelation of the monthly changes
- **Dynamic hedge ratios**
  - $h_t^* = \operatorname{Cov}_{t-1} / \operatorname{Var}_{t-1}$ from a bivariate GARCH (Lecture 3)

Appendix B: from a driftless forward to the Black-76 formula

$$\frac{dF_t}{F_t} = \sigma\, dW_t \;\Rightarrow\; \ln F_T \sim \mathcal{N}\Big(\ln F_0 - \tfrac{1}{2}\sigma^2 T,\; \sigma^2 T\Big)$$

$$C = e^{-rT}\mathbb{E}\big[(F_T - K)^+\big] = e^{-rT}\big[F_0\Phi(d_1) - K\Phi(d_2)\big]$$

- A forward costs nothing to enter, so under the pricing measure its drift is zero.
- $\mathbb{E}[F_T \mathbf{1}_{F_T>K}] = F_0\Phi(d_1)$ and $\Pr(F_T > K) = \Phi(d_2)$ (lognormal moments).

(Black, 1976; Margrabe, 1978; Schwartz, 1997)

- **Spread options**
  - An option to exchange gas for power: Margrabe's formula with $\sigma^2 = \sigma_P^2 + \sigma_G^2 - 2\rho\sigma_P\sigma_G$
  - With a strike (clean spark with fixed costs) Kirk's approximation is used in practice
- **Mean reversion**
  - Spot power reverts to its mean; Schwartz (1997) one-factor model gives forward volatilities that fall with maturity

Appendix C: conventions and conversion factors

- **Forward prices**
  - One closing price per OPCOM session; quantity on the initiator side; lei converted with the ECB EUR/RON fixing of the auction day (last fixing on or before)
  - Standard periods only: month, quarter, half-year, calendar year; baseload unless stated
- **Realised spot**
  - Mean of the daily day-ahead base prices of the delivery period (CET days); computed only when every day is present
- **Fuels and carbon**
  - Coal 6 000 kcal/kg = 6.978 MWh thermal per tonne; gas 0.202 and hard coal 0.341 t CO_2 per MWh thermal (IPCC 2006: 56.1 and 94.6 t/TJ)
  - EUA = EEX auction monthly mean to Jan 2026, then SparkChange ETC (auction/ETC ratio close to 1 in 2021–2025)
- **Hours**
  - Hour-equivalents: a 15-minute interval counts 0.25 h (since 1 October 2025)

(IPCC, 2006; OPCOM; ECB)