Future Day-Ahead Electricity Price Spreads in Germany:

Drivers, Forecasting, and Flexibility Scenarios

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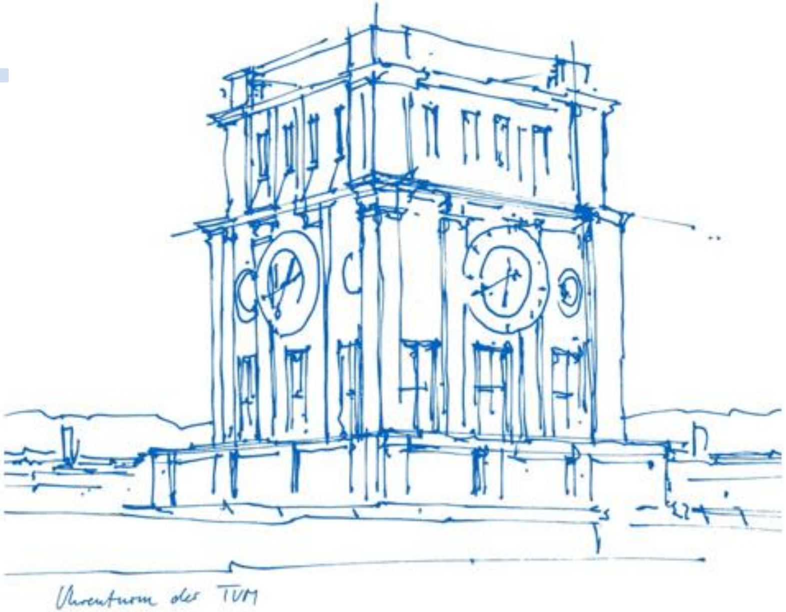


Motivation

The arbitrage signal of a renewable grid

→ Within-day price spreads (max − min of hourly DA prices) shape arbitrage revenues for batteries, demand response, and V2G.

→ They provide a market-based scarcity signal: large spreads = surplus at midday, deficit in the evening.

→ Rising variable renewable shares amplify this duck-curve effect — spreads are structurally increasing.

→ Yet most literature focuses on average prices or broad volatility; within-day spreads as a flexibility metric remain underexplored.

Max − Min

Definition of within-day spread
(hourly day-ahead prices, EUR/MWh)

2015–2025

10 years of German day-ahead market data analyzed

Literature Gap

No unified framework linking spread drivers, ex-ante forecasting, and flexibility scenario analysis for storage investments

Research Questions & Contribution

RQ 1

Which observable day-ahead fundamentals are most associated with German within-day spreads?

→ We document daily spread dynamics for Germany 2015–2025 and link spreads to the day-ahead information set available ex ante.

RQ 2

How predictable are spreads at short horizons using only ex-ante information?

→ We evaluate out-of-sample forecast performance and show that persistence dominates fundamentals at short horizons.

Key Contributions:

1 Document daily spread dynamics for Germany 2015–2025 using only ex-ante information

2 Establish division of labor: fundamentals for structure vs. AR(1) for short-horizon trading

3 Translate estimated relationships into stylized 2050 scenarios (V2G + second-life batteries)

Data

Daily dataset: Germany, 05 Jan 2015 – 30 Apr 2025

Variable	Type	Source	Note
Within-day spread (max−min hourly DA price)	**Dependent**	SMARD / EPEX	EUR/MWh
Forecasted solar share	Explanatory (ex ante)	SMARD (Bundesnetzagentur)	% of generation
Forecasted wind offshore share	Explanatory (ex ante)	SMARD (Bundesnetzagentur)	% of generation
Forecasted wind onshore share	Explanatory (ex ante)	SMARD (Bundesnetzagentur)	% of generation
Forecasted grid load	Explanatory (ex ante)	SMARD (Bundesnetzagentur)	GWh
TTF natural gas price (lagged)	Explanatory (ex ante)	Investing.com	EUR/MWh proxy
Net exports (lagged)	*Robustness only*	SMARD	*Potentially endogenous — excluded from baseline*

All explanatory variables are observable ex ante at the day-ahead stage — no look-ahead bias

Methodology

OLS Regression
Predictive regression of spread on fundamentals

HAC SE (Newey-West)
Corrects for autocorrelation & heteroskedasticity

Train / Test Split
Train: 2015–2022 (2,918 d)
Test: 2023–2024 (731 d)

Benchmarks
Historical mean, RW, AR(1), Elastic Net / ARIMAX

Baseline Model Specification

$$Spread\_t = \alpha + \beta_1 \cdot SolarShare\_t + \beta_2 \cdot WindOffshore\_t + \beta_3 \cdot WindOnshore\_t + \beta_4 \cdot Load\_t + \beta_5 \cdot GasPrice\_\{t-1\} + \varepsilon\_t$$

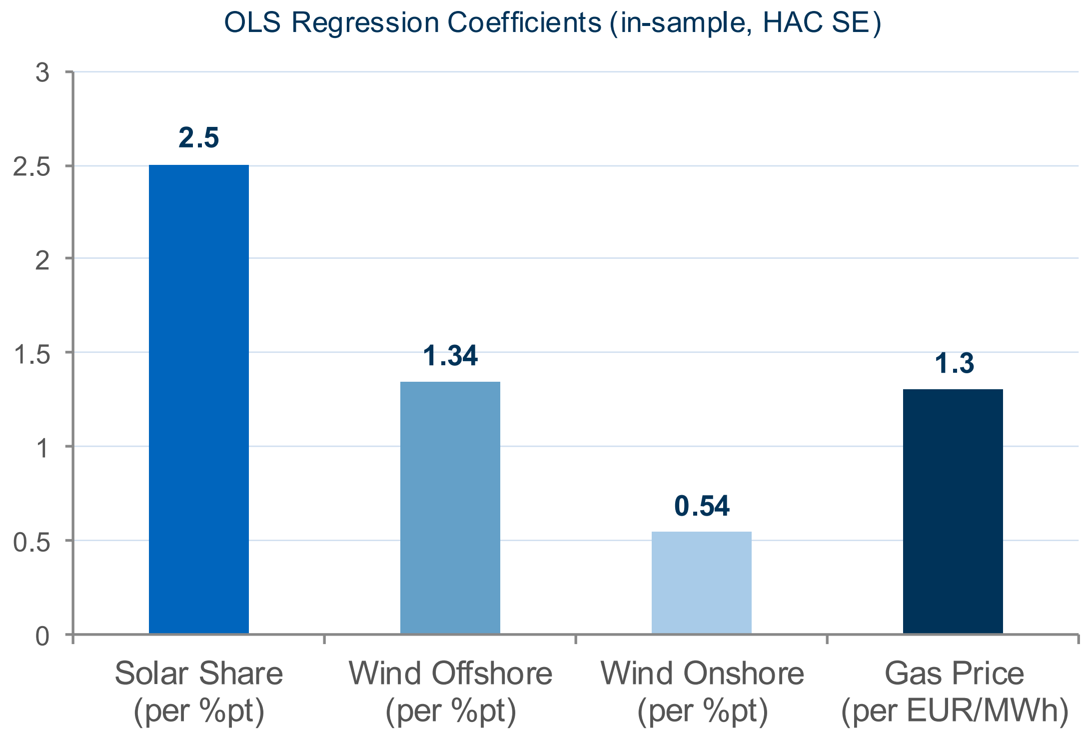
Out-of-Sample Evaluation

Strict train/test split. No model re-estimation on test data. Benchmark: historical mean, random walk, AR(1), Elastic Net, and ARIMAX.

Identification: Net Exports

Net exports excluded from baseline by design — jointly determined in the coupled European auction, hence endogenous. Robustness with lagged exports confirms: coefficient economically negligible, core results unchanged.

Results: What Drives Within-Day Spreads?



+2.5 EUR/MWh

per +1 pp solar share
(duck-curve effect: deeper midday trough)

+1.3 EUR/MWh

per +1 EUR/MWh gas price
(lifts evening peak, widens spread)

+1.34 EUR/MWh

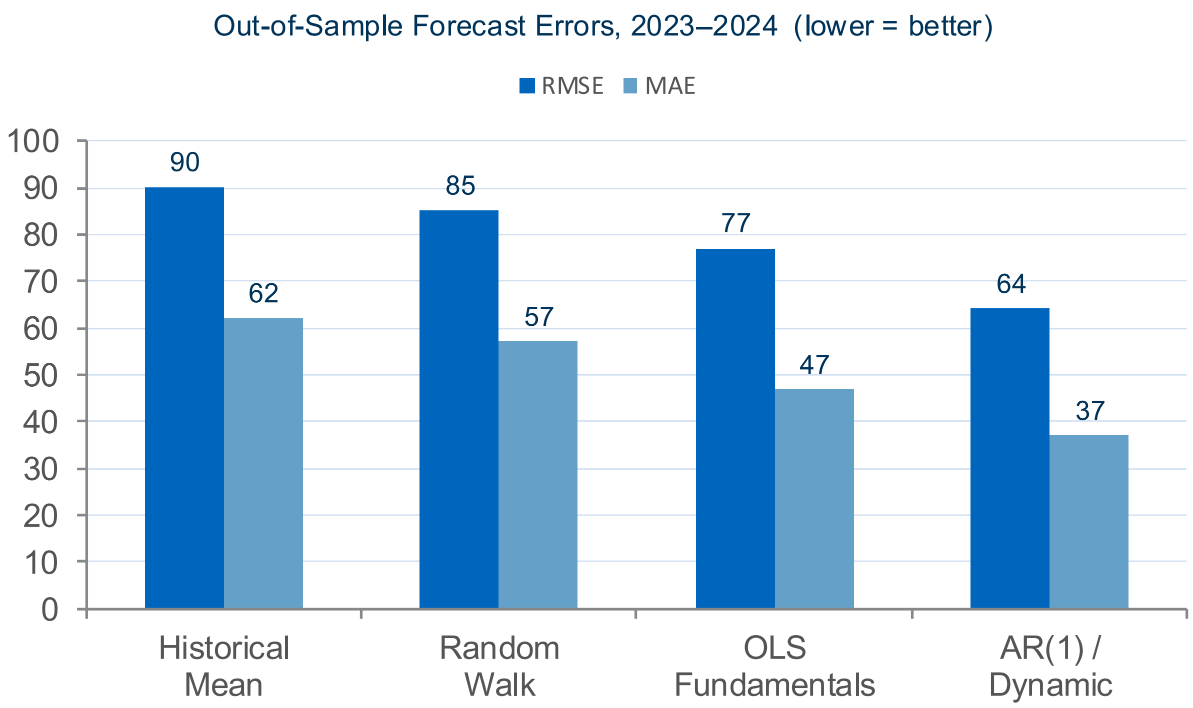
per +1 pp wind offshore
(supply surplus during windy periods)

≈ 0

Net exports: little incremental power once fundamentals are controlled for

All coefficients positive: more renewables and higher gas prices both widen spreads

Results: Short-Horizon Forecasting



RMSE ~64

AR(1) / dynamic model
best out-of-sample performer

MAE ~36.9

vs 46.7 for fundamentals-only
— 21% MAE improvement

RMSE ~77

Fundamentals OLS beats naive benchmarks; AR(1) beats OLS by 17%

Division of labor:
Fundamentals for structure, AR(1) for trading

Scenario Framework: 2050 Flexibility Matrix

We combine three dimensions into a stylized scenario matrix:

① Renewable Expansion

Projected solar and wind shares to 2050 based on published ENTSO-E / national decarbonisation pathways

② Gas Price Regime

Low gas: structural decline post-2030 (green hydrogen transition)
High gas: persistent fossil dependency

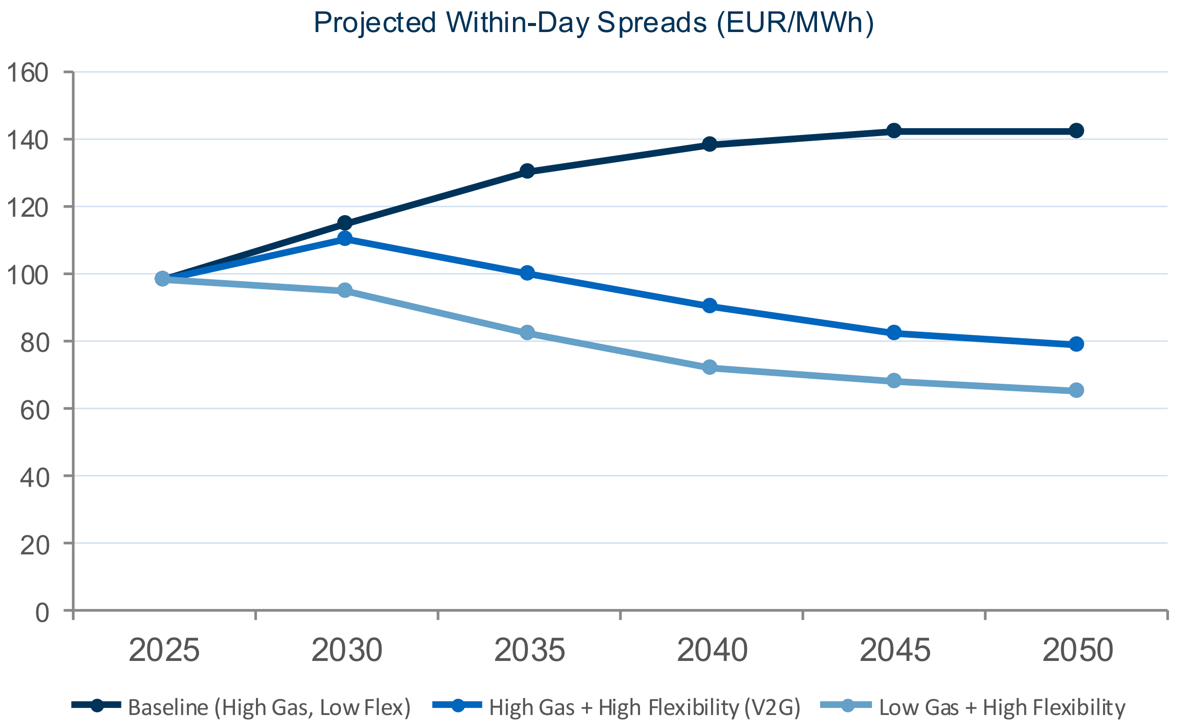
③ Flexibility Overlay

V2G and second-life battery integration implemented as illustrative spread-compression sensitivity — NOT a causal estimate

Resulting 2×2 Scenario Matrix:

	Low Flexibility	High Flexibility (V2G + 2nd-life)
High Gas	Baseline (~142 EUR/MWh by 2050)	**High Flex (~79 EUR/MWh by 2050)**
Low Gas	Low Gas, Low Flex (not modeled separately)	**Best Case (~65 EUR/MWh by 2050, est.)**

Scenario Results: Spread Paths to 2050



Scenario	2050 Spread	vs. Baseline
Baseline	~142 EUR/MWh	—
High Gas + High Flex	**~79 EUR/MWh**	**−44 %**
Low Gas + High Flex	**~65 EUR/MWh (est.)**	**−54 %**

Flexibility can halve spreads — even under high gas prices

~142 → ~79 EUR/MWh (High Gas, High Flex)

⚠ *Illustrative sensitivity; not a causal estimate*

Conclusion

01

Renewables and gas drive spreads

Solar (+2.5 per pp), wind offshore (+1.34 per pp), and gas prices (+1.3 per EUR/MWh) are the dominant in-sample drivers. Net exports add little incremental power once fundamentals are included.

02

Persistence dominates short-horizon forecasting

AR(1) / dynamic specs (RMSE ~64, MAE ~36.9) substantially beat fundamentals-only OLS (RMSE ~77, MAE ~46.7). Fundamentals explain structure; time series drives trading signals.

03

Flexibility can halve spreads by 2050

High V2G and second-life battery penetration compresses baseline spreads from ~142 to ~79 EUR/MWh even under high gas prices — underscoring strong economic motivation for scalable flexibility.

04

Policy and research implications

Grid codes, tariff design, and bidirectional charging standards needed to unlock V2G. Open research: IV/SVAR for net exports endogeneity; non-linear effects at high renewable penetrations.

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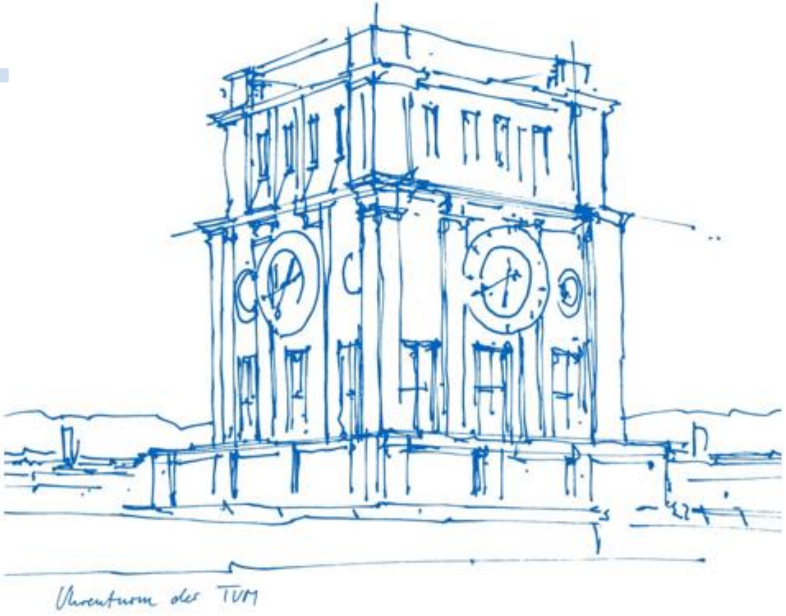

Flexibility Model: V2G & Second-Life Batteries

How EV storage applications reduce projected spreads in our scenario analysis:

Fundamentals Model Inputs

- Forecasted solar share
- Forecasted wind offshore/onshore
- Forecasted grid load
- TTF natural gas price (lagged)
- Net exports (robustness only)

→

Projected Day-Ahead Spreads

OLS coefficients applied to projected 2050 renewable shares and gas-price regimes

→ Baseline spread trajectory

⚠ Important Caveat

Flexibility is modeled as an illustrative spread-compression sensitivity applied to projected spreads.

This is NOT a causal model of how batteries affect clearing prices. It is a structured stress test of the estimated fundamentals relationship.

↓ **reduced by**

Second-Life Batteries

- Collection rate: 95–100%
- Repurposing rate: 70% LFP, 40% NCM
- Utilisation rate: 20% base case• Avg. capacity: 30 kWh/vehicle• Second-life span: ~10 years

EV Storage Applications (based on projected EV fleet size)

Vehicle-to-Grid (V2G)

- Driving demand: 60% of day
- Degradation: 9–14% extra loss over 10 yr
- Participation rate: 1% (2029)→ 10% (2038) → 15% (2045)

Endogeneity: Net Exports & Identification

The Problem: Simultaneity

- Net exports are determined in the coupled European day-ahead auction — the same process that sets prices
- Exports respond to price differences across borders, so they are jointly determined with the spread
- Including them as a regressor introduces simultaneity bias: OLS coefficients would reflect both the causal effect and the reverse feedback

Our Identification Strategy

- Baseline specification excludes net exports entirely — conservative approach that avoids simultaneity
- Robustness check: include one-day lagged net exports (pre-determined, reduces endogeneity concern)
- Result: lagged net exports add minimal incremental explanatory power once fundamentals are included
- Implication: cross-border flows are a transmission channel, not an independent driver

Why Not IV / SVAR?

- Valid instruments for net exports are hard to find: must affect exports without directly affecting German spreads
- Candidate instruments (e.g. neighboring country wind/solar) may violate exclusion restriction via integrated European market
- IV/SVAR treatment is acknowledged as an open research extension (see conclusion)

Bottom Line for This Paper

- Our core results do NOT depend on net exports — they are excluded from the baseline
- The fundamentals (solar, wind, gas, load) are all observable ex ante and plausibly exogenous to daily spread realization
- HAC (Newey-West) inference corrects for autocorrelation and heteroskedasticity in the residuals
- The key coefficients are robust across specifications with and without net exports

Key Assumptions & Limitations

Modelling Assumptions

- Linear OLS: spread-driver relationship assumed linear and constant over time
- Renewable projections from ENTSO-E / national decarbonisation pathways (not our own forecasts)
- Gas price scenarios: high = persistent fossil dependency; low = structural decline post-2030
- EV fleet size and battery degradation follow published industry projections
- Flexibility as spread compression: percentage reduction applied to baseline, not dispatch-based

Known Limitations

- Linearity may not hold at very high renewable penetrations (>80% share) — threshold / non-linear effects possible
- No market design changes modeled (capacity markets, nodal pricing, flexibility markets)
- No feedback effects: battery deployment itself would alter the merit order and change spread dynamics
- Single-country focus: German results may not transfer to different market structures
- Historical training period includes the 2022 energy crisis — structurally unusual observations

Research Extensions (on the agenda)

- IV/SVAR for net exports endogeneity: proper instrumental variable treatment once valid instruments are identified
- Non-linear models: Random Forest, GAM, or threshold regressions to capture saturation effects at high RES penetration
- Cross-country analysis: extend framework to France, Spain, or Nordics for external validity
- Dispatch-based flexibility modeling: replace sensitivity approach with explicit battery optimization model