# Harnessing uncertainty

## The role of probabilistic time series forecasting in the renewable energy transition

Alexander Backus
Data Science Manager

www.dexterenergy.ai


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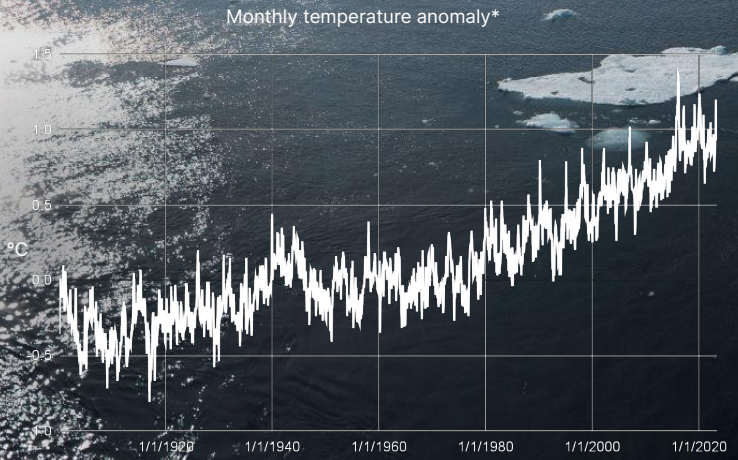
# Climate change:
# Our planet's most pressing challenge

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* ourworldindata.org/

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# The energy sector accounts for over **73%** * of greenhouse gas emissions


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* ourworldindata.org/

# The energy transition: Pivoting towards renewables


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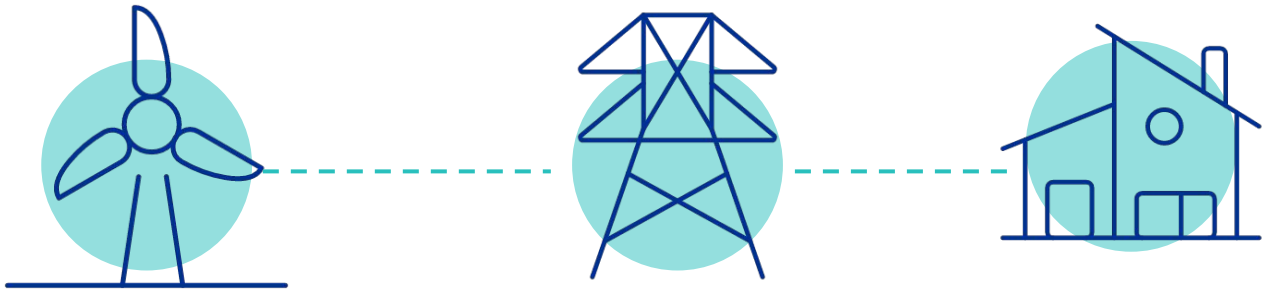
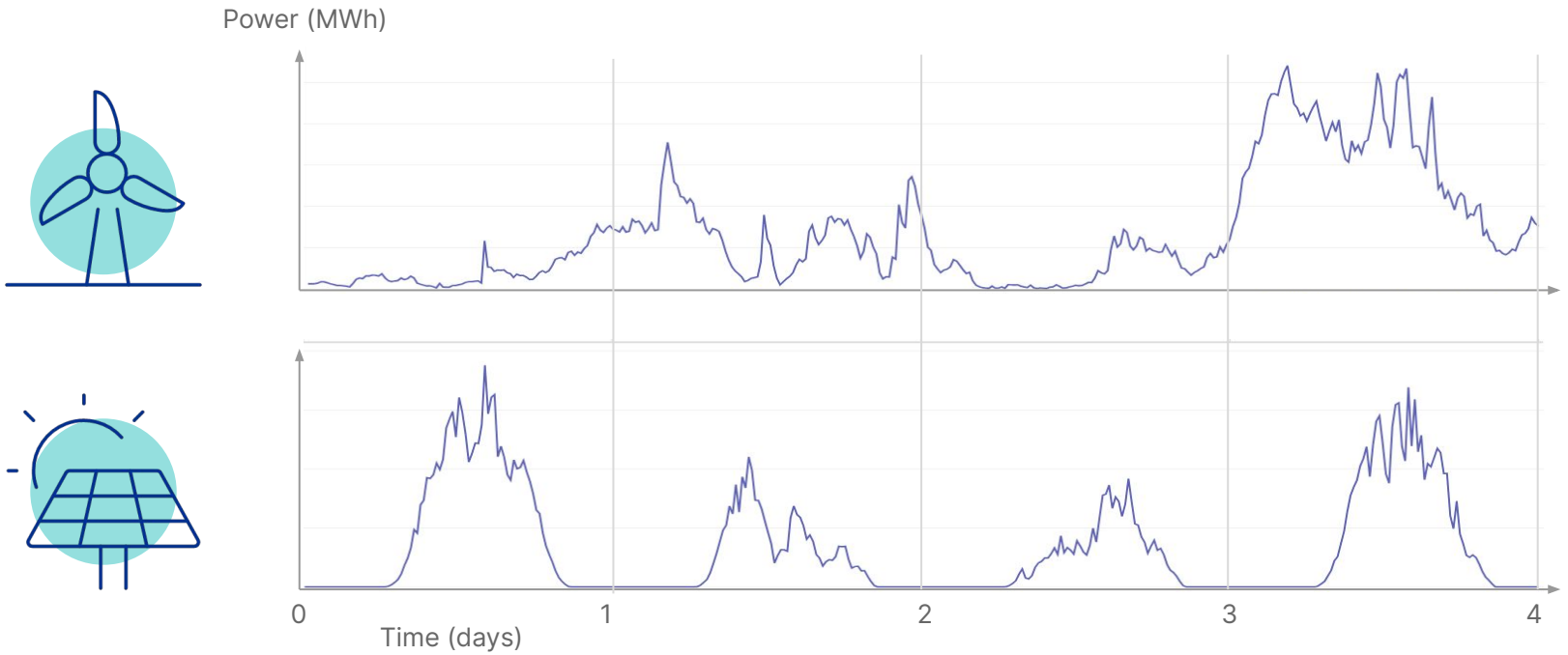
# A balancing act on the energy grid:
# Supply needs to equal demand at any moment

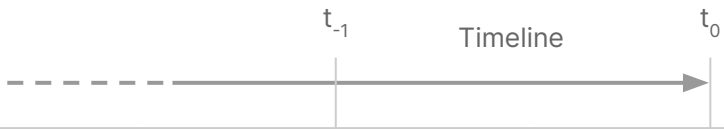


$\text{supply}_t$ = $\text{demand}_t$

# Renewable generation is non-steerable and intermittent



# Energy markets match supply and demand through price




By hypothetical renewable energy supplier

| | | |
|---|---|---|
| **Time** | 1 day before (12:00) | Time of delivery |
| **Market** | Day-ahead market | Balancing market |
| **Power** | 100 MWh (sold) | 80 MWh 🔽(generated) |
| **Price** | 100 EUR/MWh | 300 EUR/MWh 🔼 |

Shortage on the grid! 👎

$$\text{imbalance cost} = \Delta\text{power} \cdot \Delta\text{price}$$

$$= (100 - 80\ \text{MWh}) \times (300 - 100\ \text{EUR/MWh}) = \mathbf{4000\ EUR}$$

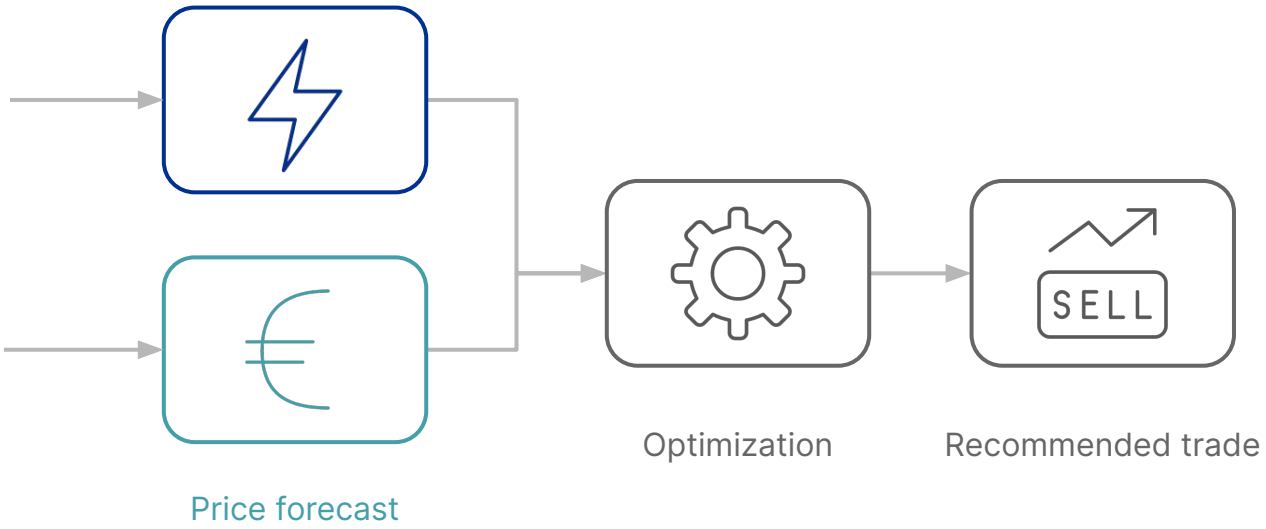
# Dexter Energy provides short-term power forecasting and trade optimization for renewable portfolios

Making renewable energy more predictable and profitable

Founded in 2016, Amsterdam
~50 FTE and growing

# Two key unknown quantities: volume and price

$$\text{imbalance cost} = \Delta\text{power} \cdot \Delta\text{price}$$



# How price forecasts can help balance the grid

| **Time** | 1 day before (12:00) | Time of delivery |
|---|---|---|
| **Market** | Day-ahead market | Balancing market |
| **Power** | **75 MWh** (sold) 🔽 | 80 MWh (generated) |
| **Power forecast** | NA | 80 MWh |
| **Price** | 120 EUR/MWh 🔼 | 220 EUR/MWh 🔽 |
| **Price forecast** | 100 EUR/MWh | 300 EUR/MWh |

How do we help balance the grid? Sell: 🤦

A) As much as we can
B) Nothing
C) A bit more
**D) A bit less**

Lower Δprice and less grid imbalance! 👍

$$\text{imbalance cost} = \Delta\text{power} \cdot \Delta\text{price}$$

$$= -5\ \text{MWh} \times 100\ \text{EUR/MWh} = \textbf{-500 EUR}$$

# How price forecasts can help balance the grid

| **Time** | 1 day before (12:00) | Time of delivery |
|---|---|---|
| **Market** | Day-ahead market | Balancing market |
| **Power** | **0 MWh** (sold) 🔽🔽 | 80 MWh (generated) |
| **Power forecast** | NA | 80 MWh |
| **Price** | 150 EUR/MWh 🔼🔼 | -10 EUR/MWh 🔽🔽 |
| **Price forecast** | 100 EUR/MWh | 300 EUR/MWh |

How do we help balance the grid? Sell: 🙋

A) As much as we can
**B) Nothing**
C) A bit more
**D) A bit less**

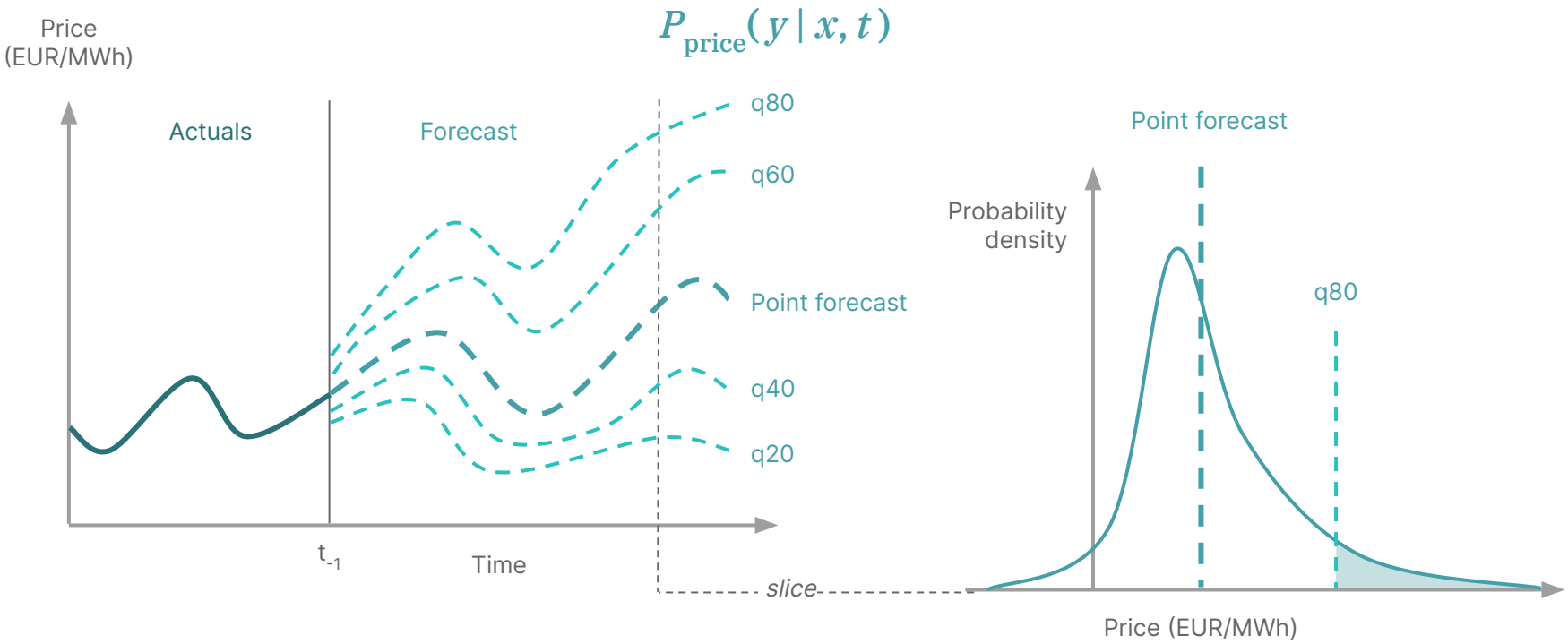
Market flipped into a surplus state! 👎

⚠️ Price maker effect

$$\text{imbalance cost} = \Delta\text{power} \cdot \Delta\text{price}$$

$$= -80\ \text{MWh} \times -160\ \text{EUR/MWh} = \mathbf{12800\ EUR}$$

# Quantify uncertainty to allow risk-based steering



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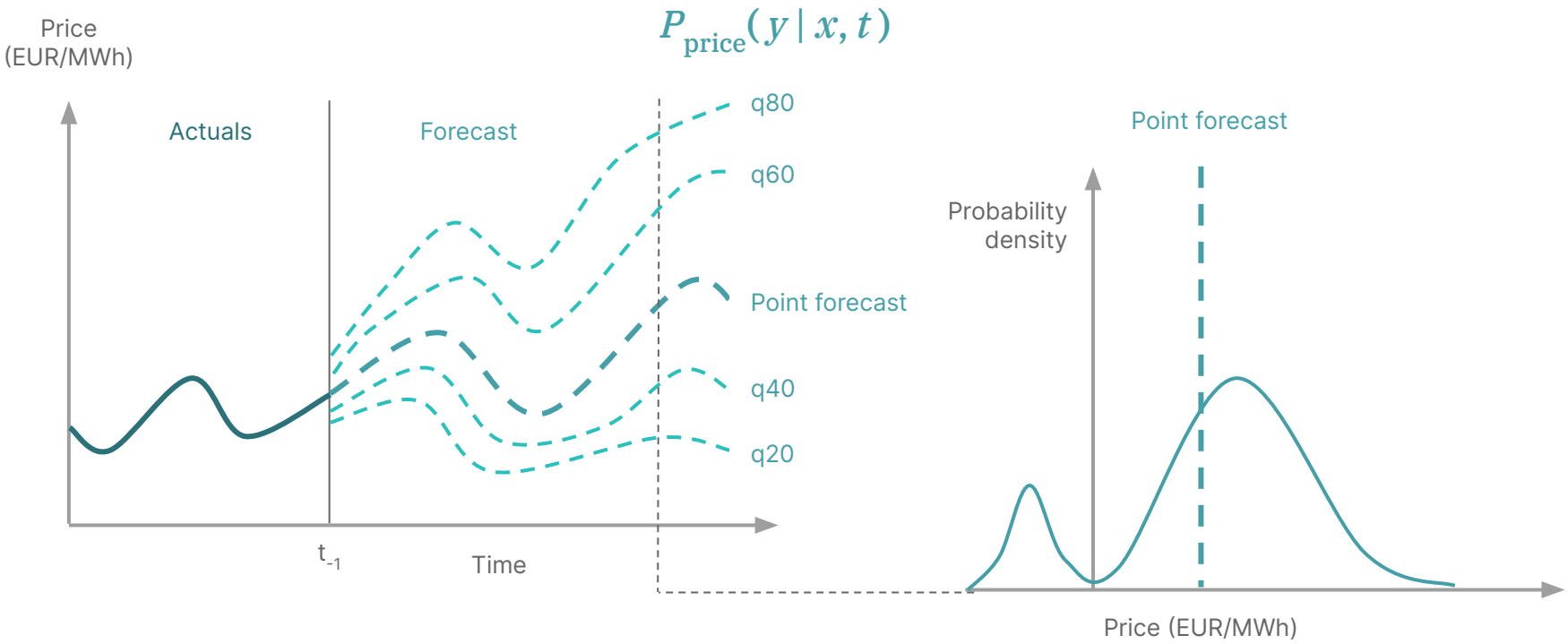
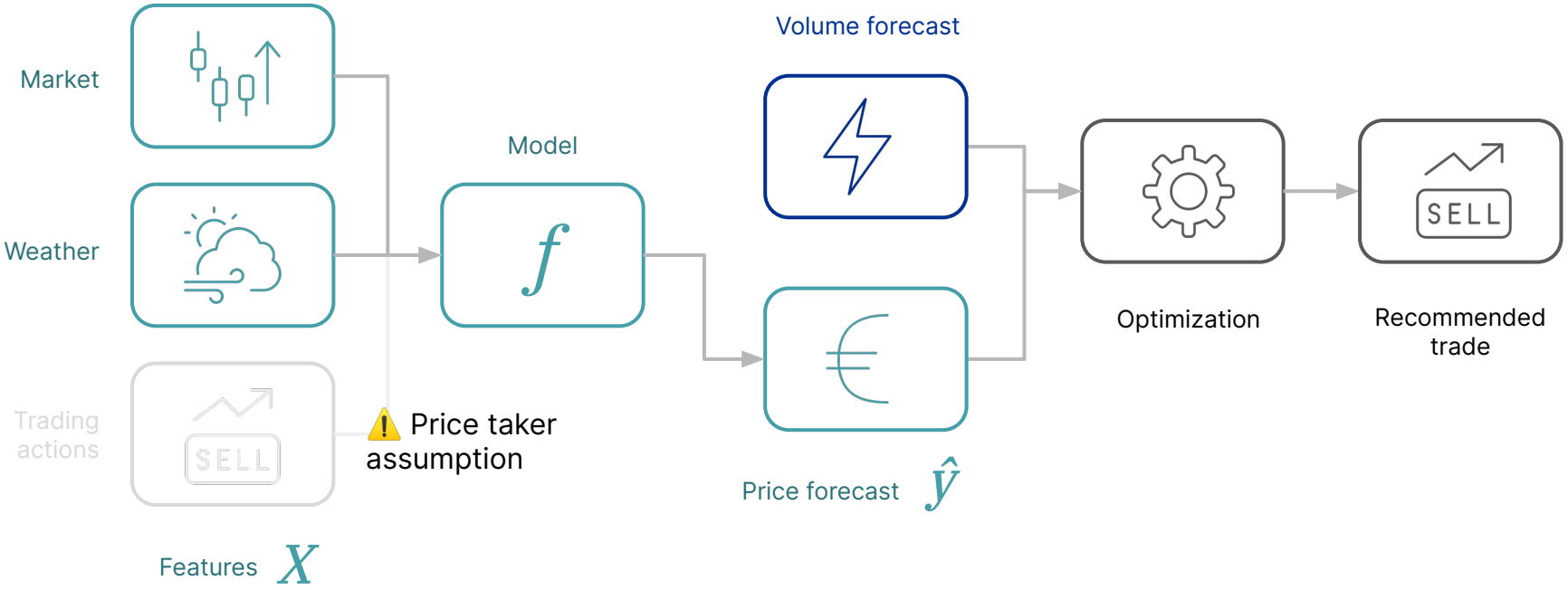


# How to obtain probabilistic forecasts?

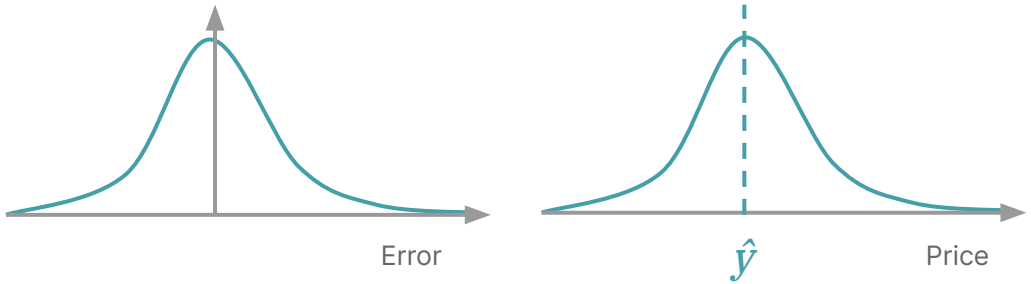
Time series regression problem



# Residuals of a calibration set give a baseline estimate of the typical uncertainty profile

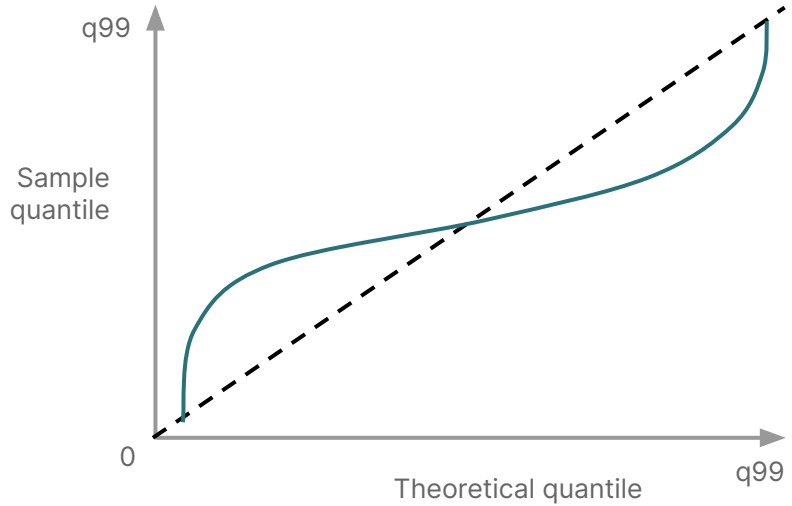
| Training | Calibration | Testing |
|---|---|---|
| **1.** | **2.** | **3.** |
| Train point forecast model | Predict on calibration set and get error distribution | Overlay error distribution on new point predictions |

$$\hat{y} = f(X)$$

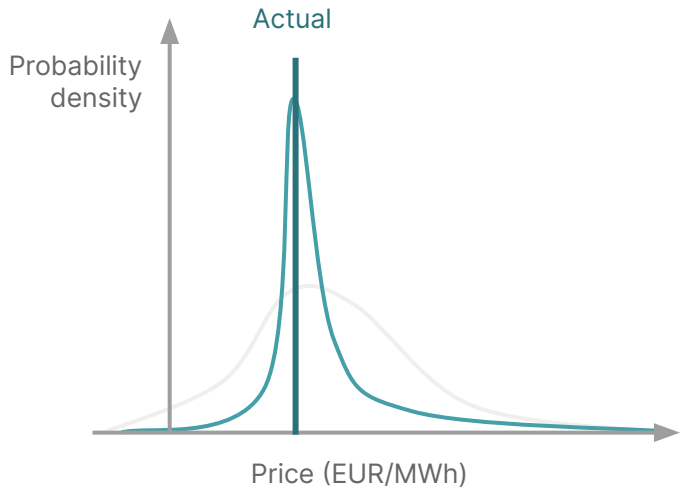


# Calibration and sharpness define the quality of a probabilistic forecast

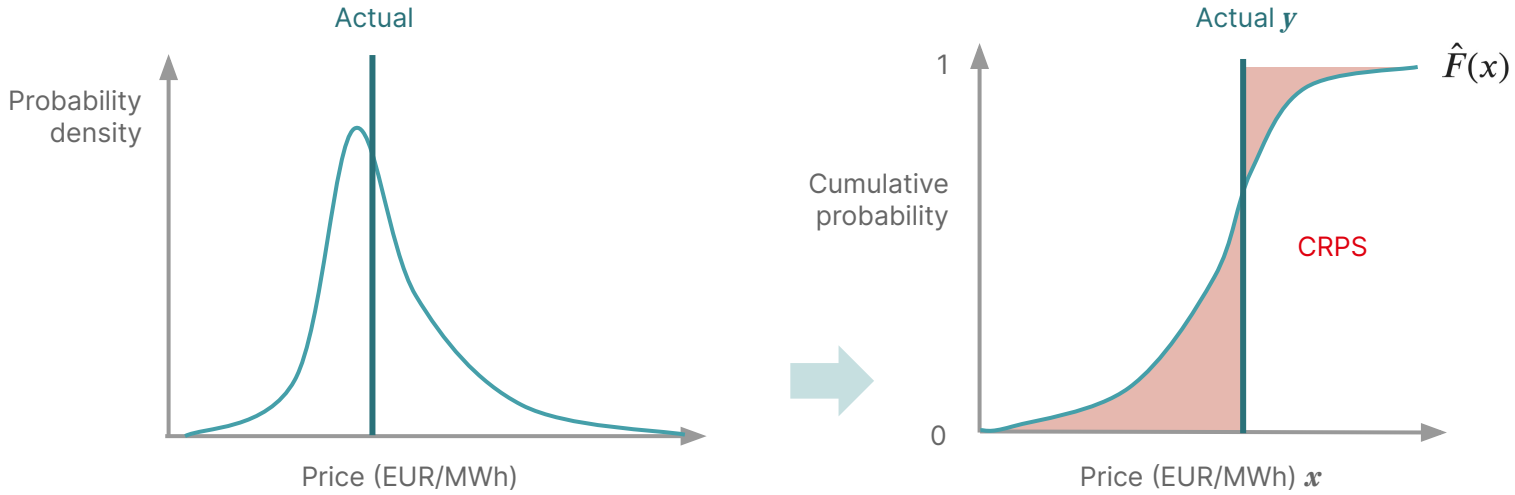
Calibration




Sharpness



# Continuous Ranked Probability Score is a single metric to evaluate probabilistic forecasts




$$CRPS(\hat{F}, y) = \int_{-\infty}^{\infty} \left( \hat{F}(x) - \mathbb{1}(x - y) \right)^2 dx$$

https://www.lokad.com/continuous-ranked-probability-score/
https://datumorphism.leima.is/cards/time-series/crps/

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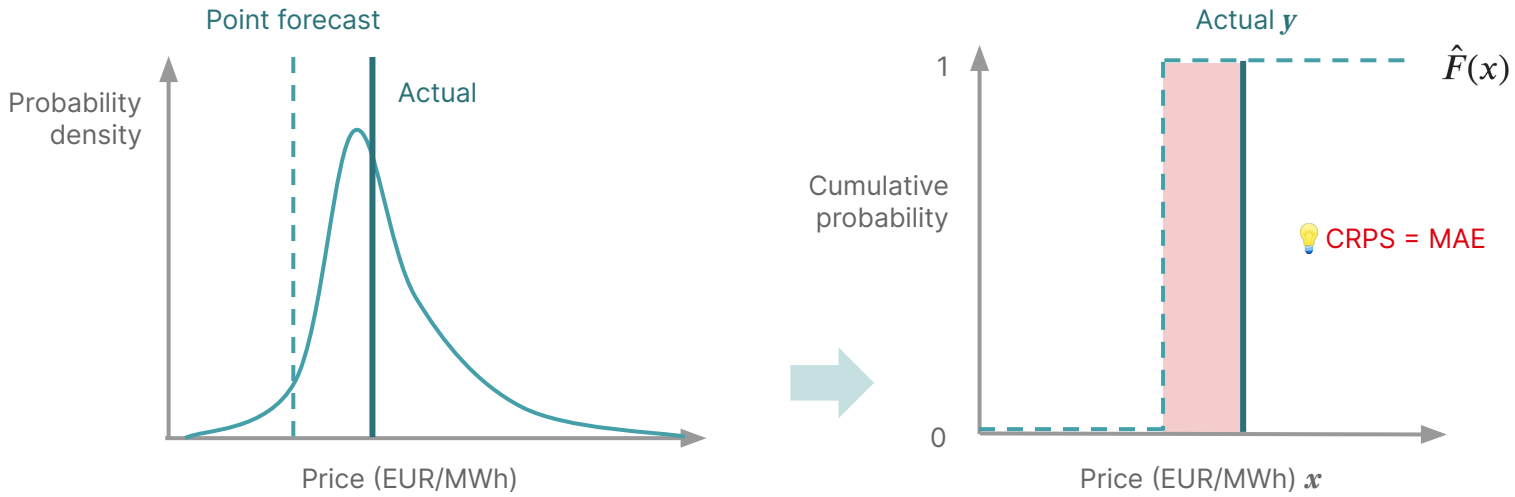


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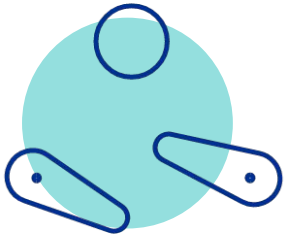
# Three methods to obtain conditional uncertainty estimates

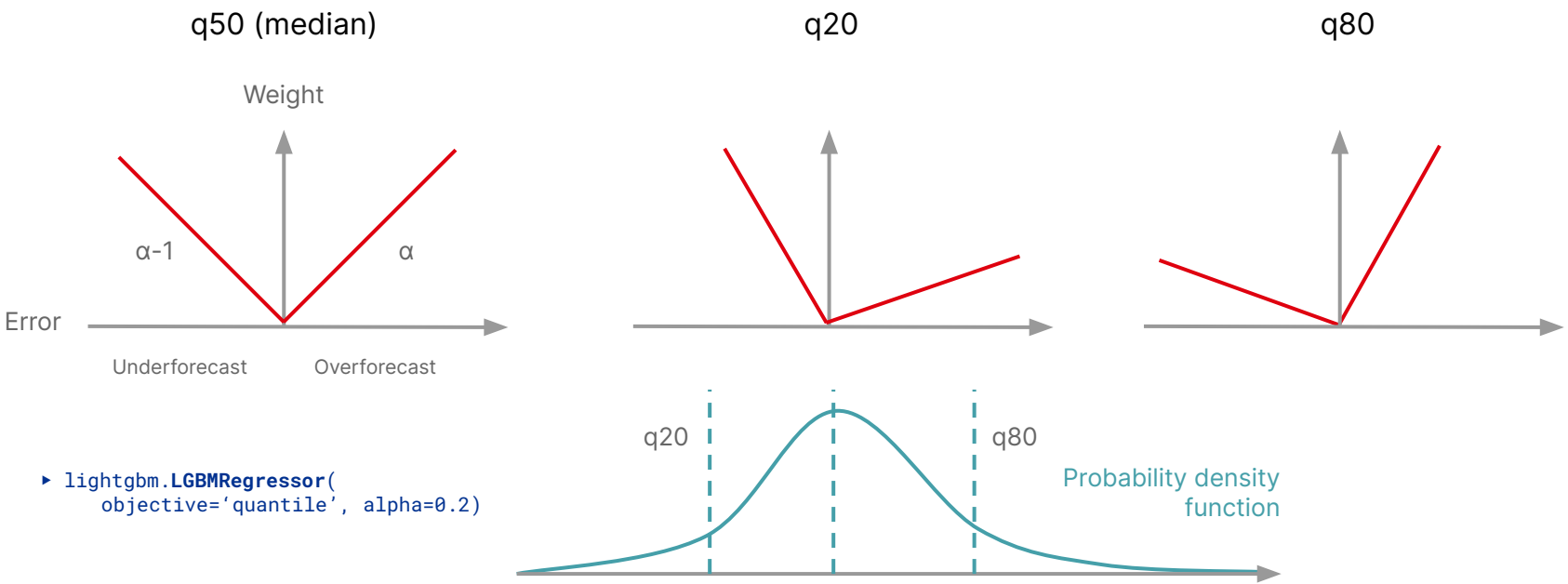


Quantile loss

Quantile forest

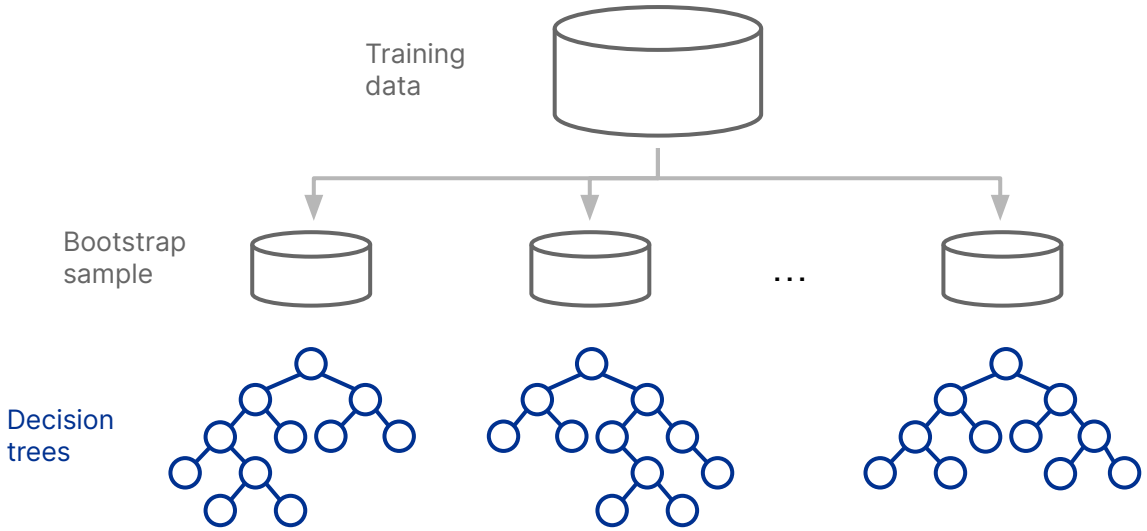
Quantile binning

# Quantile loss: asymmetrically weight errors during model training




- `lightgbm.LGBMRegressor( objective='quantile', alpha=0.2)`

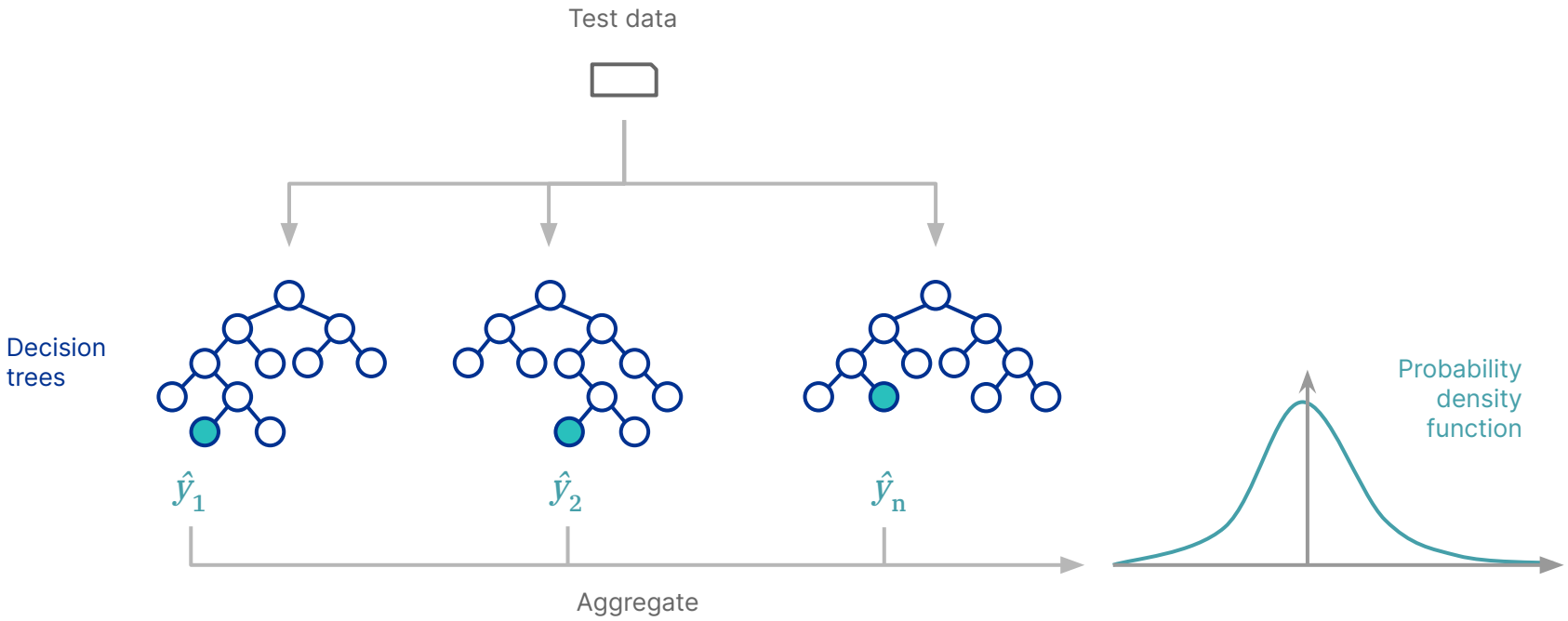
# Quantile forest: aggregate ensemble predictions




- `sklearn.ensemble.`**`RandomForestRegressor`**`(max_depth=None, min_samples_leaf=1)`

Meinshausen (2006) "Quantile regression forests." J Mach Learn Res 7:983–999

# Quantile forest: aggregate ensemble predictions

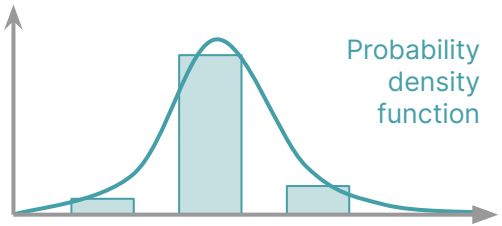



Meinshausen (2006) "Quantile regression forests." J Mach Learn Res 7:983–999

# Quantile binning: reduce quantile regression problem to a classification problem

| **Features** | **Target** $y$ | $y \in [0, 10)$ | $y \in [10, 20)$ | $y \in [20, 30)$ |
|---|---|---|---|---|
| $X_1$ | 23 | 0 | 1 | 0 |
| $X_2$ | 8 | 1 | 0 | 0 |
| ... | ... | ... | ... | ... |
| $X_{n+1}$ | **?** | 0.04 | 0.87 | 0.09 |

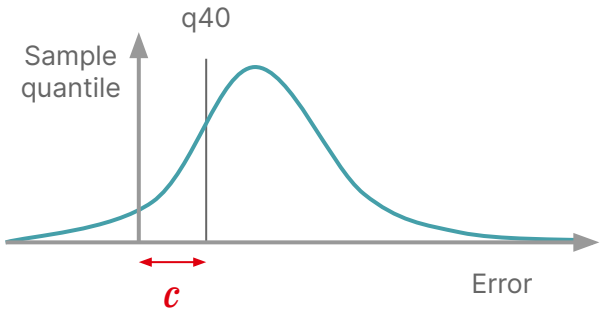
1. Bin continuous target into intervals
   - `sklearn.preprocessing.`**`KBinsDiscretizer`**
2. Train a multiclass classifier
   - `sklearn.multiclass.`**`OneVsRestClassifier`**
3. Predict and combine



# Conformal prediction can be used to obtain calibrated uncertainty estimates

| Training | Calibration | Testing |
|---|---|---|
| **1.** | **2.** | **3.** |
| Train quantile regression model | Predict on calibration set and extract correction value from error distribution | Add correction value to original quantile prediction to ensure coverage |

$$f_{\text{q40}}(X)$$



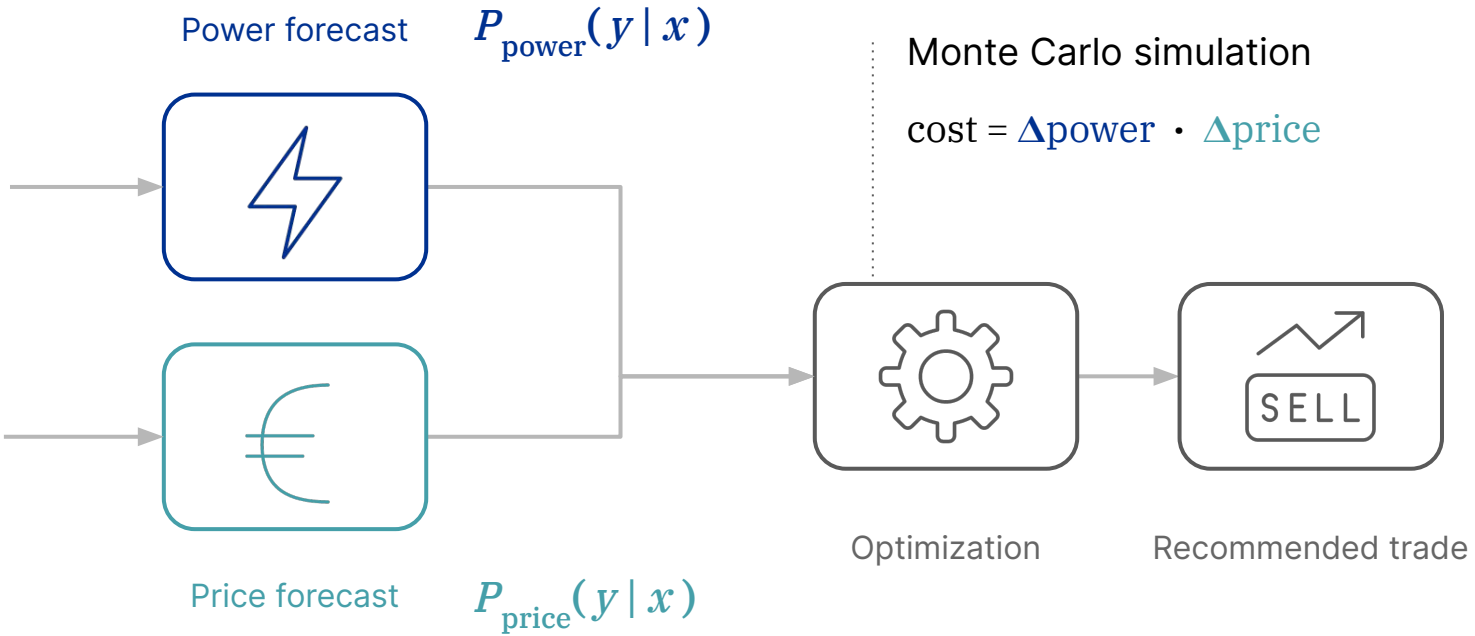

$$\hat{y}_{\text{q40}} = f_{\text{q40}}(X) + c$$

- `mapie.time_series_regression.MapieTimeSeriesRegressor`

More on this topic: https://github.com/valeman/awesome-conformal-prediction

Chen Xu and Yao Xie (2021) "Conformal Prediction Interval for Dynamic Time-Series." ICML

# Combining probabilistic price with power forecasts




More information and different approaches see:
Pinson (2023) "Distributionally robust trading strategies for renewable energy producers."
IEEE Transactions on Energy Markets, Policy and Regulation 1(1), pp. 37-47

# Key takeaways


Probabilistic forecasting adds value by enabling **risk-based trading** strategies

Existing machine learning models can be extended to **estimate quantiles**

Probabilistic forecasting can help accelerate the **energy transition**

# Thank you

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