Electricity price forecasting in the 2020s (MMXXs)

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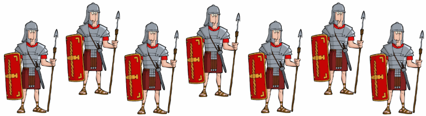
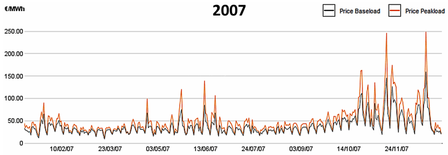


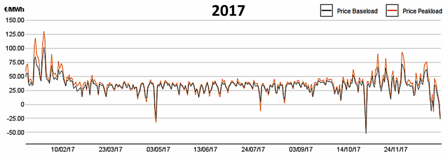
* Based on joint work with K.Hubicka, A.Jędrzejewski, K.Maciejowska, G.Marcjasz, J.Nasiadka, W.Nitka, T.Serafin, B.Uniejewski (PWr), J.Lago (Amazon), J.Nowotarski (BNY Mellon), C.Kath, M.Narajewski, F.Ziel (Essen), C.Challu, K.Olivares (Carnegie Mellon)

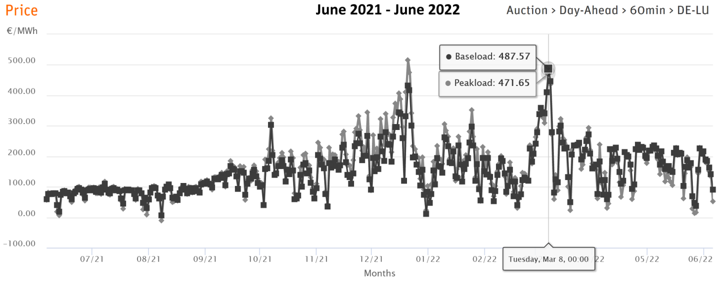

THE WORLD IS CHANGING ...

The power markets are changing ...

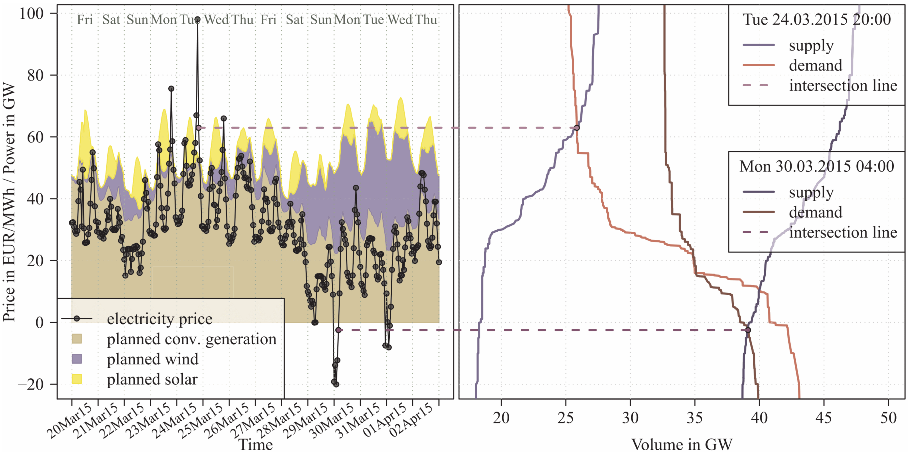
Here: 2007 vs. 2017 vs. 2021/22 average daily EPEX prices for Germany





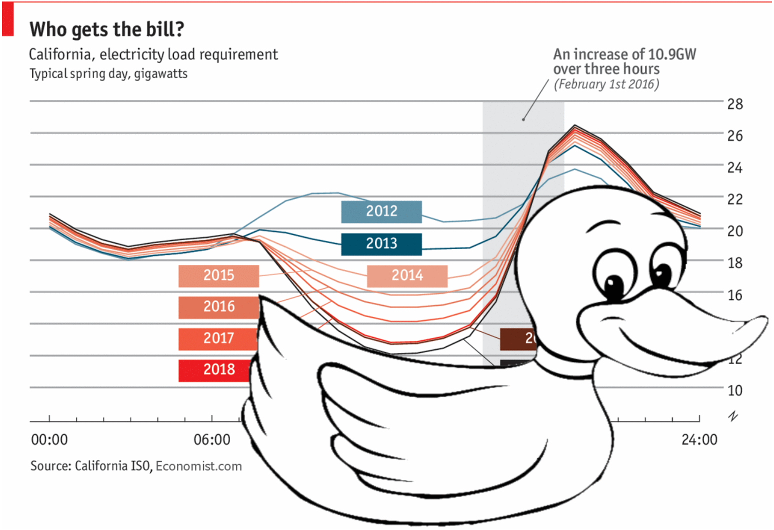


... in particular due to increased wind ...

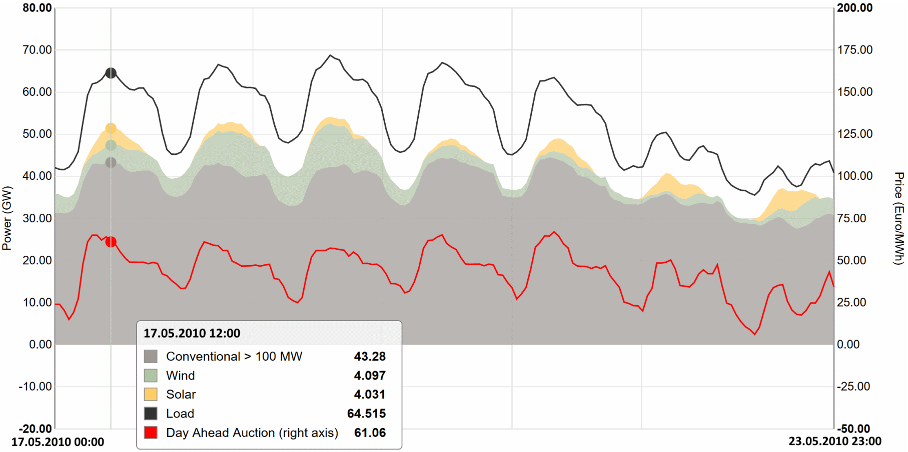


Source: Ziel & Steinert (2018, RSER)

... and solar penetration

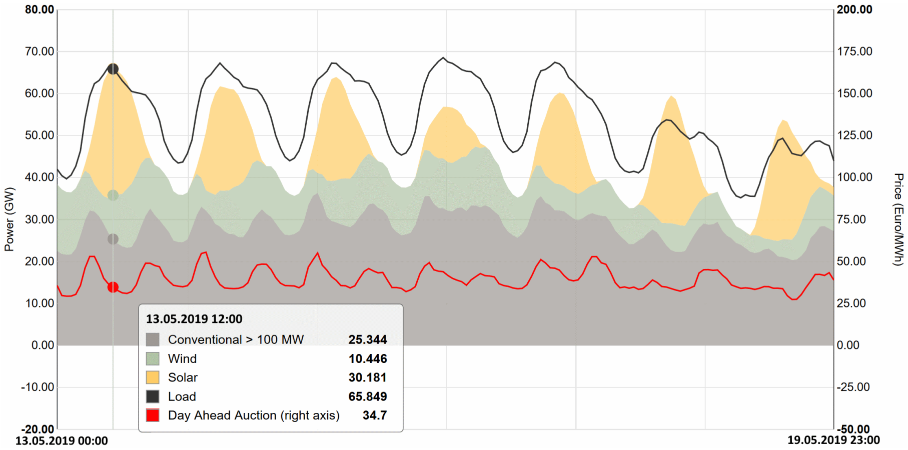


Germany 2010: No ducks



Source: www.energy-charts.de

Germany 2019: 'Duck curve' (or 'peak shaving')

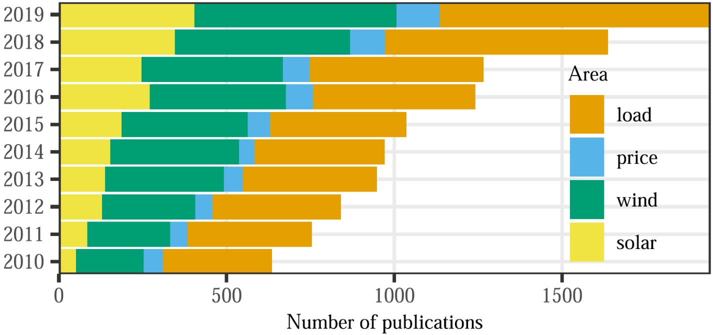


Source: www.energy-charts.de

But the (Academic) Empire ...

Load, price, wind & solar forecasting*

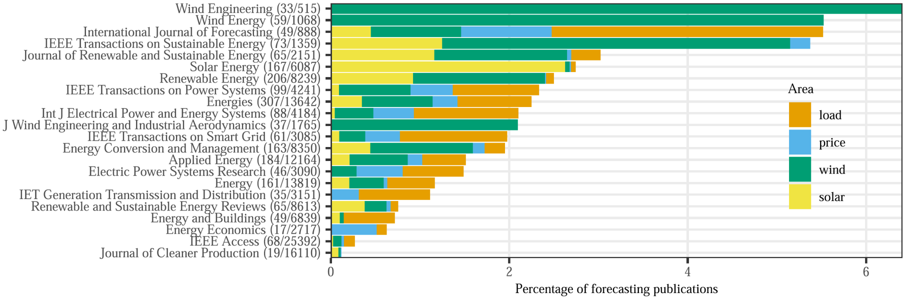
(Hong, Pinson, Wang, Weron, Yang & Zareipour, 2020, IEEE OAJPE)



* Scopus indexed

Percentage of energy forecasting publications*

(Hong, Pinson, Wang, Weron, Yang & Zareipour, 2020, IEEE OAJPE)



* Top 10 journals in each area (2010-2019); some are ranked top 10 across multiple areas

** Numbers of forecasting/total publications for each journal are shown in parentheses

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   - Identifying breakpoints
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   - Probabilistic
   - Path (ensemble)
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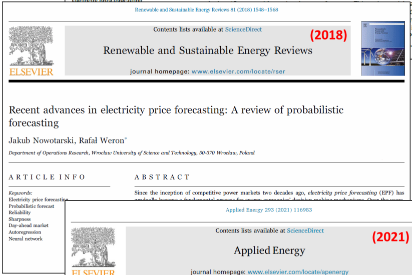
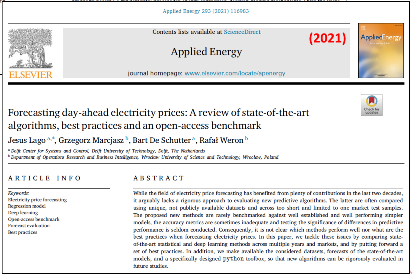




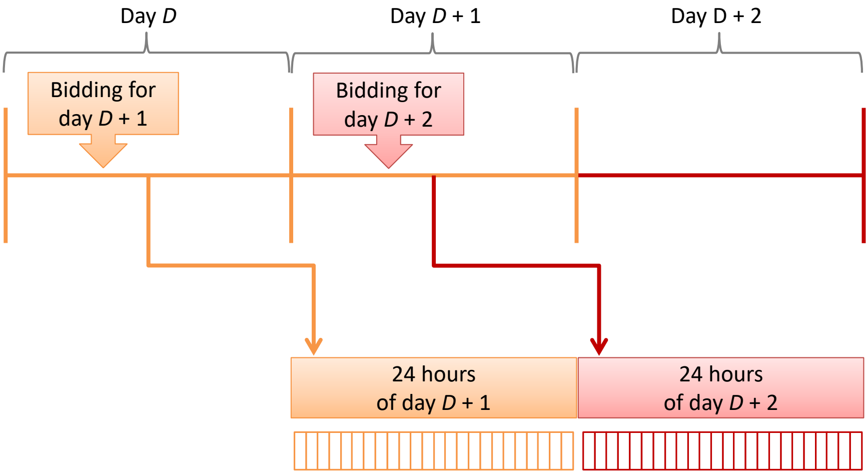
Why forecast electricity spot prices?

- Risk is managed against recourse to the spot markets
- Forward prices are assessed based on spot price forecasts, adjusted by risk premia
  - Electricity is non-storable → no physical cost-of-carry theory
- The workhorse of European trading is the day-ahead market

eex	EPEX SPOT		TSO
DERIVATIVES >	DAY-AHEAD >	INTRADAY >	BALANCING
Years/months/weeks before delivery	One day before delivery	<1 hour before delivery	Real-time
Price variations are HEDGED	**Optimization of GENERATION**	**Valuation of FLEXIBILITY**	**Ensuring SYSTEM SECURITY**

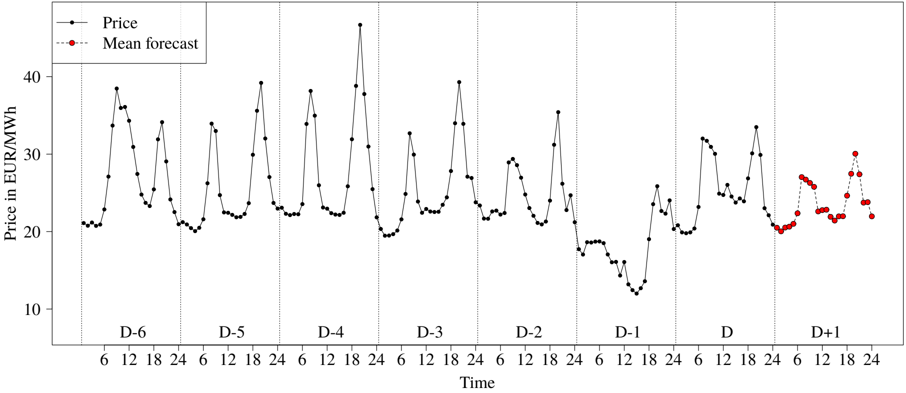
The workhorse of European power trading

The day-ahead market (> 90% of papers)

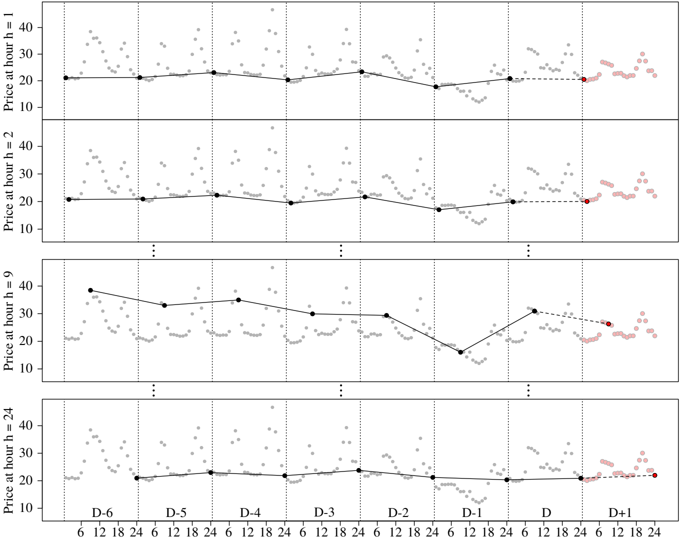


Day-ahead point forecasting: Univariate ...

(Ziel & Weron, 2018, ENEECO)

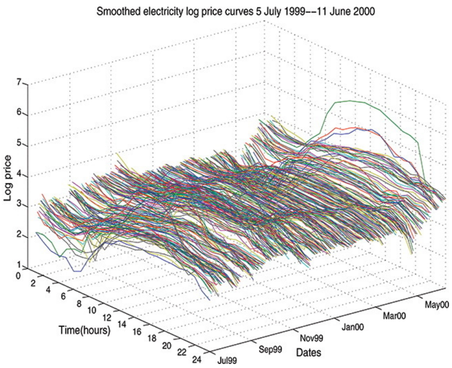


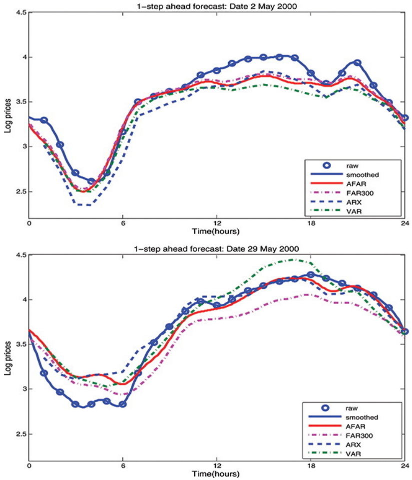
... multivariate ...



... or functional (data analysis)?

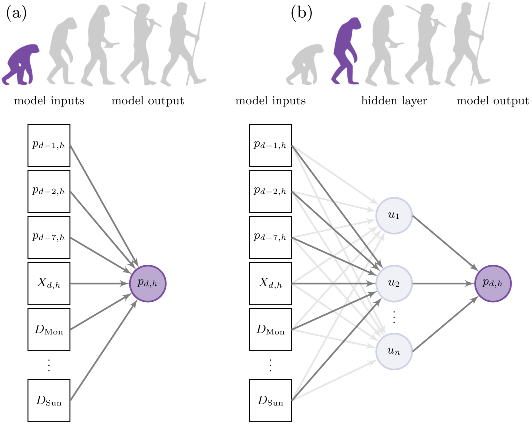
(Chen & Li, 2017, JBES; Chen et al., 2019, Ann.Appl.Stat.)





Which modeling framework?

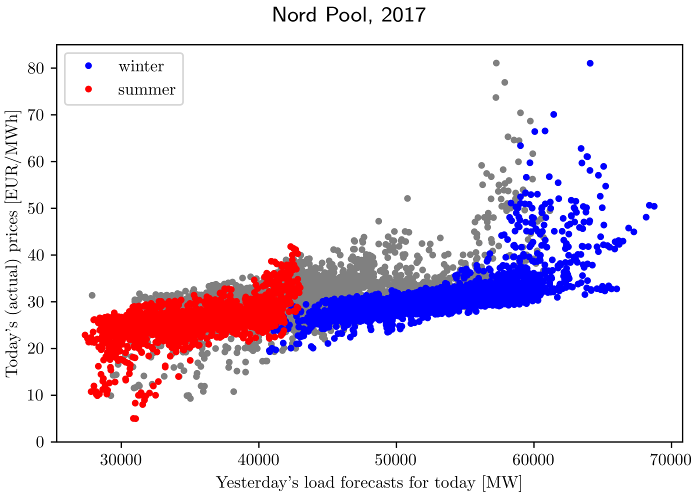
(Jędrzejewski, Lago, Marcjasz & Weron, 2022, IEEE-PEM)



Early EPF models: **(a)** linear regression and **(b)** a single-output shallow neural network

Why nonlinear?

(Jędrzejewski, Lago, Marcjasz & Weron, 2022, IEEE-PEM)

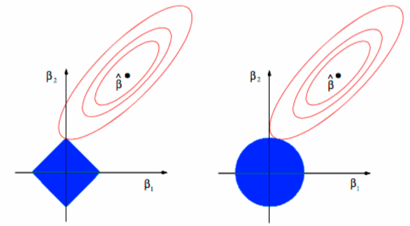


LASSO-Estimated AR (LEAR)

(Uniejewski et al., 2016; Ziel, 2016; Ziel & Weron, 2018; Jędrzejewski et al., 2022)

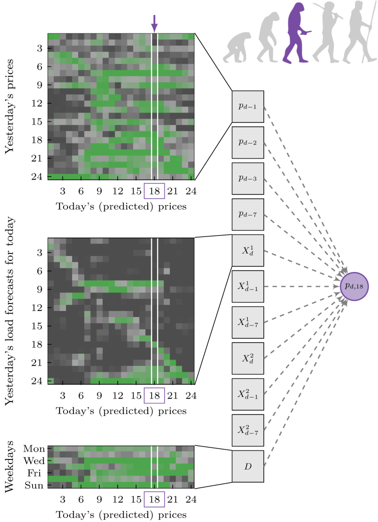
Minimize the residual sum of squares (RSS) + a penalty:

$$\hat{\beta} = \underset{\beta_j}{\operatorname{argmin}} \left\{ \mathrm{RSS} + \lambda \sum_{j=1}^{n} |\beta_j|^q \right\}$$



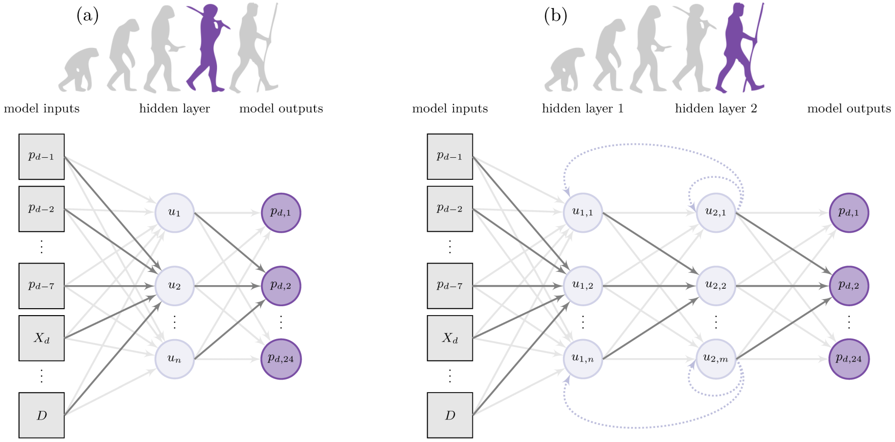
Blue areas – constraint regions, e.g., $|\beta_1| + |\beta_2| \leqslant t$

Red ellipses – contours of the LS error function



Multi-output and deep neural networks (DNNs)

(Lago et al., 2021, APEN; Jędrzejewski et al., 2022, IEEE-PEM)



Multi-output NN architectures: **(a)** shallow and **(b)** deep with 2 hidden layers

What about performance?

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[a] *Delft Center for Systems and Control, Delft University of Technology, Delft, The Netherlands*
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ARTICLE INFO

Keywords:
Electricity price forecasting
Regression model
Deep learning
Open-access benchmark
Forecast evaluation
Best practices

ABSTRACT

While the field of electricity price forecasting has benefited from p
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using unique, not publicly available datasets and across too sh
The proposed new methods are rarely benchmarked against w
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set of best practices. In addition, we make available the conside
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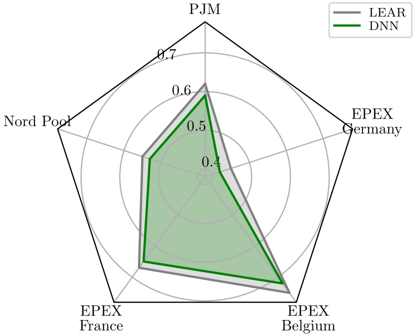
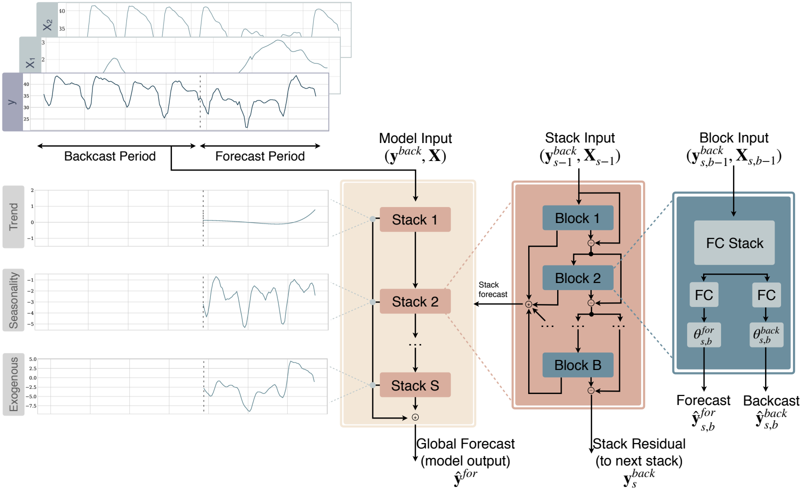
future studies.

rMAE (relative to a naive forecast)



Interpretable NNs: NBEATSx

(Olivares, Challu, Marcjasz, Weron & Dubrawski, 2022, IJF)



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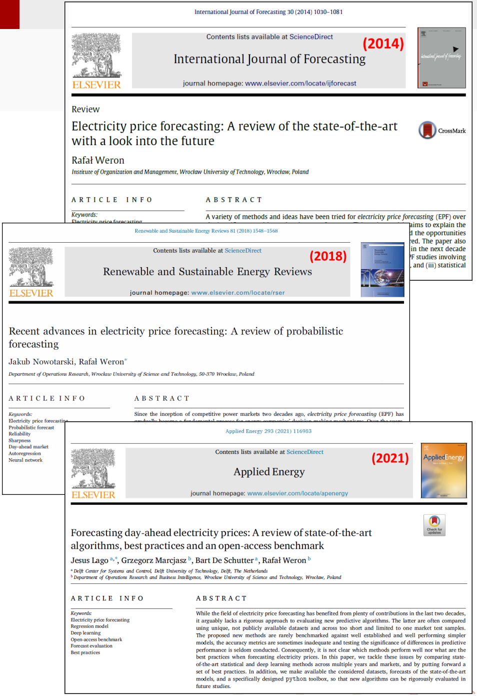

International Journal of Forecasting 30 (2014) 1030–1081

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ELSEVIER

Review

Electricity price forecasting: A review of the state-of-the-art with a look into the future

Rafał Weron

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A variety of methods and ideas have been tried for *electricity price forecasting* (EPF) over ... aims to explain the ... d the opportunities ... red. The paper also ... in the next decade ... PF studies involving ... , and (iii) statistical

Renewable and Sustainable Energy Reviews 81 (2018) 1548–1568

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ELSEVIER

Recent advances in electricity price forecasting: A review of probabilistic forecasting

Jakub Nowotarski, Rafał Weron*

Department of Operations Research, Wrocław University of Science and Technology, 50-370 Wrocław, Poland

ARTICLE INFO

Keywords:
Electricity price forecasting
Probabilistic forecast
Reliability
Sharpness
Day-ahead market
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ABSTRACT

Since the inception of competitive power markets two decades ago, *electricity price forecasting* (EPF) has ...

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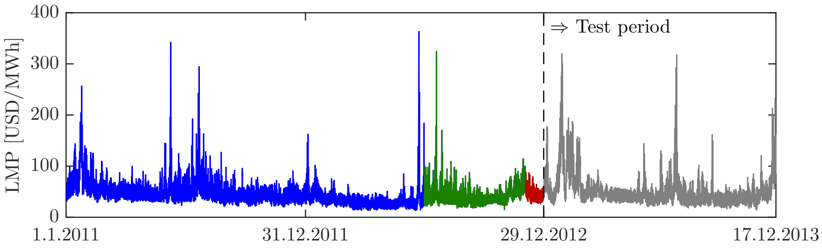
ABSTRACT

While the field of electricity price forecasting has benefited from plenty of contributions in the last two decades, it arguably lacks a rigorous approach to evaluating new predictive algorithms. The latter are often compared using unique, not publicly available datasets and across too short and limited to one market test samples. The proposed new methods are rarely benchmarked against well established and well performing simpler models, the accuracy metrics are sometimes inadequate and testing the significance of differences in predictive performance is seldom conducted. Consequently, it is not clear which methods perform well nor what are the best practices when forecasting electricity prices. In this paper, we tackle these issues by comparing state-of-the-art statistical and deep learning methods across multiple years and markets, and by putting forward a set of best practices. In addition, we make available the considered datasets, forecasts of the state-of-the-art models, and a specifically designed `python` toolbox, so that new algorithms can be rigorously evaluated in future studies.

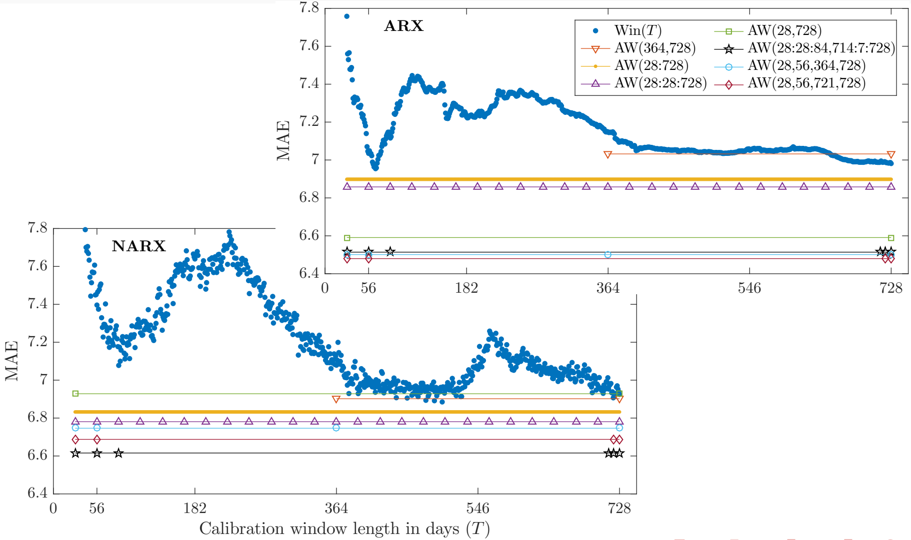
Searching for the optimal calibration window



- Which window length is optimal?
  - 728-day, 182-day, 56-day, ...
  - Longer – better reflect trends and yield more stable parameters
  - Shorter – adapt quicker to changes in the price behavior
- EPF literature: Typically selected ad-hoc
  - Ranging from 10 days to 6 years

Averaging across calibration windows

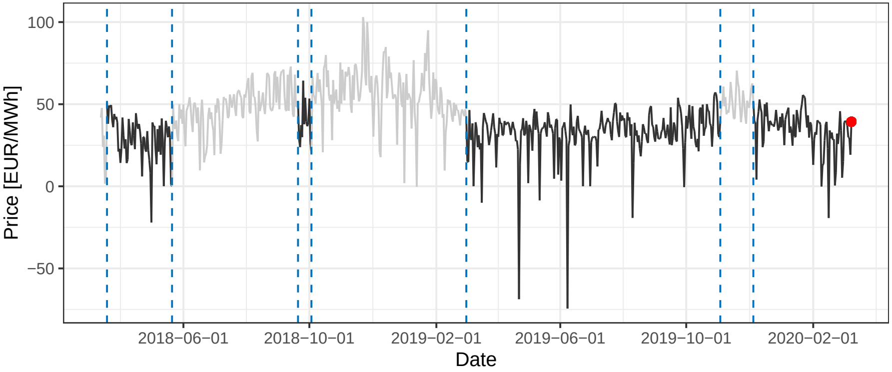
Structural breaks: Pesaran, Pick (2011, JBES); EPF: Hubicka et al. (2019, IEEE-TSE)



Detection of change/breakpoints

(de Marcos, Bunn, Bello & Reneses, 2020, Energies; Nasiadka, Nitka & Weron, ICCS 2022)

Breakpoints (blue) split the calibration window into similar (**black**) and remaining (= left out; gray) subperiods:



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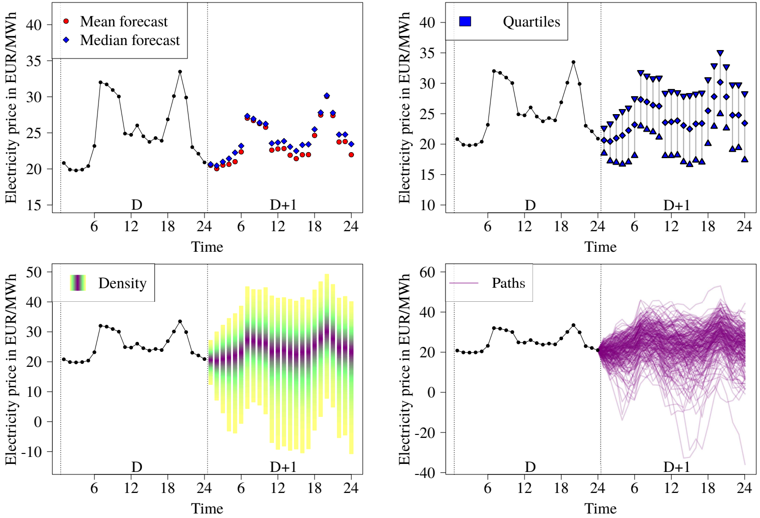
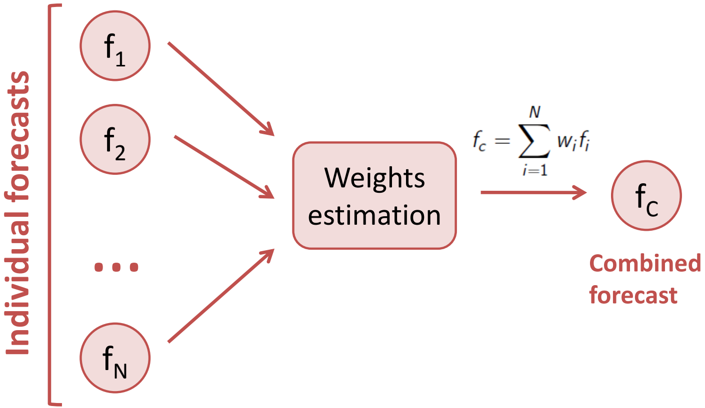
Point → probabilistic → path forecasting

($<$ 10% of EPF papers)



Point forecast averaging: The idea



- Dates back to the 1960s and the works of Bates, Crane, Crotty & Granger

Quantile Regression Averaging: The idea

(Nowotarski & Weron, 2015, COST)

Individual point forecasts

$\hat{Y}_{1,t}$

$\hat{Y}_{2,t}$

⋮

$\hat{Y}_{m,t}$

Quantile regression:

$$\min_{\boldsymbol{\beta}_q} \left[\sum_t \left(q - 1_{Y_t < \boldsymbol{X}_t \boldsymbol{\beta}_q} \right) \left(Y_t - \boldsymbol{X}_t \boldsymbol{\beta}_q \right) \right]$$

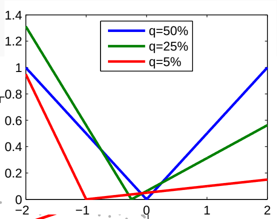
$$\boldsymbol{X}_t = \left[1, \hat{Y}_{1,t}, \dots, \hat{Y}_{m,t} \right]$$

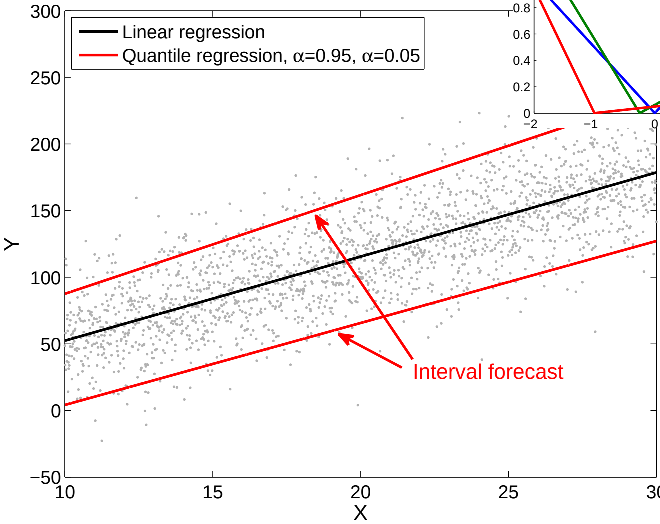
$\boldsymbol{\beta}_q$ - vector of parameters

$$\left[\hat{Y}_t^L, \hat{Y}_t^U \right]$$

Combined interval forecast, e.g., for $\boldsymbol{q = 0.05}$ & $\boldsymbol{0.95}$

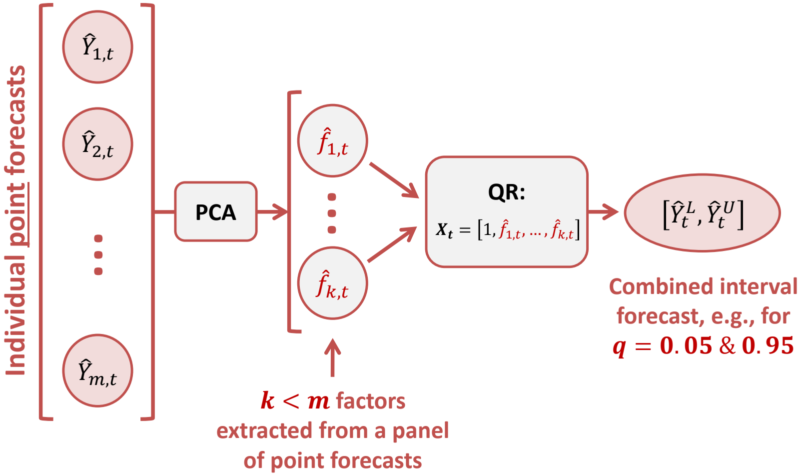
Quantile regression





FQRA: When the number of predictors is large

(Maciejowska, Nowotarski & Weron, 2016, IJF)



LQRA: When the number of predictors is large

(Uniejewski & Weron, 2021, ENEECO) $\sim$ 5% improvement over QRA

Individual point forecasts

$\hat{Y}_{1,t}$

$\hat{Y}_{2,t}$

⋮

$\hat{Y}_{m,t}$

QR with LASSO penalty:

$$\min_{\boldsymbol{\beta}_q} \left[\sum_t \left(q - 1_{Y_t < \boldsymbol{X}_t \boldsymbol{\beta}_q} \right) \left(Y_t - \boldsymbol{X}_t \boldsymbol{\beta}_q \right) + \lambda \sum |\beta_q| \right]$$

$$\boldsymbol{X}_t = [1, \hat{Y}_{1,t}, \ldots, \hat{Y}_{m,t}]$$

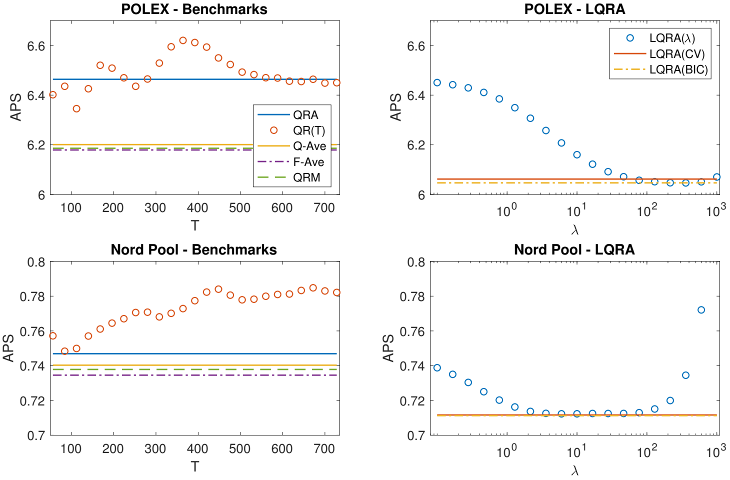
$\boldsymbol{\beta}_q$ - vector of parameters

$[\hat{Y}_t^L, \hat{Y}_t^U]$

Combined interval forecast, e.g., for $\boldsymbol{q = 0.05}$ & $\boldsymbol{0.95}$

LQRA: Aggregate Pinball Scores (APS)*

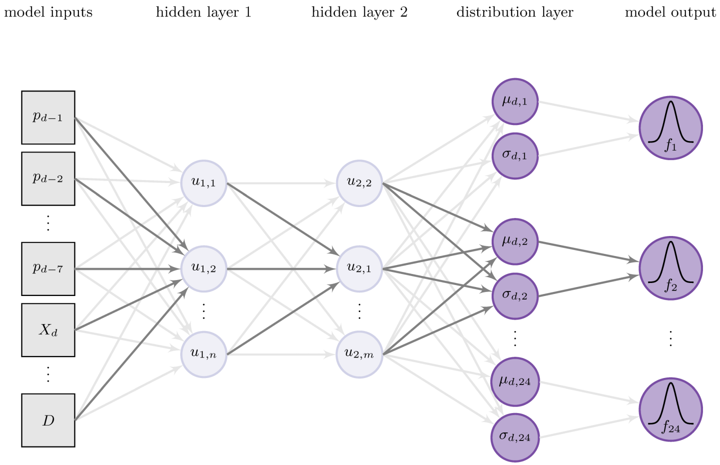
(Uniejewski & Weron, 2021, ENEECO)



*Arithmetic averages over 99 percentiles and all hours in the test period

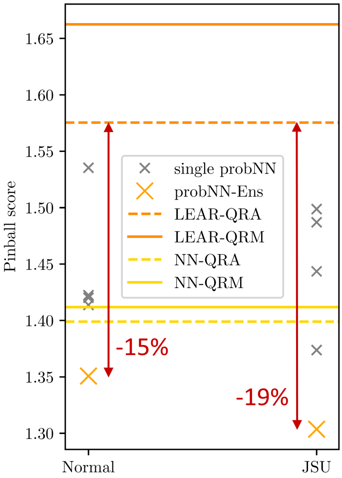
Probabilistic neural nets

(Jędrzejewski et al., 2022, IEEE-PEM; Marcjasz, Narajewski, Weron & Ziel, 2022, WP)

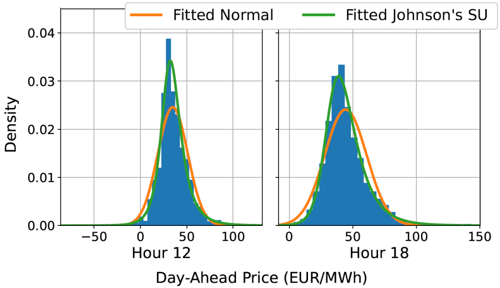


Perform surprisingly well ... after averaging

(Marcjasz, Narajewski, Weron & Ziel, 2022, WP)



	MAE	RMSE	pinball
Naive	9.336	14.378	3.585
LEAR-QRA	4.161	6.699	1.575
LEAR-QRM	4.285	6.782	1.662
NN-QRA	3.668	5.830	1.399
NN-QRM	3.670	5.822	1.412
probNN-Ens N	3.663	5.969	1.351
probNN-Ens JSU	**3.542**	**5.741**	1.304



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1. Intro
2. Model evolution
   - Models and frameworks
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International Journal of Forecasting 30 (2014) 1030–1081
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(2014)

Review

Electricity price forecasting: A review of the state-of-the-art with a look into the future

Rafał Weron
Institute of Organization and Management, Wrocław University of Technology, Wrocław, Poland

ARTICLE INFO

Keywords:
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(2018)

Recent advances in electricity price forecasting: A review of probabilistic forecasting

Jakub Nowotarski, Rafał Weron*
Department of Operations Research, Wrocław University of Science and Technology, 50-370 Wrocław, Poland

ARTICLE INFO

Keywords:
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Probabilistic forecast
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ABSTRACT

Since the inception of competitive power markets two decades ago, *electricity price forecasting* (EPF) has ...

Applied Energy 293 (2021) 116983
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(2021)

Forecasting day-ahead electricity prices: A review of state-of-the-art algorithms, best practices and an open-access benchmark

Jesus Lago[a,*], Grzegorz Marcjasz[b], Bart De Schutter[a], Rafał Weron[b]
[a] Delft Center for Systems and Control, Delft University of Technology, Delft, The Netherlands
[b] Department of Operations Research and Business Intelligence, Wrocław University of Science and Technology, Wrocław, Poland

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Keywords:
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Regression model
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ABSTRACT

While the field of electricity price forecasting has benefited from plenty of contributions in the last two decades, it arguably lacks a rigorous approach to evaluating new predictive algorithms. The latter are often compared using unique, not publicly available datasets and across too short and limited to one market test samples. The proposed new methods are rarely benchmarked against well established and well performing simpler models, the accuracy metrics are sometimes inadequate and testing the significance of differences in predictive performance is seldom conducted. Consequently, it is not clear which methods perform well nor what are the best practices when forecasting electricity prices. In this paper, we tackle these issues by comparing state-of-the-art statistical and deep learning methods across multiple years and markets, and by putting forward a set of best practices. In addition, we make available the considered datasets, forecasts of the state-of-the-art models, and a specifically designed python toolbox, so that new algorithms can be rigorously evaluated in future studies.

Economic/financial impact of forecasting errors

(2010)

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 25, NO. 1, FEBRUARY 2010

Economic Impact of Electricity Market Price Forecasting Errors: A Demand-Side Analysis

Hamidreza Zareipour, *Member, IEEE*, Claudio A. Cañizares, *Fellow, IEEE*, and Kankar Bhattacharya, *Senior Member, IEEE*

***Abstract*—Several techniques have been proposed in the literature to forecast electricity market prices and improve forecast accuracy. However, no studies have been reported examining the economic impact of price forecast inaccuracies on forecast users. Therefore, in this paper, the application of electricity market price forecasts to short-term operation scheduling of two typical and inherently different industrial loads is examined and the associated economic impact is analyzed. Using electricity market price forecasts as the expected next-day electricity prices, optimal operating schedules and the associated costs are determined for each load. These costs are compared with those of a "perfect" price forecast scenario in which actual prices are used to determine the operating schedules. Numerical results and discussions are provided based on price forecasts with different error characteristics.**

***Index Terms*—Demand-side management, economic benefit, economic value, forecasting error, price forecasting, scheduling.**

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ELSEVIER

(2018)

The value of forecasts: Quantifying the economic gains of accurate quarter-hourly electricity price forecasts

Christopher Kath[a,*,1], Florian Ziel[b]

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[b] University Duisburg-Essen, House of Energy Markets and Finance, Germany

net regression forecast model for German quarter-hourly electricity spot
verse on day-ahead prediction approaches, both the intraday continuous
ave not been studied intensively with a clear focus on predictive power.
g, we check for the impact of early day-ahead (DA) EXAA prices on intra-
his paper is the complementary discussion of economic benefits. A precise
be utilized. We elaborate possible trading decisions based upon our fore-
monetary effects. We find that even simple electricity trading strategies
mpact if combined with a decent forecasting technique.

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energies

(2020)

MDPI

Article

Balancing Generation from Renewable Energy Sources: Profitability of an Energy Trader

Christopher Kath [1,2], Weronika Nitka [3,4], Tomasz Serafin [3,4], Tomasz Weron [3,4], Przemysław Zaleski [3,5] and Rafał Weron [3,*]

1 RWE Supply & Trading GmbH, 45141 Essen, Germany; christopher.kath@rwe.com
2 House of Energy Markets and Finance, University of Duisburg-Essen, 45141 Essen, Germany
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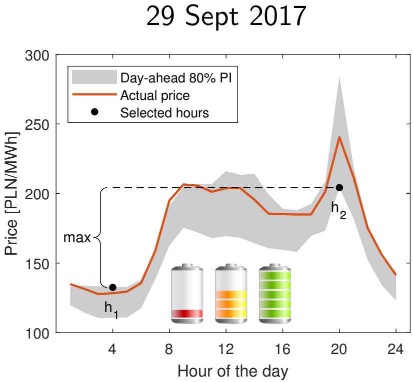
tomek.weron@gmail.com (T.W.); przemyslaw.zaleski@pwr.edu.pl (P.Z.)

Quantile-based trading strategies

(Uniejewski & Weron, 2021, ENEECO)



Simultaneously bid day-ahead:

- buy 1 MW for $\hat{P}^{1-\alpha}_{d,h_1}$ at hour h_1
- sell 0.8 MW at $\hat{P}^{\alpha}_{d,h_2}$ at hour h_2

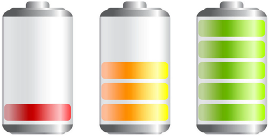
$\leftarrow$ With $\alpha = 10\%$ the spread is maximized for $\hat{P}^{90\%}_{d,4} = 133$ and $\hat{P}^{10\%}_{d,20} = 204$ PLN/MWh

- If bid(s) not accepted, settle in the balancing market

Quantile-based trading strategies: Results

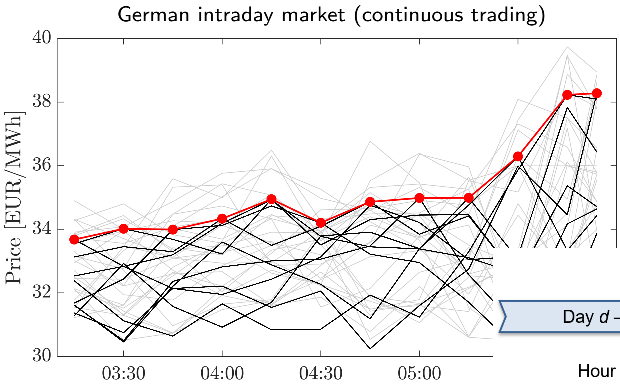
(Uniejewski & Weron, 2021, ENEECO)

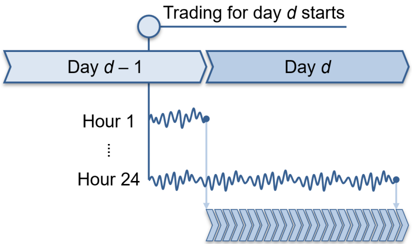
Strategy			**Profit**		
Naive (4am–12pm)			33 065.29		
Point forecasts-based			37 722.39		
Quantile-based	*1–99%*	*5–95%*	*10–90%*	*20–80%*	*25–75%*
Q-Ave	41 317.92	43 328.89	43 432.31	43 289.09	43 033.88
F-Ave	39 848.26	43 369.44	44 052.04	44 088.11	43 130.34
QRM	41 163.29	43 054.28	43 124.12	43 731.54	42 240.25
LQRA(77)	42 360.05	44 135.49	44 713.52	44 684.40	43 624.65
LQRA(BIC)	42 886.10	43 993.23	44 502.81	**45 396.21**	42 741.57
LQRA(CV)	41 693.80	43 971.88	44 238.45	45 073.19	43 103.88



Prediction bands-based trading strategies

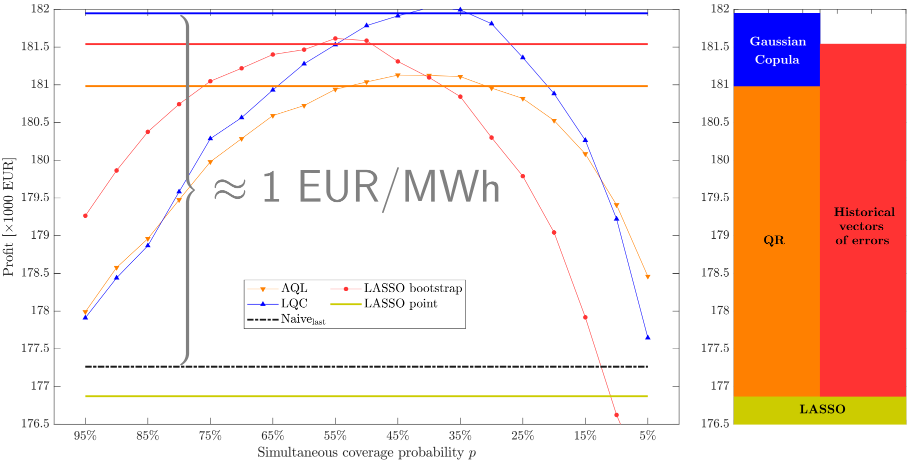
(Serafin, Marcjasz & Weron, 2021, WP)





Profits: Selling 1 MW every hour for 200 days

(Serafin, Marcjasz & Weron, 2021, WP)



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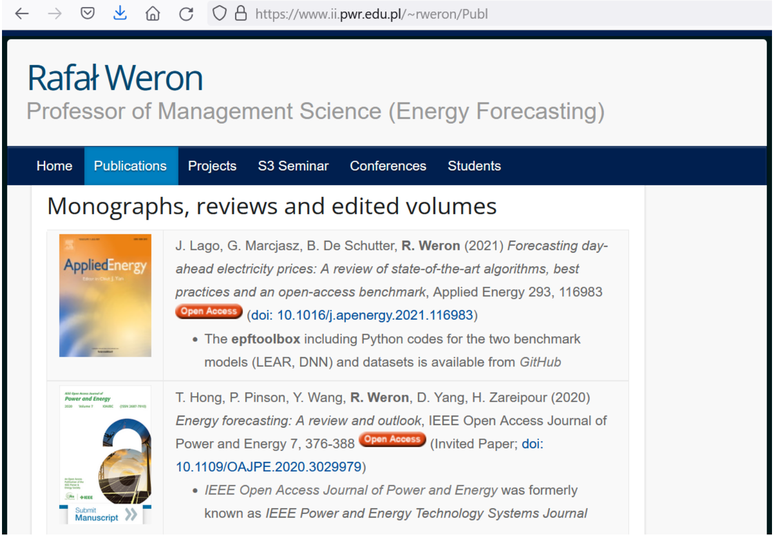
Articles & working papers on https://www.ii.pwr.edu.pl/∼rweron/Publ



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Rafał Weron

Professor of Management Science (Energy Forecasting)

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Monographs, reviews and edited volumes

J. Lago, G. Marcjasz, B. De Schutter, **R. Weron** (2021) *Forecasting day-ahead electricity prices: A review of state-of-the-art algorithms, best practices and an open-access benchmark*, Applied Energy 293, 116983 Open Access (doi: 10.1016/j.apenergy.2021.116983)

- The **epftoolbox** including Python codes for the two benchmark models (LEAR, DNN) and datasets is available from *GitHub*

T. Hong, P. Pinson, Y. Wang, **R. Weron**, D. Yang, H. Zareipour (2020) *Energy forecasting: A review and outlook*, IEEE Open Access Journal of Power and Energy 7, 376-388 Open Access (Invited Paper; doi: 10.1109/OAJPE.2020.3029979)

- *IEEE Open Access Journal of Power and Energy* was formerly known as *IEEE Power and Energy Technology Systems Journal*