Recent advances in electricity price forecasting: A 2023 perspective

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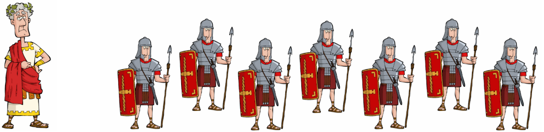
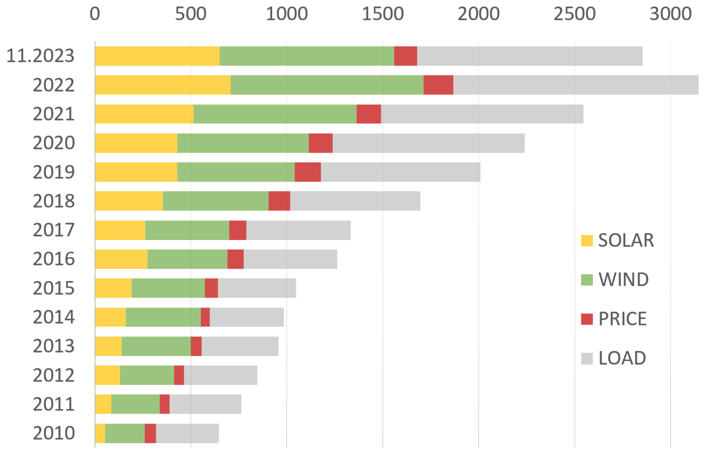


* Based on joint work with K.Maciejowska, G.Marcjasz, J.Nasiadka, W.Nitka, T.Serafin, B.Uniejewski (WrocławTECH), C.Challu, K.Olivares (Carnegie Mellon), A.Jędrzejewski (U.Cergy-Pontoise), F.Ziel (U.Duisburg-Essen), K.Hubicka (UBS), C.Kath (RWE), J.Lago (Amazon), M.Narajewski (Statkraft), J.Nowotarski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

Energy (load, price, wind & solar) forecasting*

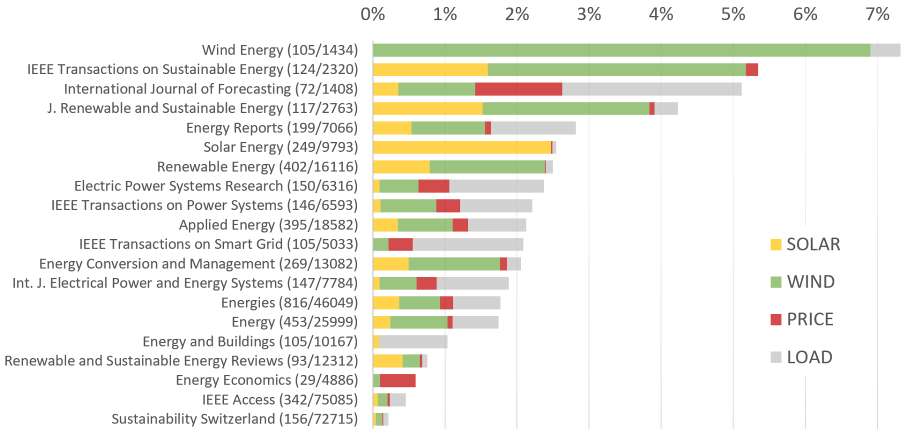
(Hong, Pinson, Wang, Weron, Yang & Zareipour, 2020, IEEE OAJPE)



* Number of Scopus indexed publications (29.11.2023 update)

Percentage of energy forecasting publications*

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

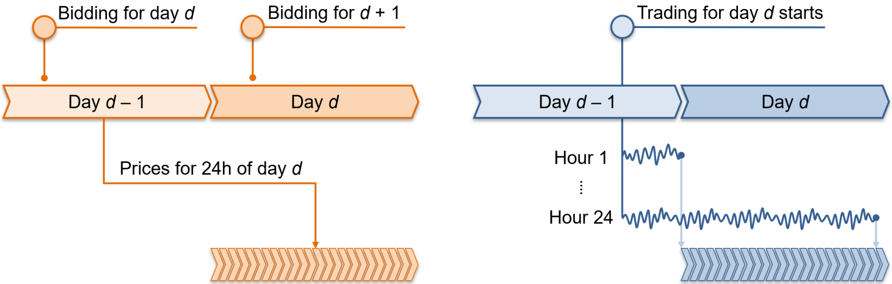


* Top 10 journals in each area (2010-11.2023); some are ranked top 10 across multiple areas

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

Day-ahead (> 90% of papers) vs. intraday markets

Auction vs. continuous trading



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1. Intro
2. Model evolution
   - Models and frameworks
   - Regularization
   - Going deep
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   - Averaging
   - Identifying breakpoints
4. Beyond point forecasts
   - Probabilistic
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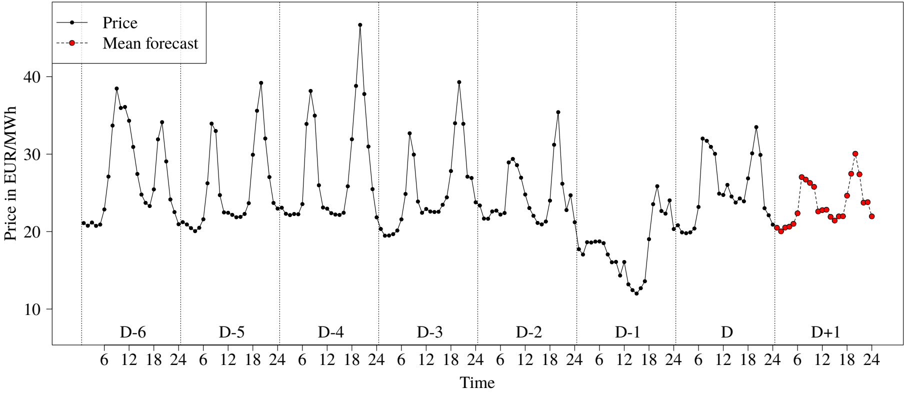
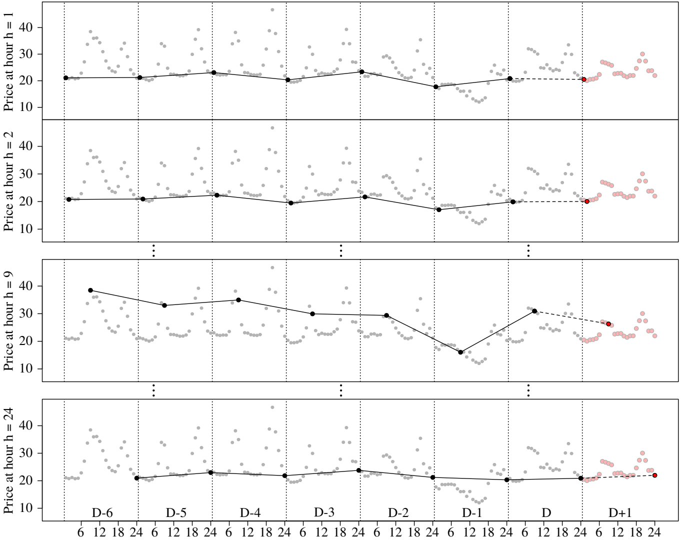
Day-ahead point forecasting: Univariate ...

(Ziel & Weron, 2018, ENEECO)

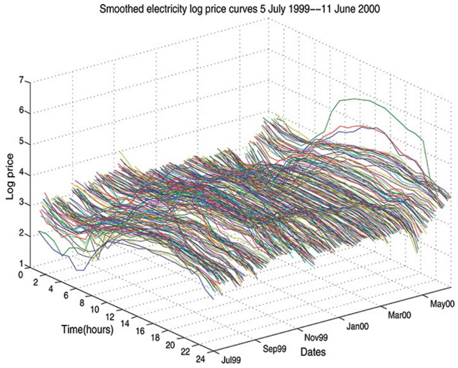


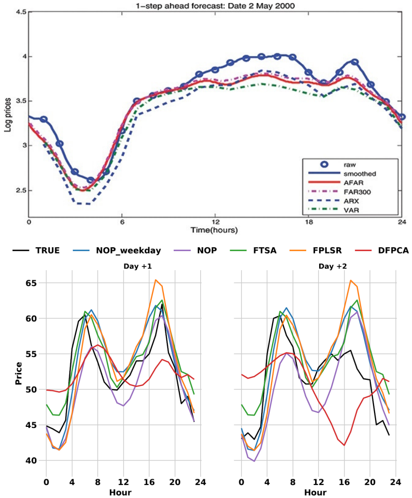
... multivariate ...



... functional (data analysis) ...

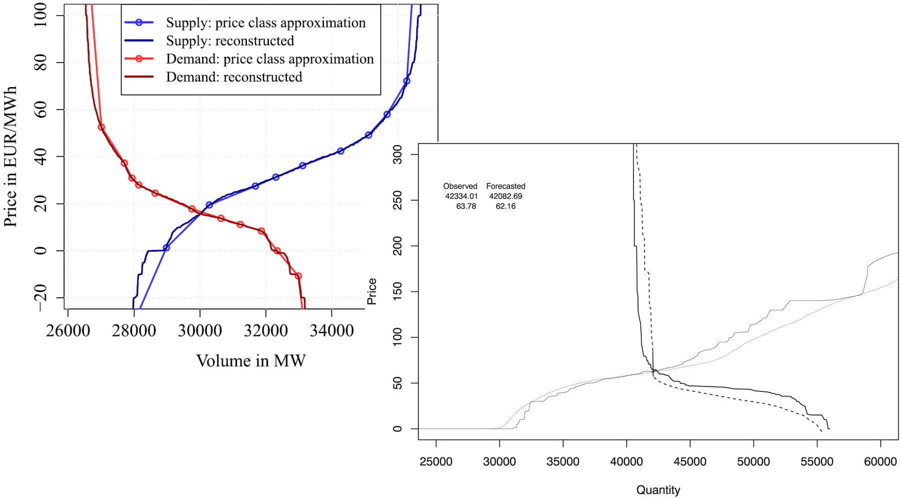
(Chen & Li, 2017, JBES; Chen et al., 2019, Ann.Appl.Stat; Wang & Cao, 2023, Environmetrics)





... or supply & demand curves?

(Ziel & Steinert, 2016, ENEECO; Shah & Lisi, 2020, J.Forecasting)



Which modeling framework?

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

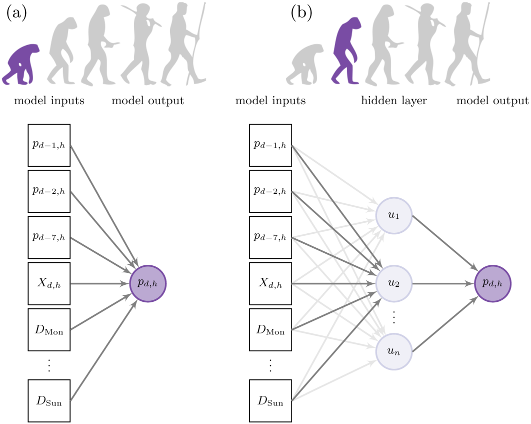
A simple autoregressive structure with exogenous variables (ARX):

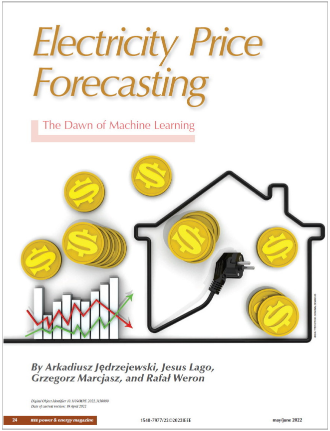
$$p_{d,h} = \underbrace{\beta_1 p_{d-1,h} + \beta_2 p_{d-2,h} + \beta_3 p_{d-7,h}}_{\text{autoregressive effects}} + \underbrace{\beta_4 X_{d,h}^{(1)} + \beta_5 X_{d,h}^{(2)}}_{\text{exogenous variables}} + \underbrace{\beta_6 D_{Sat} + \beta_7 D_{Sun} + \beta_8 D_{Mon}}_{\text{weekday dummies}} + \varepsilon_{d,h},$$

e.g., load (demand) and renewable generation day-ahead forecasts

Which modeling framework?

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

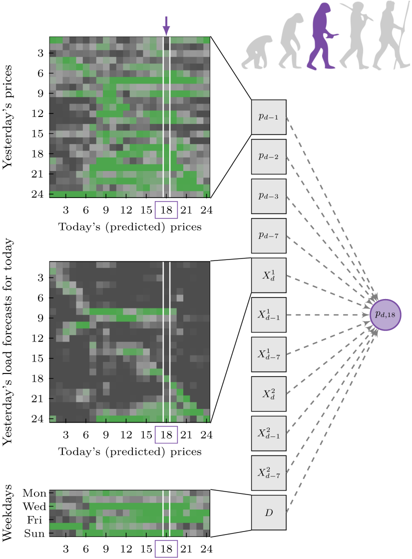




Early EPF models: **(a)** linear regression and **(b)** a single-output shallow neural network

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:

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

LASSO-Estimated AR (LEAR)

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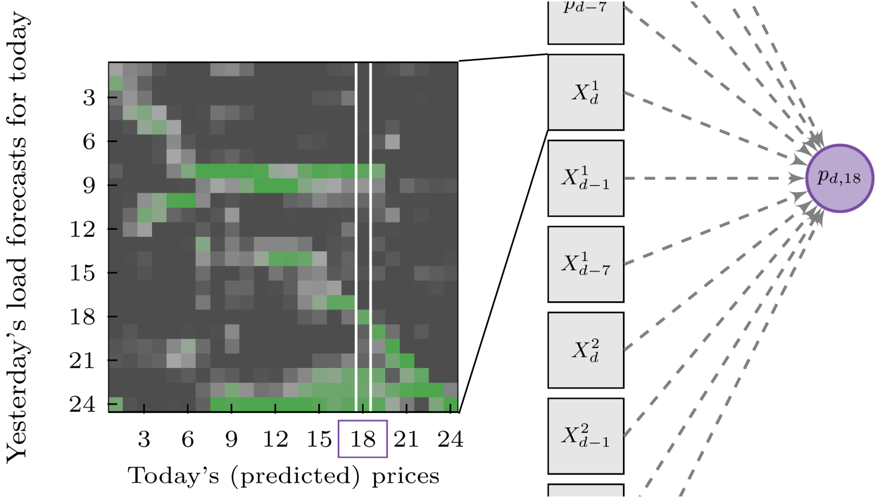
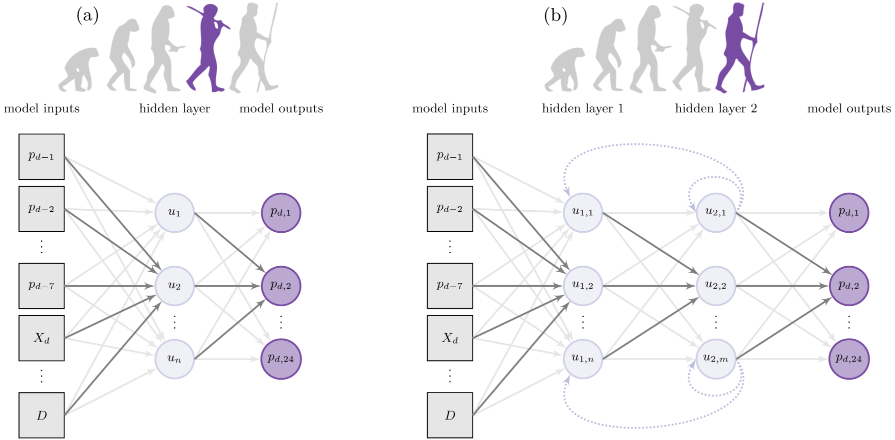


Multi-output and deep neural networks (DNNs)

(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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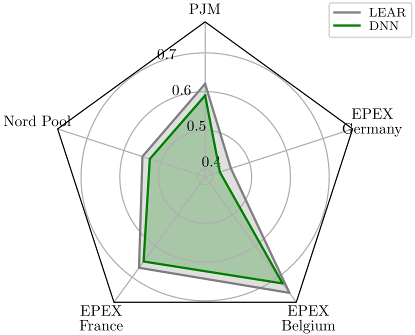
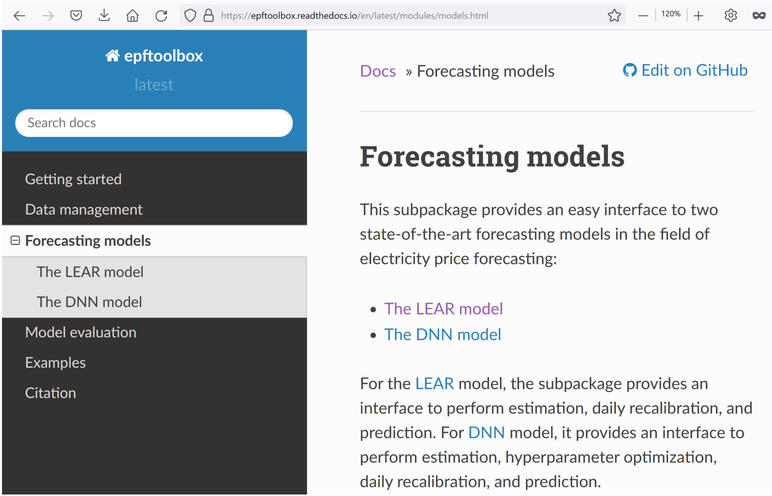
future studies.

rMAE (relative to a naive forecast)



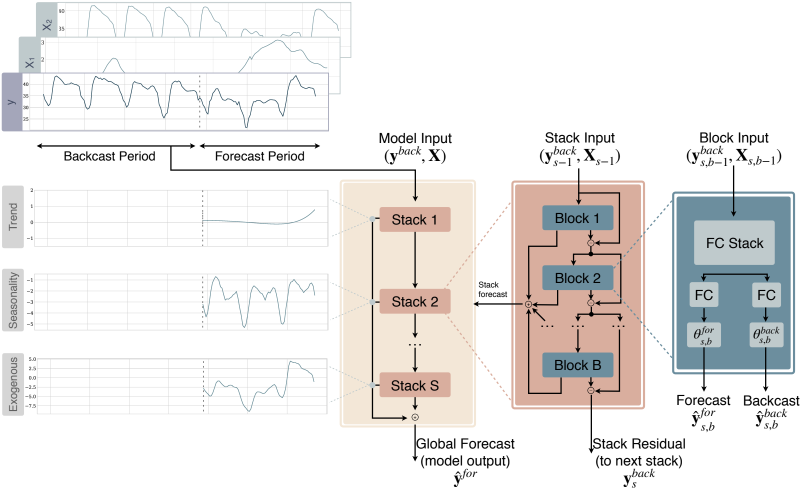
epftoolbox: LEAR and DNN Python codes

(Lago et al., 2021, APEN)



Interpretable NNs: NBEATSx

(Olivares, Challu, Marcjasz, Weron & Dubrawski, 2023, IJF)



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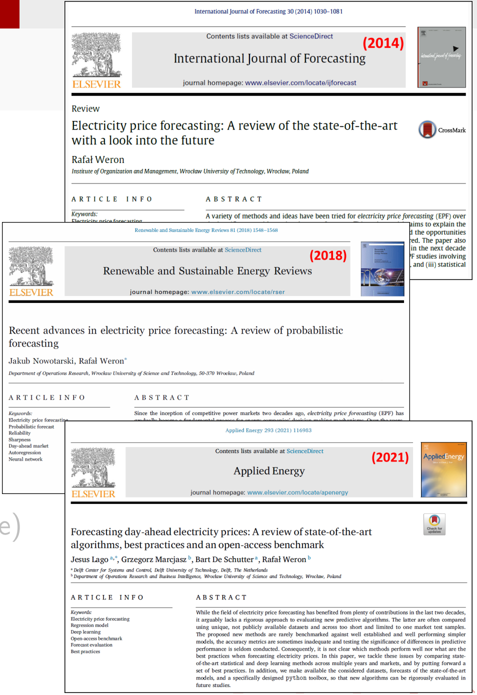

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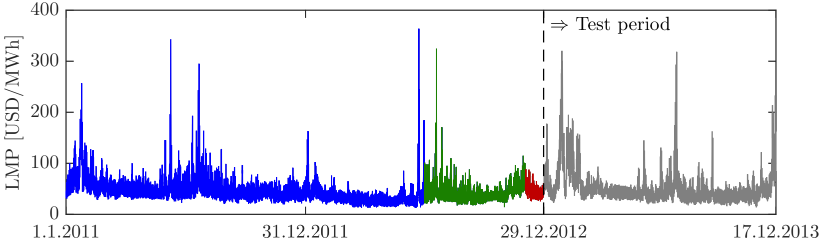
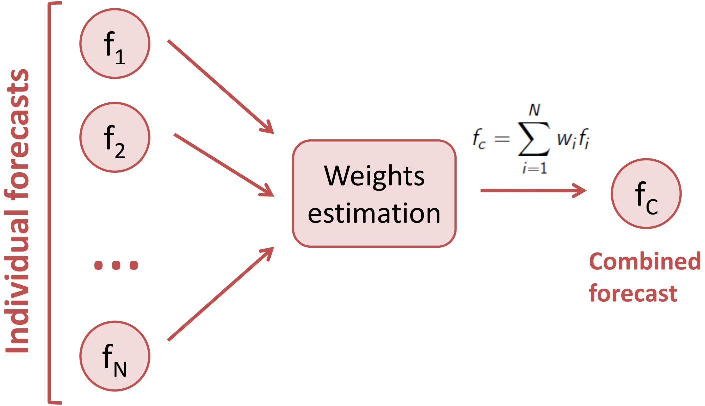
Searching for the optimal calibration window



- 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

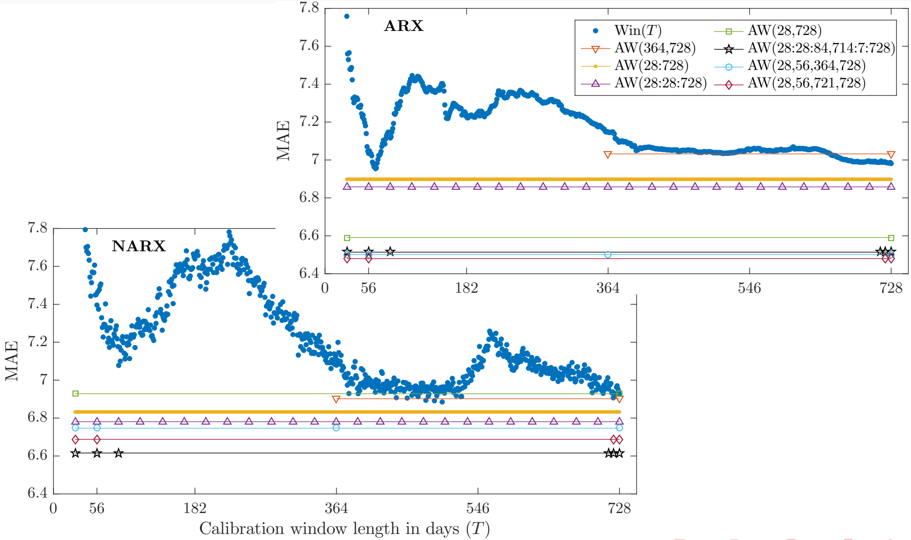
Point forecast averaging: The idea



- Dates back to the 1960s and the works of Bates, Crane, Crotty & Granger
- 'AI world': *committee machines*, *ensemble averaging*, *expert aggregation*

Averaging across calibration windows

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



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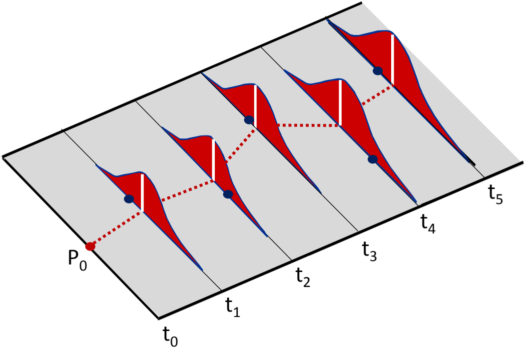
Probabilistic (interval, density) forecasting

- We cannot observe the true underlying distribution

  $\Rightarrow$ we cannot compare the *predictive distribution* $\hat{F}_{Y_t}$ with the actual one F_{Y_t} ... only with past observations $Y_\tau, \tau < t$

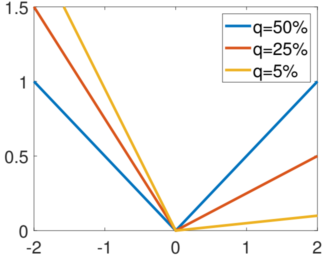
- Gneiting et al. (2007a, 2007b, 2014): '*maximize **sharpness** subject to **reliability***'



Sharpness and the pinball score (or loss)

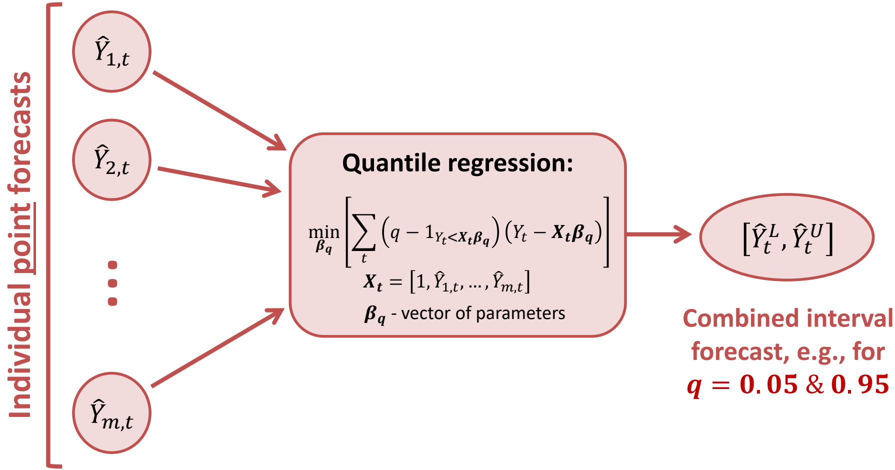
$$\mathbf{PS}\left(\hat{Y}_t^q, Y_t, q\right) = \begin{cases} (1-q)\left(\hat{Y}_t^q - Y_t\right) & \text{for } Y_t < \hat{Y}_t^q \\ q\left(Y_t - \hat{Y}_t^q\right) & \text{for } Y_t \geqslant \hat{Y}_t^q \end{cases}$$

- $\hat{Y}_t^q$ is the forecast of the q-th quantile
- Y_t is the actual observation
- Also known as the quantile score or the linlin/bilinear/newsboy loss
- For an aggregate PS (**APS**) average:
  - across all t in the test period
  - across all quantiles → CRPS

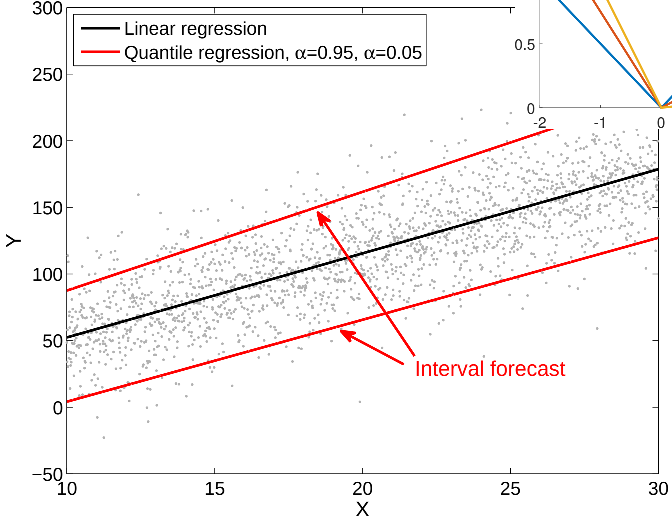


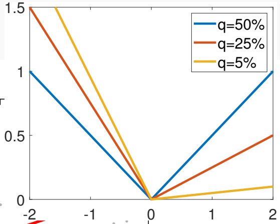
Quantile Regression Averaging: The idea

(Nowotarski & Weron, 2015, COST)



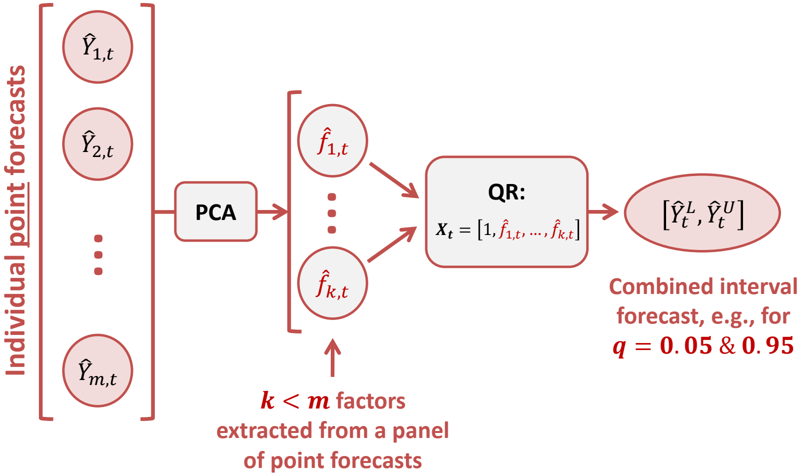
Quantile regression





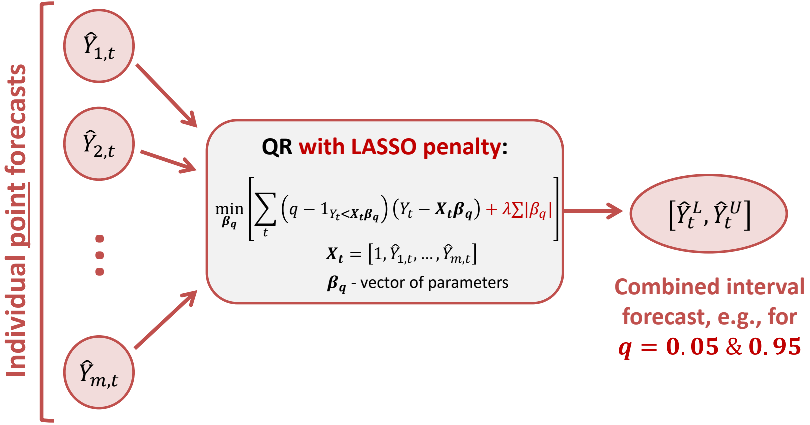
FQRA: When the number of predictors is large

(Maciejowska, Nowotarski & Weron, 2016, IJF)



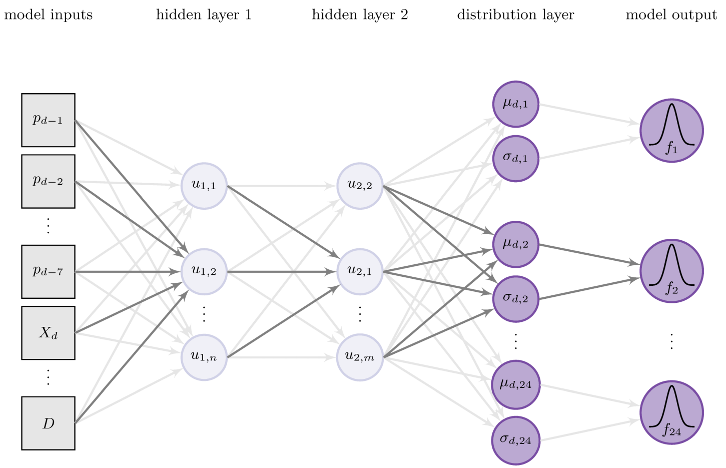
LQRA: When the number of predictors is large

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



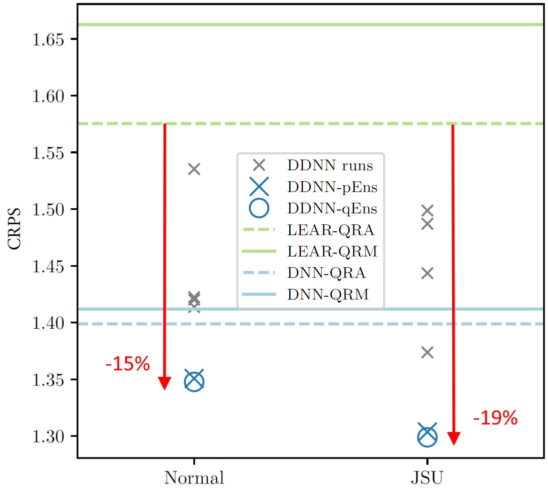
Distributional Deep Neural Nets (DDNN)

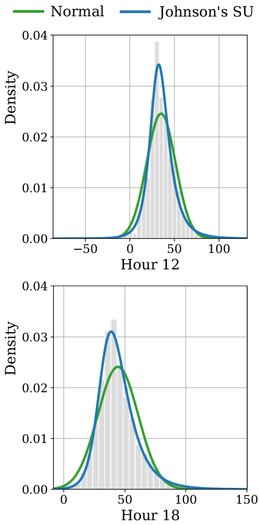
(Jędrzejewski et al., 2022, IEEE-PEM; Marcjasz, Narajewski, Weron & Ziel, 2023, ENEECO)



Perform surprisingly well ...

(Marcjasz, Narajewski, Weron & Ziel, 2023, ENEECO)





... also for point forecasts

(Marcjasz, Narajewski, Weron & Ziel, 2023, ENEECO)

	MAE	RMSE	CRPS
LEAR-Ens	4.372	6.375	-
naive	9.336	14.358	3.585
LEAR-QRA	4.161	6.676	1.575
LEAR-QRM	4.285	6.788	1.662
DNN-QRA	3.668	5.845	1.399
DNN-QRM	3.670	**5.821**	1.412
DDNN-N-pEns	3.663	5.962	1.351
DDNN-N-qEns	3.670	5.962	1.348
DDNN-JSU-pEns	**3.542**	6.146	1.304
DDNN-JSU-qEns	3.564	6.174	**1.299**

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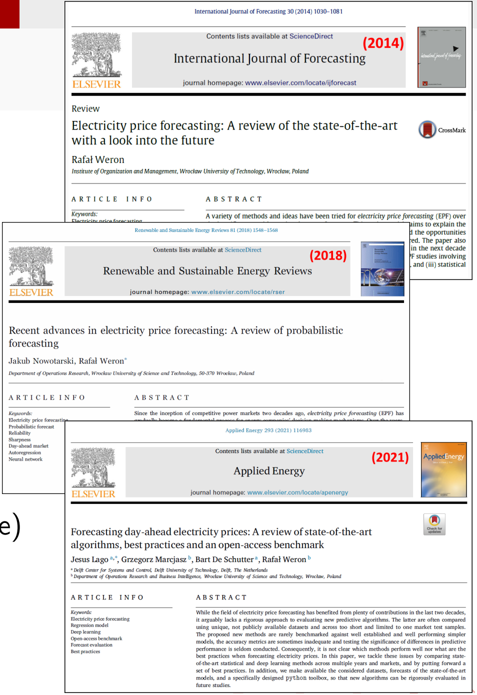

International Journal of Forecasting 30 (2014) 1030–1081

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Review

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Rafał Weron

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

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

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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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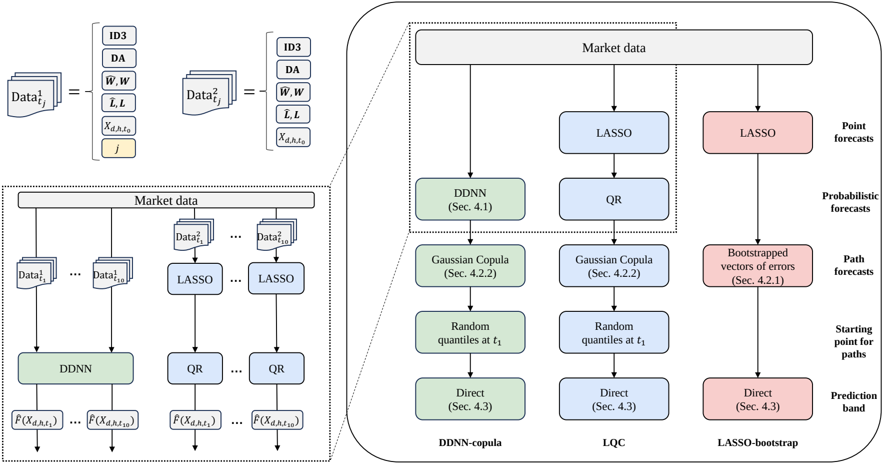
Path (trajectory, ensemble) forecasts

(Serafin, Marcjasz & Weron, 2022, ENEECO; 2023, WP)



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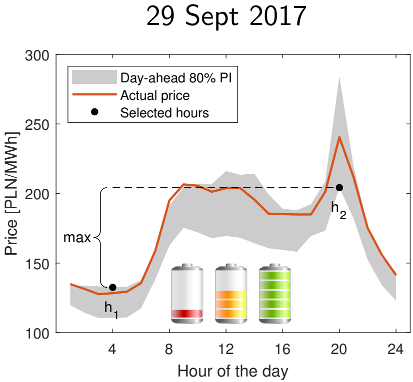
Quantile-based trading strategies

(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

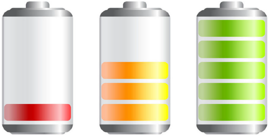
$\leftarrow$ With $\alpha = 10\%$ the spread is maximized for $\hat{P}^{90\%}_{d,4} = 133$ and $\hat{P}^{10\%}_{d,20} = 204$ PLN/MWh

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

Quantile-based trading strategies: Results

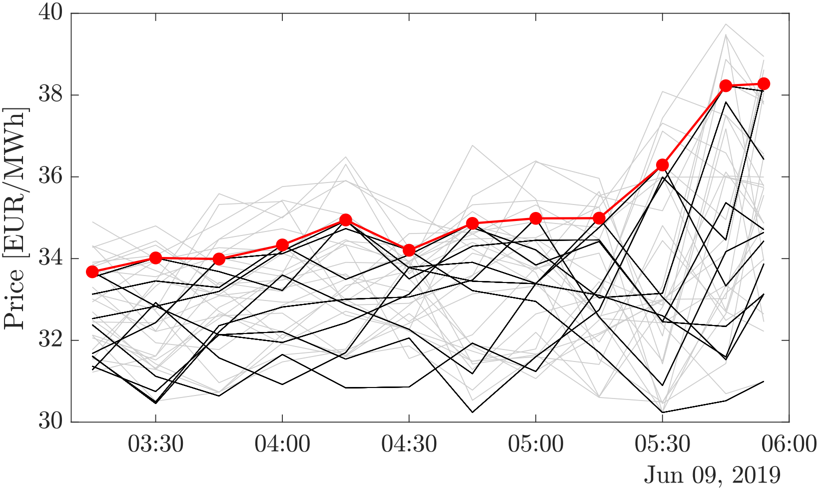
(Uniejewski & Weron, 2021, ENEECO)

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, 2022, ENEECO)



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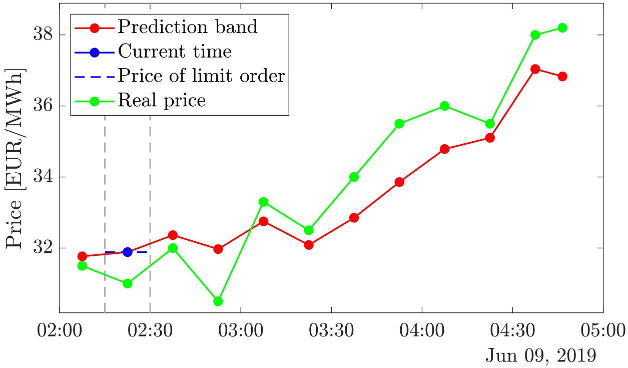
- The prediction band determines the price of the *limit order* which is placed in the market every 15 minutes



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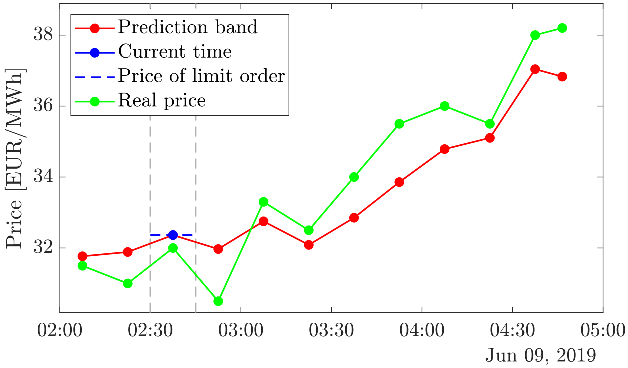
- If the order is not filled, the limit order is modified to match the next value of the prediction band



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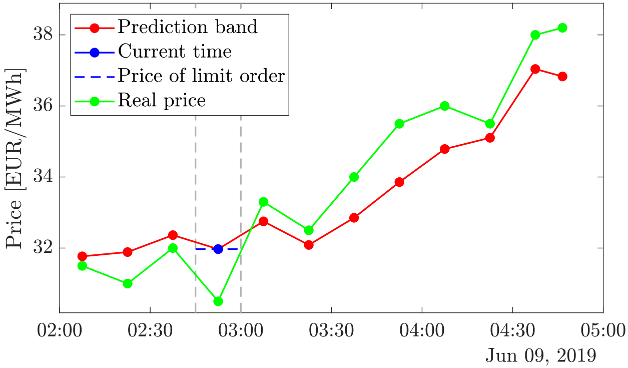
- If the order is not filled, the limit order is modified to match the next value of the prediction band … again and again …



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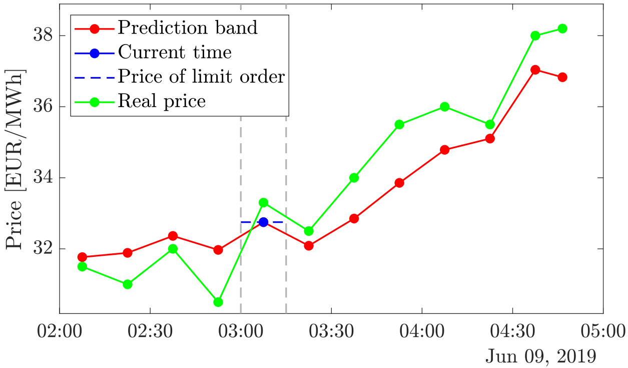
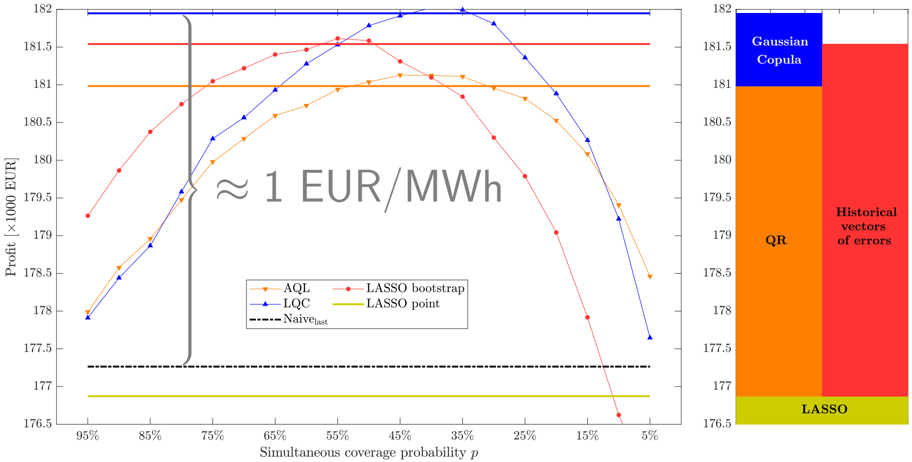


- If none of the orders was filled, the electricity is sold at the last price in the market

Profits: Selling 1 MW every hour for 200 days

(Serafin, Marcjasz & Weron, 2022, ENEECO)



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Articles & working papers on https://p.wz.pwr.edu.pl/∼weron.rafal/Publ

Rafał Weron

Professor of Management Science (Energy Forecasting)

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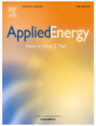

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- The **epftoolbox** including Python codes for the two benchmark models (LEAR, DNN) and datasets is available from *GitHub*

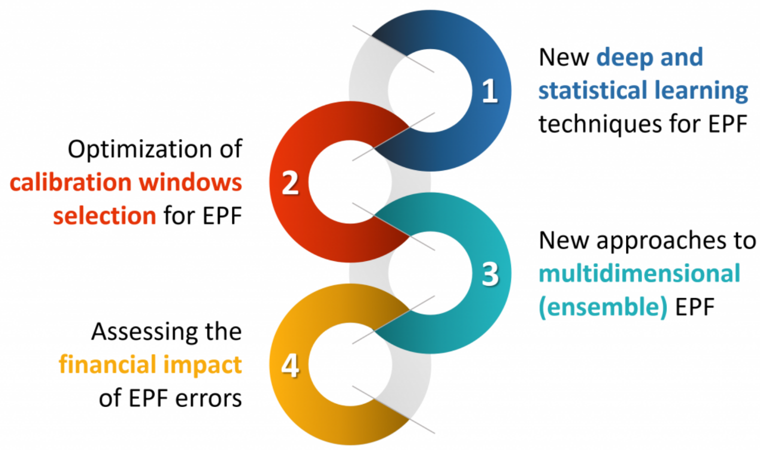
T. Hong, P. Pinson, Y. Wang, **R. Weron**, D. Yang, H. Zareipour (2020) *Energy forecasting: A review and outlook*, IEEE Open Access Journal of Power and Energy 7, 376-388 Open Access (Invited Paper; doi: 10.1109/OAJPE.2020.3029979)

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

CrossFIT (2019-2024)

Crossing Frontiers in electricity prIce forecasTing

(https://kbo.pwr.edu.pl/en/research/research-projects/ncn-2018-30-a-hs4-00444)



PRIORITY (2023-2026)

PRobabilistic mid- and long-term prIce fORecasting In electriciTY markets
(https://kbo.pwr.edu.pl/en/research/research-projects/dfg-ncn-2021-43-i-hs4-02578-2)