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Review of the Doctoral Dissertation by Weronika Nitka entitled *Decision support for electricity market participants: point and probabilistic forecasting using resampling methods and statistical learning*

Prepared at: Faculty of Computer Science and Management, Wrocław University of Science and Technology **Supervisors:** Prof. dr. hab. Rafał Weron (primary supervisor) and Dr. hab. Katarzyna Maciejowska (assistant supervisor).

General Remarks

The doctoral dissertation of MSc Weronika Nitka aims to develop data-driven prognostic methods to support decision-making processes for small and medium-sized enterprises operating in electricity markets. The presented methods are designed to have low or medium computational complexity and a high degree of automation. The dissertation comprises a series of five publications addressing four key research tasks to fill gaps related to this overarching goal.

1. Conducting a critical study of calibration sample selection methods to automate electricity price forecasting;
2. Using resampling methods to create probabilistic distributions of electricity prices and assess uncertainties;
3. Using forecasts of renewable energy production and electricity demand to plan trading strategies in day-ahead and intraday markets;
4. Developing short-term trading decision support methods that leveraged probabilistic average distributions.

These objectives synthesize the contributions of the articles included in the dissertation. In particular, the results are evaluated using both statistical and economic criteria, highlighting their practical applicability.

Since the dissertation takes the form of a publication cycle, the accompanying documentation consists of a 50-page synthesis of the results and their relevance to entities

operating in the electricity market, along with an appendix containing the five articles forming the basis of the thesis. In total, the work comprises 132 pages.

All the works forming the basis of the doctoral dissertation were coauthored, with at least one coauthor being the primary supervisor or assistant supervisor in four of the articles. Article (4) was published in the prestigious journal *Energy Economics* (rated 200 points on the Polish Ministry of Science and Higher Education (MNiSW) list), two articles (1) and (2) were included in the proceedings of the ICCS conference (140 points MNiSW), and one (5) appeared in the journal *Operations Research and Decisions* (70 points MNiSW), published by Wrocław University of Science and Technology. Article (3) is submitted for publication and is currently available in the ArXiv repository. The published works have collectively garnered 48 citations so far, with the majority attributed to article (4) (41 citations). The level of publication and recognition of these works is well above the standard typically expected of a doctoral dissertation. This demonstrates not only the high quality of the research, but also the significant impact and contribution it makes to the field of electricity market forecasting and decision support. Such achievements are commendable and position the candidate's work as exemplary within the academic community.

The doctoral candidate's contribution was leading in article (5) (75% contribution) and proportional to the number of authors in the remaining works. Contributions included co-implementation of models, visualization, co-writing, and, in the case of article (2), co-conceptualization. This level of contribution is appropriate for a doctoral candidate and meets the required standards.

Dissertation evaluation

In the Introduction, the doctoral candidate rightly emphasizes the disparity in analytical and financial resources between large and small market participants, creating a need for simple, universal, and practical forecasting tools. I highly value the justification for the proposed approach presented in the dissertation. Particularly noteworthy is the recognition that electricity producers must consider not only prices, but also demand and the futures market, although the development of this aspect remains uncertain.

Market Evolution and Challenges

The candidate highlights that the evolution of the market, specifically decentralization driven by the development of renewable energy, has increased volatility and uncertainty in energy markets. Forecasting has become a challenge not only for supply but also for demand. This is especially relevant in Poland, where, as noted rightly, there are 1.4 million prosumers. Next, the candidate addresses critical challenges associated with the increasing use of renewable energy sources. Due to their intermittent and nondispatchable nature, the energy output of these sources is difficult or nearly impossible to predict and control accurately. Furthermore,

its generation depends on weather conditions and is often uncorrelated with energy consumption patterns. It is also correctly observed that the backup sources meant to complement renewable energy are either in early development stages (e.g., hydrogen, large-scale chemical batteries) or expensive (e.g., fossil fuel power plants). Lastly, while renewable energy sources are less susceptible to geopolitical risks compared to conventional sources, they are highly sensitive to weather conditions and the impacts of climate change. However, I noticed that there is no mention of the Dunkelflaute phenomenon, which significantly drives up electricity prices in European countries.

Enterprise Perspective and Energy Storage

The candidate subsequently introduces the perspective of an enterprise participating in the energy market, which serves as the basis for the analyses presented in the attached works. In particular, the company possesses an energy storage system intended for arbitrage on the electricity market, filling up during low prices and discharging during high prices. It is assumed that the company is small enough not to influence the prices of the spot market. However, I have an issue with this assumption: If the strategy proves profitable, many similar entities will adopt it, which may lead to market impact and price equalization. As a result, while the market will benefit (with more stable prices), the entities that drive this stabilization may operate on very thin margins, rendering their activities unprofitable.

Clarity and understanding of the research problem

The presentation of the research problem is very clear and shows that the doctoral candidate has a deep understanding of the electricity market and the challenges associated with its transformation. There is slight consternation regarding the fact that while part of the dissertation relates to the Polish market (eg Figure 2.1), the research conducted focuses on the electricity market in Germany. Are both markets heading in the same direction in the long term, considering Germany's phase-out of nuclear energy and Poland's opposite plans? Should we expect a convergence in electricity prices and the development of similar mechanisms between these markets?

In the motivations, MSc. Weronika Nitka addresses key challenges faced by small and medium-sized enterprises (SMEs) in electricity markets. The work focuses on developing practical and computationally efficient methods for point and probabilistic forecasting, using statistical learning and resampling techniques. The candidate demonstrates a deep understanding of the evolving electricity market, particularly the impacts of decentralization, increased volatility, and the integration of renewable energy sources. By addressing uncertainties in energy supply and demand, the research provides robust tools to support trading and decision-making strategies in dynamic and unpredictable market environments. These methods are tested and validated using both statistical and economic criteria, emphasizing their real-world applicability.

Furthermore, the dissertation underscores the importance of considering both price fluctuations and demand patterns, especially for enterprises equipped with energy storage systems, which can optimize market opportunities through strategic arbitrage. However, the potential for widespread adoption of these strategies is critically evaluated, acknowledging the possibility of market equilibrium and reduced profitability for individual entities. The clarity and relevance of the research problem, coupled with the rigor of the proposed solutions, exemplify the candidate's comprehensive expertise and the dissertation's high academic and practical value.

In the first paper (Paper 1), the candidate for PHD introduces the autoregressive hybrid nearest neighbor (ARHNN) method, an innovative approach to electricity price forecasting that combines ARX models with k nearest neighbor (KNN). This method automates calibration sample selection by identifying historical data that are most similar to current conditions, reducing reliance on arbitrary decisions or expert judgment. A validation step optimizes the size of the calibration sample (k), and the forecasts are averaged to improve accuracy. Tested on German day-ahead market data, ARHNN outperformed traditional methods, demonstrating flexibility across short and long calibration samples. It offers not only enhanced forecast accuracy, but also actionable insights into data relevance, making it a practical tool for organizations already employing ARX models or other forecasting techniques.

In the second paper, a calibration sample selection method based on the narrowest-over-threshold (NOT) algorithm is presented, designed to address structural breaks in electricity price data. Structural breaks, caused by external events like geopolitical changes, disrupt data stability and violate common forecasting model assumptions. The NOT algorithm detects these breaks by analyzing subsamples of the data and identifying points where statistical properties, such as mean or variance, shift significantly. By isolating relevant subperiods, the algorithm creates calibration samples that align with the current market regime. This approach, tested with data from the German electricity market, demonstrated superior forecast accuracy compared to traditional fixed-length windows, particularly during volatile conditions. In addition, it revealed patterns in market behavior, such as shorter calibration windows during turbulent periods and longer windows in stable markets. This method provides both improved forecasts and valuable insight into market dynamics.

Paper 3 introduces the Multiple Split method for joint probabilistic forecasting of electricity prices and renewable energy. It supports renewable energy utilities' decision-making by optimizing market bids and mitigating financial risks. Using German EPEX SPOT market data (2015-2019), the study enhances autoregressive models with variables like lagged prices and fuel indices, targeting multivariate forecasts. The method employs resampling,

dividing training data into estimation and calibration samples, ensuring joint parameter estimation and multivariate distributions. It outperforms traditional methods in reliability and extreme event prediction, though slightly less sharp (CRPS). Its flexibility and interpretability make it practical for utilities in dynamic markets.

In the next paper (Paper 4), the Ph.D. candidate investigates the enhancement of load, wind, and solar generation forecasts to improve electricity price predictions for day-ahead and intraday markets. Using ARX models, the study corrects biases in TSO forecasts, achieving notable accuracy improvements, particularly for load. Enhanced forecasts significantly improved intraday price predictions, reflecting the reliance on real-time trading values. However, the day-ahead price forecasts showed limited benefits, as market participants depend on predicted, not actual, fundamentals during trading. A trading strategy that uses these enhanced forecasts increased annual revenue highlighting the economic potential of accurate predictions, although achieving maximum financial value remains challenging.

In the last paper (paper 5) MCs Weronika Nikta explores the use of ensemble forecasting, specifically combining predictive distributions for electricity prices, to improve decision making in day-ahead electricity market bidding. The focus is on whether minimizing the Continuous Ranked Probability Score (CRPS), a standard metric for probabilistic forecasts, leads to optimal trading decisions. The study highlights that the combination of forecasts is a simple but effective technique to improve predictive accuracy, particularly in forecasting electricity prices. Existing research suggests that small ensembles of high-performance forecasts are preferable. The section also investigates the impact of weighting methods, finding that optimizing weights provides additional benefits only under specific conditions. The results demonstrate that the combination of probabilistic forecasts significantly improves both the precision of the forecast and the financial results in the trading strategies.

Research provides insights into the practical use of CRPS-minimized ensembles for day-ahead market strategies, suggesting their value in managing risks and maximizing profitability in electricity trading.

In some studies, the assumption is made that the energy storage system can be charged and discharged instantly. Is this assumption technically valid? If not, how would removing this assumption affect the results?

The undeniable essence and value of the prepared studies lie in the management of the energy system over relatively short periods (e.g., the day-ahead market). However, the development of the market and emerging regulations must take into account a broader

perspective. The increasing installed capacity of energy storage systems will smooth out price fluctuations, thereby reducing arbitrage opportunities and profitability. A similar situation is currently observed with wind farms, where projects are being frozen or cancelled due to low expected revenues (when there is wind, energy prices are low). Is it possible to avoid such a situation and what must be done to ensure the success of the energy transition?

Typically, the data in published studies ends before the energy market crisis in Europe, which introduced unprecedented disruptions. Can the results obtained be applied to this period, or do they primarily pertain to patterns observed earlier? Now, with greater saturation of renewable energy in the market, should we expect difficulties in price modeling? To what extent does this depend on the accuracy of meteorological forecasts?

The Ph.D. thesis presents four major contributions to electricity market forecasting and decision support. First, it introduces the Autoregressive Hybrid Nearest Neighbors (ARHNN) method (Paper 1), which automates calibration sample selection by combining ARX models with k-nearest neighbors, significantly enhancing forecast accuracy and adaptability. Second, it pioneers the application of the Narrowest-Over-Threshold (NOT) algorithm (Paper 2) to detect structural breaks in price data, enabling dynamic calibration sample selection that improves point forecasts by aligning them with prevailing market conditions. Third, it develops the Multiple Split method (Paper 3), a novel nonparametric approach to generating multidimensional probabilistic forecasts, capturing variable dependencies, and addressing uncertainty effectively, especially for extreme market events. Finally, the thesis advances decision support strategies by enhancing fundamental variable forecasts (Paper 4) and proposing methods to combine predictive distributions using the Continuous Ranked Probability Score (CRPS) (Paper 5), aligning statistical accuracy with financial outcomes in day-ahead market bidding. These contributions collectively bridge gaps in forecasting methodology and practical application, with a strong focus on dynamic market environments. These achievements are significant in merit, especially for new market participants or smaller enterprises, offering practical and impactful tools to navigate the complexities of electricity markets. This dual focus on statistical rigor and business applicability aligns with the evolving needs of the energy market and contributes meaningfully to both fields.

Conclusions

The doctoral dissertation of MSc. Weronika Nitka possesses undeniable value, stemming from several factors. First, it addresses current issues in the field of forecasting theory while being firmly grounded in empirical research. The results obtained in the course of the work are unique and highly valuable, both from a theoretical perspective and in terms

of practical applications in managing companies operating in the energy sector. Furthermore, the scientific achievements of the author, including the main publications that form the basis of the dissertation, are part of the global scientific discourse and represent the forefront of research in the prediction of electricity prices.

In summary, I would like to emphasize that the reviewed dissertation more than adequately meets all the requirements of a doctoral dissertation. Therefore, I propose that MSc Weronika Nitka be admitted to the next stages of the doctoral process, leading to the awarding of the doctoral degree in Economic Sciences in the discipline of Management and Quality Sciences. Given the exceptional merits of the doctoral dissertation, I recommend that MSc Weronika Nitka be recognized with an appropriate award.

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