Review

by Assoc. Prof. Dr. Mila Ilieva ILIEVA – OBRETENOVA

University of Mining and Geology "St. Ivan Rilski", Sofia, Bulgaria

regarding the doctoral thesis
for the acquisition of the educational and scientific degree "Doctor" in the field of higher education: 5. "Technical Sciences" Professional direction: 5.2. "Electrical Engineering, Electronics, and Automation"
Scientific Specialty: "Application of the principles and methods of cybernetics in various fields of science"
(02.21.10)

Thesis Title:

MATHEMATICAL METHODS FOR RESEARCH MODELING, ANALYSIS, AND FORECASTING IN THE ENERGY SECTOR AND ENERGY MARKETS

Author of the thesis: Master Eng. Ekaterina Popovska

Research Consultant: Assoc. Prof. Dr. Eng. Galya Georgieva - Tsaneva

1. General Provisions and Biographical Data

In 2013, Eng. Ekaterina Popovska completed her higher education at the University "St. Cyril and Methodius," Faculty of Electrical Engineering and Information Technologies, Skopje, Macedonia, earning a master's degree in Electrical Engineering and Information Technologies. Since 2019, she has been a doctoral student in the Medical Robotics section at the Institute of Robotics, Bulgarian Academy of Sciences (IR-BAS), and as of December 1, 2023, she has been enrolled at IR-BAS as a researcher. Over the past decade, Eng. Popovska has held various responsible positions, effectively combining her technical skills with managerial qualities.

She has served as the Head of the "Production Planning and Sales" department at Kozloduy Nuclear Power Plant. Before that, Eng. Popovska played a key role as the Head of the "Energy Regulations, Market Monitoring, and Data Analysis" department at the Independent Bulgarian Energy Exchange, as well as a senior expert at the Energy and Water Regulatory Commission. Since then, she has demonstrated a keen interest and active involvement in scientific research across various domains related to the energy sector and energy market modeling.

M.Eng. Popovska has also acted as a Lecturer in the "Energy Markets and Services" program at the Center for Educational Services (CES) of the Faculty of Economics at Sofia University "St. Kliment Ohridski" and the "Utilities" magazine. She has taught topics related to Big Data, analysis of opportunities for manipulation of the energy market, fundamental and technical analysis of the electricity market, and artificial intelligence methods for analyzing and forecasting electricity prices in Bulgaria.

2. General Description of the Submitted Materials

As a committee member, I have received the following documents:

1. Order No. 21a dated January 24, 2023, from the Director of the Institute of Robotics - Bulgarian Academy of Sciences. 2. Professional autobiography following the European template. 3. Diploma for completed higher education. 4. List of publications on the dissertation topic. 5. Copies of the publications on the dissertation topic.6. List of identified citations. 7.

Contributions. 8. Declaration of originality. 9. Transcript of exams and credits obtained. 10. Order of enrollment in the doctoral program. 11. Abstract. 12. Dissertation.

3. Relevance, Objective, and Tasks

The dissertation focuses on current and significant aspects of the energy sector, exploring methods for assessing and forecasting electricity prices. The relevance of the problem is thoroughly examined, emphasizing the increasing uncertainty in prices resulting from the integration of renewable sources and smart grids.

The objective of the dissertation is to develop an effective methodology and algorithms for forecasting electricity prices on the exchange market, with a specific focus on the "Day Ahead" market. This aspect of the objective necessitates the investigation and analysis of various methods for assessing price movements.

To achieve the stated objective, the dissertation formulates four key tasks, sequentially addressed in the research. The first task involves developing a methodology for studying and analyzing data on electricity prices, emphasizing the importance of selecting methods for analyzing real long-term data based on market conditions. The second task focuses on investigating short-term exchange prices for electricity and using techniques to enhance energy forecasting. The third task includes the creation of software procedures for analysis, simulation, and forecasting, while the fourth task aims to determine the most effective simulation models for forecasting.

4. General Characteristics of the Dissertation

The dissertation comprises 183 pages, including an introduction, 4 chapters, conclusion, contributions, a bibliography, 9 tables, and 37 figures. The bibliography contains 139 titles, all in Latin script, and includes 2 internet addresses. The appendices, spanning 22 pages, encompass a list of identified citations and codes of software programs.

Chapter 1 encompasses a comprehensive literature review, exploring various methods for forecasting and analyzing electricity prices. This chapter presents updates and trends in the development of time series forecasting methods for electricity prices, drawing on scientific articles and research from leading global and Bulgarian authors. It analyzes various methods of scientific knowledge, including the functioning of systems represented by models developed through simulation modeling methods. The chapter covers methods for both short-term and long-term time series stability, concepts, and methods, with a focus on application and modeling in complex energy systems.

In Chapter 2, an analysis of long-term stability methods is conducted. Fractal analysis and the fluctuation analysis method are employed to examine long-term stability. The chapter discusses the methodology for studying long-term stability in time series, focusing on electricity market prices. It introduces an algorithm for implementing the R/S method (Rescaled range), emphasizing key steps. Additionally, the fluctuation analysis method with detrending (DFA) is presented for investigating long-term correlations in time series. The fundamental steps of the DFA method, including the detrending process and fluctuation calculations, are explained. An algorithm for calculating the Hurst exponent using DFA is presented. The final part of the chapter outlines a methodology for forecasting electricity prices in the long term, detailing six steps, including data collection, model selection, data pre-processing, model validation, forecasting, and evaluation. This approach can be applied to both R/S and DFA methods.

The concluding remarks summarize the findings of the research, highlighting that both the R/S and DFA methods are successfully used to analyze long-term stability in electricity prices. In

comparison, the DFA method exhibits a smaller relative error and is considered more accurate, making it suitable for investigating the Hurst exponent in time series.

Chapter 3 presents a comprehensive approach to studying and forecasting electricity prices using two different methods: SARIMA (Seasonal Autoregressive Integrated Moving Average) and LSTM (Long Short-Term Memory) through the Python programming language. SARIMA is initially explored, proving effective for analyzing and forecasting values in time series with seasonal effects, trends, and noise. The chapter demonstrates that SARIMA is an efficient method for forecasting electricity prices, especially when seasonality is essential. The subsequent part introduces an algorithm based on the LSTM recurrent neural network model. This algorithm is an automated process focusing on processing and analyzing time series, achieving high accuracy in predicting future electricity prices. It is crucial to note that LSTM is evaluated as a suitable method, particularly for short-term forecasts and for hourly or more frequent time intervals. The methodology presented in the chapter combines data processing, time series analysis, and forecasting, involving steps such as data pre-processing, model creation, and testing their effectiveness. The chapter emphasizes the importance of selecting a suitable method based on data characteristics, such as seasonality, as demonstrated by the successful application of SARIMA in the presence of seasonal influences on electricity prices. In summary, Chapter 3 presents an analytical process aiming for effective short-term forecasting of electricity market prices, incorporating various methods and preparation, modeling, and evaluation steps.

In Chapter 4 of the dissertation, precise data recording is presented, followed by an in-depth analysis of results stemming from empirical research in the field of electricity price forecasting. The detailed analysis and summary of results from fractal analysis, ARIMA models, and the recurrent neural network contribute to understanding the characteristics of time series for electricity prices. The chapter covers various methods and models used to optimize forecasting processes in the energy sector. Different models and their results are clearly presented.

The initial examination focuses on LSTM and ARIMA methods, analyzing hourly and daily time series. The results indicate that LSTM is effective for short-term forecasts, especially with hourly data where accuracy is high. However, for long-term forecasts of electricity prices, the method encounters challenges due to the instability of energy markets. Subsequently, the chapter moves on to a comparative analysis of four different forecasting methods: Hurst and DFA methods, ARIMA, and LSTM. The study emphasizes that Hurst and DFA provide valuable information on correlations and trends in time series of electricity prices. Simultaneously, ARIMA faces limitations with seasonal time series, while LSTM excels in greater accuracy for short-term forecasts.

5. Contributions

I acknowledge all the contributions made by the doctoral candidate, including:

Scientific-Practical Contributions:

1. Developed a methodology for researching, analyzing, and forecasting electricity prices based on ARIMA, SARIMA, and LSTM methods, providing optimal predictions for electricity market prices based on various input factors.
2. Created a methodology for studying and analyzing the long-term stability of time series data for electricity market prices based on the DFA method, a novel approach in this field.
3. Experimentally investigated the application of statistical methods to determine the Hurst exponent (R/S method) on electricity prices. The studies show a maximum relative error of 6% when calculating H, where H is an estimate of the Hurst exponent, demonstrating the applicability of this method for studying the fractality of time series for electricity prices.

4. Experimentally proved that the DFA method is more suitable for forecasting long-term electricity price data compared to the R/S method. The comparative analysis conducted shows a maximum relative error in determining the Hurst exponent of 1.2% when applying DFA, compared to 6% when using the R/S statistical method.
5. Demonstrated the advantage of forecasting short-term data using the SARIMA method (compared to the ARIMA method), as the variable nature of electricity prices exhibits seasonality.

Practical Contributions:

1. Implemented and analyzed algorithms for the analysis and forecasting of long-term electricity price data based on the application of the R/S method for determining the Hurst exponent and the DFA method.
2. Implemented and analyzed algorithms for the analysis and forecasting of short-term electricity price data based on the application of ARIMA, SARIMA, and LSTM methods.
3. Created demonstration procedures for the analysis and forecasting of energy prices based on the specified input parameters.
4. I believe that the contributions are more than sufficient in terms of both quality and quantity and are supported by publications in prestigious journals.

6. Abstract and Publications on the Dissertation

The presented abstract accurately represents the content of the dissertation and complies with the requirements of the Bulgarian Law for the Development of Academic Staff in the Republic of Bulgaria (DASRBA) and its regulations (PP-DASRBA).

The credit reference for the dissertation indicates that, out of the required minimum of **250 credits**, the doctoral candidate has accumulated **450 credits**.

The number and quality of publications by Ms. Eng. Popovska related to the dissertation leave a very favorable impression. There are a total of 6 publications, with 2 of them having a Scientific Journal Ranking (SJR).

7. Opinion, Recommendations, Remarks

The dissertation is exceptionally well-structured, providing a clear and comprehensive analysis of the mathematical methods employed for research, modeling, analysis, and forecasting in the field of energy and energy markets. The results and conclusions are systematically and competently presented. The content of the dissertation meets all the requirements for obtaining the academic and scientific degree of Doctor.

The primary challenges facing the investigated mathematical methods in the context of energy markets are successfully identified. The importance of mathematical models for addressing the complexity of modern energy systems is emphasized throughout the work. The author convincingly justifies the use of various methods such as R/S analysis, DFA, ARIMA, and LSTM for analyzing and forecasting time series of electricity prices. The diverse approaches provide an extensive overview of the essence and application of the studied methods. Each method is applied within different time horizons and seasons, with results analyzed in detail.
The work focuses on both short-term and long-term forecasts, examining the advantages and limitations of each methodology. The conclusions from the research are fourfold, highlighting the potential for improving forecast accuracy by selecting an appropriate method for specific conditions. The conclusion synthesizes the achieved results and provides a summary of the scientific and applied contributions made. The work offers clear recommendations for the use of different methods depending on time horizons and data characteristics.

I recommend the dissertation as a significant and relevant contribution to the field of science. The work provides an extensive overview of various mathematical methods and their applicability, making it a valuable source for scholars and practitioners in the energy and finance sectors. The author demonstrates a high level of expertise and an excellent understanding of the topic. The dissertation showcases high-quality research, a clear methodology, and excellent presentation of results. It is a valuable contribution to the field and deserves the attention of the scientific community.

Despite the successful results, the dissertation explicitly acknowledges its limitations, related to model assumptions and data constraints. The author suggests ideas for future research, including expanding methods and models, using more extensive data, and continually improving analytical tools for effectively forecasting energy markets.

8. Conclusion with a Clear Positive or Negative Assessment of the Dissertation

The dissertation work has yielded scientifically and practically significant results, representing an original contribution to the field. These contributions have been published in reputable specialized scientific journals and presented at prestigious international scientific forums.

M.Eng. Popovska's dissertation meets the requirements of the Law on the Development of the Academic Staff in the Republic of Bulgaria, its implementing regulations, the Bulgarian Academy of Sciences regulations, as well as the regulations of the Institute of Robotics at the Bulgarian Academy of Sciences for obtaining the educational and scientific degree of "Doctor." Based on the analysis conducted, I provide a positive assessment of the presented dissertation, recommending that the Scientific Jury confer the educational and scientific degree of "Doctor" upon M. Eng. Ekaterina Popovska in the field of higher education: 5. "Technical Sciences," Professional direction: 5.2. "Electrical Engineering, Electronics, and Automation," Scientific specialty: (02.21.10) "Application of the principles and methods of cybernetics in various fields of science."