REWIEW

from

Prof. Olympia Roeva, PhD

Institute of Biophysics and Biomedical Engineering - BAS

Bioinformatics and Mathematical Modeling Department

for awarding of the educational and scientific degree "Doctor of Philosophy",

Field of higher education: 5. Technical sciences

Professional field:

5.2 Electrical engineering, electronics and automation,

Scientific speciality: 02.21.10 Application of the principles and methods of cybernetics in various fields of science

with a candidate

Eng. Ekaterina Popovska-Slavova, M.Sc.

Dissertation title

"Mathematical methods for research, modeling, analysis and forecasting in energy and energy markets"

1. Relevance of the problem developed in the PhD thesis in scientific and scientific-applied terms.

In recent years, researchers have been trying to propose efficient price prediction algorithms in the electricity market. The development of strategies and algorithms for forecasting the price of electricity is a particularly relevant topic since accurate information about the future price is the best way for market participants to implement strategies to increase their profit.

The PhD thesis examines and solves problems related to mathematical methods for research, modeling, analysis and forecasting in energy and energy markets. The problem developed in the dissertation is undeniably relevant both in scientific and scientific-applied terms.

2. Degree of knowledge of the state of the problem and creative interpretation of the literature

The PhD student presented the state and problems in the field under consideration. An overview of methods, models and key indicators for forecasting electricity prices has been done, based on literature sources published in the last 15 years. As a result, the main conclusions from the literature review were synthesized and the purpose of the PhD thesis was formulated, namely "development of a methodology and algorithms for research, analysis, modeling and forecasting of prices on the "Day Ahead" electricity market, part of the organized stock market by using the methods for the analysis of time series of data." To fulfil the set goal, the following tasks are defined:

1. Development of a methodology for research and analysis of electricity price data. Selection of appropriate methods for the analysis of real continuous (long-term) data obtained from the energy market in Bulgaria and the region depending on the conditions.
2. Development of a methodology for researching data on electricity prices in the analysis of real short-term data on stock exchange prices of electricity. Investigating techniques to improve energy forecasting.
3. Preparation of demonstration software procedures for analysis, simulation and forecasting of electricity prices by applying the selected scientific methods and analysis models.
4. Determining the most effective forecasting simulation models with which to make future realistic analyses of the behaviour of the studied data depending on the market fundamentals.

3. Correspondence of the chosen research methodology with the set goal and tasks of the PhD thesis

The chosen methodology and adopted approaches correspond to the level of modern theory and achievements. To achieve the set goal of the PhD thesis, the PhD student applies ARIMA and SARIMA methods, a recurrent neural network model with long-term short-term memory (LSTM), fractal analysis of time series to calculate the Hurst exponent using the Rescaled Range (R/S) method, etc.

4. General analytical characteristics of the PhD thesis

The PhD thesis is well structured and logically consistent according to the defined tasks to be solved. The thesis is in the volume of 183 pages and contains 4 chapters (one overview chapter and three chapters with research results), a conclusion, contributions, a list of publications on the PhD thesis, noted citations and a bibliography. In 4 appendices, the program codes (Matlab and Python) used to obtain the results of the PhD thesis are presented.

Chapter 1 is an overview and presents the state of the considered problem according to literature data. A bibliography numbering 139 sources was used, including fundamental publications for the field, as well as current publications from the last 10 years.

Chapter 2, Methods for the study of long-term stability of time series data of electricity exchange prices, deals with research on stability in complex systems for long-term processes based on different methods: methods for calculating the Hurst exponent by R/S and detrended fluctuation analysis (DFA). In Chapter 2, for the first time, a methodology for the study and analysis of the long-term sustainability of time series data of electricity exchange prices based on DFA is presented. The results of Chapter 2 are included in two publications.

Chapter 3, Methods for the Study of Short-Term Persistence of Time Series Data of Exchange Electricity Prices, deals with research on persistence in complex systems for short-term processes. An autoregression model with an integrated moving average (ARIMA and seasonal-ARIMA (SARIMA)) was used, as well as a model of a recurrent neural network with long-term short-term memory (Long short-term memory networks, LSTM). As a result, a methodology for research, analysis and forecasting of electricity prices is proposed. The methodology is based on SARIMA and LSTM methods, which provide optimal forecasts for electricity market prices depending on the various input factors. The results of Chapter 2 are included in two other publications.

Chapter 4, Data Review and Analysis of Empirical Research Results, summarizes the results presented in Chapters 2 and 3 and presents empirical evidence for the effectiveness of the applied methods for quantifying sustainability for long-term and short-term processes. The results show the advantages of DFA for long-term forecasts and of the SARIMA model for short-term forecasts.

In Chapter 5, the PhD student summarizes the work on the PhD thesis and draws the essential conclusions from the obtained results. Possible directions for future research in the field are also formulated.

5. Evaluation of contributions of the PhD thesis and their significance

I accept the contributions formulated in the dissertation as follows:

Scientific and applied contributions

1. A methodology for research, analysis and forecasting of electricity prices has been developed, based on ARIMA, SARIMA and LSTM methods, which provide optimal forecasts for electricity market prices depending on various input factors.
2. A methodology for the study and analysis of the long-term sustainability of the time series of data on exchange prices of electricity based on the DFA method has been developed, which has not been done before.
3. The application of statistical methods for determining the Hurst exponent (R/S method) on electricity prices was experimentally investigated. Research shows a maximum relative error of 6% when calculating H, which shows the applicability of this method to study the fractality of electricity price time series.
4. It has been experimentally proven that the DFA method is more suitable for forecasting long-term electricity price data than the R/S method. The comparative analysis made

shows a maximum relative error in determining the Hurst exponent of 1.2% when applying DFA against 6% when implementing the R/S statistical method.
5. In the analysis of short-term data, the advantage of forecasting using the SARIMA method (compared to the ARIMA method) has been proven, since the variable nature of electricity prices show seasonality.

Applied Contributions

1. 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 have been programmed and analysed.
2. Algorithms for the analysis and forecasting of short-term electricity price data based on the application of the ARIMA, SARIMA and LSTM methods have been programmed and analysed.
3. Demonstration procedures have been developed for the analysis and forecasting of energy prices depending on the type of set input parameters.

6. Assessment of the degree of personal involvement of the PhD student in the contributions

In 4 of the publications on the PhD work Eng. Ekaterina Popovska-Slavova is the first author, which gives me a reason to assume that the research and the formulated contributions are the personal work of the PhD student.

7. Assessment of PhD thesis publications

6 publications are presented for the PhD thesis. Two of them are in the ACM International Conference Proceeding Series, which is referenced in Scopus and has an impact rank (SJR). As I have already mentioned, in four of the publications the PhD student is the first author, which testifies to her personal and responsible participation. 7 citations of 3 of the publications are also presented, which shows both the high scientific level and the relevance of the published results.

8. Assessment of the compliance of the autoreferate with the requirements for its preparation, as well as the adequacy of reflecting the main points and contributions of the PhD thesis

The autoreferate correctly reflects the content of the PhD thesis and gives an idea of the problems under consideration, the results obtained, as well as the contributions of the dissertation.

9. Critical notes on the PhD thesis

I would like to point out that the critical notes, comments and recommendations made at an earlier stage were taken into account by the PhD student and reflected in the thesis.

I have the following comments on the final PhD thesis:

1. Some of the figures are of poor quality, especially *Figure 3.2. An illustration of an LSTM architecture* where the subfigure text is hard to read.
2. In item 4.6. Conclusions from the research done in Chapter 4, a technical error was made when formulating the 7 conclusions. It is presented:

   Conclusion 3: *DFA proves to be a more suitable method than R/S analysis for forecasting electricity prices, especially for data with* ***short-term dependencies*** *and fluctuations.*

   Conclusion 6: *The SARIMA model is preferred for* ***long-term*** *and seasonal time series.*

   In my opinion, for Conclusion 3 it should be "***long-term dependencies***" and for Conclusion 6 – "***short-term and seasonal***".

1. Declaration of originality of results is an integral part of the PhD thesis, not a separate document.

10. Conclusion with a clear positive or negative assessment of the PhD thesis

Based on the above, I highly appreciate the scientific and scientific-applied work of Eng. Ekaterina Popovska-Slavova, M.Sc.

All the requirements, conditions and criteria of Law on the Development of the Academic Staff in the Republic of Bulgaria, the Internal Regulations for its application, as well as the Regulations for the terms and conditions for acquiring scientific degrees and occupying academic positions in IR - BAS have been fulfilled. I give a positive assessment of the dissertation work and recommend to the respected Scientific Jury to award Eng. Ekaterina Popovska-Slavova the educational and scientific degree "Doctor of Philosophy" in the field of higher education: 5. Technical sciences, professional field: 5.2 Electrical engineering, electronics and automation, scientific speciality: 02.21.10 Application of the principles and methods of cybernetics in various fields of science.

26.01.2024 г. Scientific Jury member:

Sofia /Prof. Olympia Roeva/