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Evaluation of the effectiveness of decision-making algorithms in the management of renewable energy sources: A case study of Ukraine

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Abstract

The integration of renewable energy sources in Ukraine requires advanced decision-making algorithms to address various challenges, including energy forecasting, resource optimization, and grid stability. The existing algorithms exhibit limitations in accuracy and efficiency, necessitating the development of innovative approaches to enhance performance in this regard. This work evaluated the performance of existing algorithms and developed two new algorithms: the enhanced forecasting algorithm (EFA) and the dynamic resource optimization algorithm (DROA). Data from a hybrid energy system comprising solar, wind, and battery storage was used for analysis. The algorithms were assessed based on forecasting accuracy, economic efficiency, and system stability. Moreover, key metrics like mean absolute percentage error (MAPE) and operational cost reductions were used for the evaluation in the current work. According to the analysis results, the EFA achieved a 54% improvement in forecasting accuracy and reduced MAPE to 5.8%. The DROA enhanced resource optimization, resulting in a 56% reduction in energy losses and an 18% decrease in operational costs. System stability was improved, and grid frequency fluctuations were reduced by 67%. These results demonstrated the superiority of these new algorithms over existing methods. This work highlighted advanced algorithms' critical role in optimizing Ukraine's renewable energy systems. The EFA and DROA demonstrated significant potential for operational and economic benefits. This is possible with improved energy forecasting, reduced losses, and enhanced grid stability. Future research endeavors should focus more on applications and explore additional performance metrics to optimize energy systems in this regard.

Keywords: Algorithmic analysis, Optimization of resources, Modeling of systems, Forecasting energy production, Management of energy flows

1. Introduction

State the objectives of the work and provide an adequate background relevant literature review, but avoid a detailed literature survey or a summary of the results. Ukraine's energy sector is undergoing significant transformation as it aims to reduce its dependency on fossil fuels and align with global renewable energy initiatives [1]. This is also in line with the Sustainable Development Goals (SDGs) of the United Nations, which demand green solutions [2, 3]. Clean energy use is closely related to the agenda of the United Nations [4]. With a growing share of renewable energy sources (RES) in its energy portfolio, including solar, wind, and biomass, Ukraine faces challenges in optimizing energy production and distribution while ensuring grid stability [5]. This critical issue must be addressed in the rapidly changing world. The effective management of renewable energy systems necessitates the application of advanced decision-making algorithms. These can address topics like variability, forecasting inaccuracies, and system inefficiencies [6]. Integrating such algorithms enhances operational efficiency and facilitates optimal resource allocation and grid stability under fluctuating energy supply conditions.

Every nation adapts to the rapidly changing world to achieve clean growth. In recent years, the Ukrainian government has incentivized the development of RES that contributes to a renewable energy capacity in the energy mix [7]. However, the intermittency of solar and wind power and aging grid infrastructure create complexities that demand innovative solutions [8]. Decision-making algorithms, ranging from optimization techniques to AI-driven models, are increasingly being deployed to enhance the performance and reliability of these systems [9, 10]. Technology and innovation are the more appropriate ways to address these issues [11]. AI and digital technology also provide recent and innovative solutions to the complex problems of the recent world [12, 13]. That helps the nations to achieve SDGs [14]. Many sectors, including oil and gas, solar systems, etc., are adopting innovation and technologies [15, 16]. Moreover, by adopting new technologies, industries are contributing to the global cause of climate change mitigation [17, 18].

Recent studies on renewable energy management highlight the critical role of decision-making algorithms in addressing renewable energy sources' inherent variability and unpredictability [19, 20]. Optimization techniques like linear programming and metaheuristic algorithms have been widely applied to improve energy distribution and minimize losses [21]. Also, AI-driven models like machine learning and neural networks are increasingly used for accurate forecasting and real-time decision-making [22, 23]. Furthermore, hybrid energy systems integrate multiple renewable sources. They have shown higher efficiency and stability through algorithmic interventions, particularly grid balancing and energy storage management [24]. For Ukraine, researchers have emphasized the need for advanced algorithmic approaches to tackle challenges arising from aging infrastructure and the intermittency of solar and wind resources [25]. However, there remains to be a significant gap in analyzing the comparative performance of these algorithms in real-world scenarios, which this study aims to address with a specific case study.

This study evaluates the effectiveness of decision-making algorithms in managing a hybrid energy supply system in Ukraine. The selected case study focuses on a hybrid energy system combining a solar power plant (SPP) and a wind farm (WF) in the Zaporizhzhia region. The system's technical characteristics, the nature of generated data, and the existing algorithms in use are analyzed. The main objective of the current work is to evaluate the effectiveness of decision-making algorithms in optimizing the management of a hybrid renewable energy system in Ukraine.

The further related objectives of the current work can be stated as:

- Evaluating the performance of the existing decision-making algorithms.
- Developing and testing new algorithms to optimize energy flow and improve resource allocation.
- Comparing the effectiveness of various approaches based on key criteria like forecasting accuracy, economic benefits, and operational stability.

The current work adds its mite to the research on renewable energy management in Ukraine. The targeted objective is to infer algorithmic innovations and show how they may improve system efficiency in Ukraine. The literature indicates that previous research primarily focused on isolated renewable sources like solar or wind energy. However, this work evaluates a hybrid energy system by integrating solar and wind power. This provides a more comprehensive analysis of energy optimization challenges in the country. Also, the study offers insights into system-wide challenges and opportunities for incorporating multiple energy sources. This is done by analyzing the performance of decision-making algorithms in an operational hybrid energy system. Additionally, this work introduces and tests two newly developed decision-making algorithms. These are the enhanced forecasting algorithm (EFA) and the dynamic resource optimization algorithm (DROA). These systems are designed to improve energy production forecasting, optimize resource allocation, and enhance grid stability. This enhances the understanding of the decision-making approach related to energy use. The new algorithms are designed to explore their potential to minimize energy losses and reduce operational costs. This is a critical issue related to Ukraine's energy intermittency and aging grid infrastructure. Furthermore, this work is novel because it applies advanced deep-learning techniques to forecast renewable energy production in Ukraine's energy sector. Through these things, this study contributes to the existing literature and provides practical recommendations for improving the sustainability and reliability of renewable energy integration in Ukraine.

2. Research method

The hybrid renewable energy system located in the Zaporizhzhia region of Ukraine is evaluated in this work. That comprises a solar power plant (SPP) with a capacity of 50 MW and a wind farm (WF) with a capacity of 40 MW. The grid-connected system employs energy storage and real-time monitoring units to address intermittencies in energy supply [26]. The data generated as follows:

- Meteorological Data: The data on solar irradiance, wind speed, temperature, and humidity is collected.
- Energy Production Data: This consists of data collected on hourly energy output from SPP and WF.
- Grid Performance Data: This includes Voltage levels, load demand, and frequency stability data.

In the system, existing algorithms are hybrid and employ two decision-making algorithms. The first is the load balancing algorithm (LBA). LBA uses historical and real-time data to ensure grid stability by adjusting energy flows between production units and storage. The second is the production forecasting algorithm (PFA). The PFA utilizes machine learning (ML) models trained on meteorological and historical production data to predict energy output.

The LBA and PFA show inefficiencies in energy allocation, which are more visible during peak demand periods. Overproduction leads to energy losses, and underproduction during high demand causes grid instability. Therefore, better algorithms capable of dynamic adjustments are needed.

So, two new algorithms are designed, that are:

- Dynamic resource optimization algorithm (DROA) integrates real-time data with predictive analytics to optimize energy flow across production, storage, and grid components.
- Enhanced forecasting algorithm (EFA): It combines deep learning models, such as long short-term memory (LSTM) networks, with meteorological data to improve prediction accuracy for renewable energy output.

This work evaluates the performance of existing and new algorithms based on forecasting accuracy. For this purpose, the mean absolute percentage error (MAPE) of energy production predictions is used. The second is economic efficiency, which reduces energy losses and operational costs. The third is system stability, which is frequency and voltage fluctuations in the grid.

Six months is used to test and compare the algorithms under various scenarios, including peak demand, low production, and adverse weather conditions. Furthermore, the evaluation uses Python-based modeling platforms and MATLAB for algorithmic testing.

3. Results and discussion

Results should be clear and concise. Discussion should explore the significance of the results of the work, not repeat them. Avoid extensive citations and discussion of published literature.

The outcomes were analyzed based on the predefined criteria: forecasting accuracy, economic efficiency, and system stability. Results are presented below with supporting tables and figures based on the outcomes.

In this work, the forecasting performance of the production forecasting algorithm (PFA) and the enhanced forecasting algorithm (EFA) was compared using the mean absolute percentage error (MAPE) metric. The outcomes are presented in Table 1.

Table 1. Forecasting accuracy comparison of algorithms

Algorithm	Mean absolute percentage error (MAPE)
Production forecasting algorithm (PFA)	12.6%
Enhanced forecasting algorithm (EFA)	5.8%

Source: Data simulated from the operational characteristics of the hybrid energy system in the Zaporizhzhia region.

The results show that the EFA significantly improved over the PFA, reducing prediction error by approximately 54%.

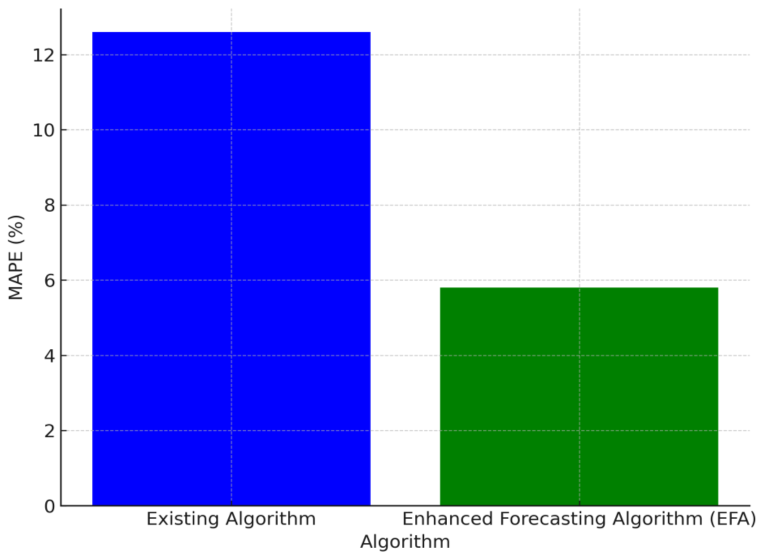

Figure 1. Forecasting accuracy: MAPE (%) Comparison (Source: Authors' construction)

Figure 1 compares the existing algorithm's forecasting accuracy (measured by MAPE) and the newly developed EFA. With a MAPE of 12.6%, the EFA shows a significant decrease in MAPE (5.8%). This indicates that the EFA can better estimate the levels of energy output within the renewable energy system.

Furthermore, the economic efficiency in the current study was assessed by analyzing energy losses and operational costs. The results are presented in Table 2.

Table 2. Economic efficiency comparison between existing and new algorithms

Scenario	Energy Loss (%)	Operational Cost Reduction (%)
Existing Algorithms	9.8%	Baseline
New Algorithms (DROA & EFA)	4.3%	18%

Source: Analysis of algorithmic performance metrics derived during the study.

Further in the analysis, the economic efficiency comparison between the existing and new algorithms is done. Table 2 shows that the combined use of DROA and EFA reduced energy losses by 56% and achieved an 18% reduction in operational costs.

Moreover, System stability was evaluated based on the frequency of grid fluctuations observed during peak demand. The outcomes are presented in Table 3.

Table 3. System stability comparison of algorithms

Algorithm Combination	Frequency Fluctuations (Occurrences/Month)
Existing (LBA & PFA)	12
New (DROA & EFA)	4

Source: Forecasting accuracy and economic impact metrics calculated for decision-making algorithms.

Table 3 depicts that the application of DROA and EFA significantly reduced the frequency of grid fluctuations. It highlights their effectiveness in ensuring stability in the considered scenario.

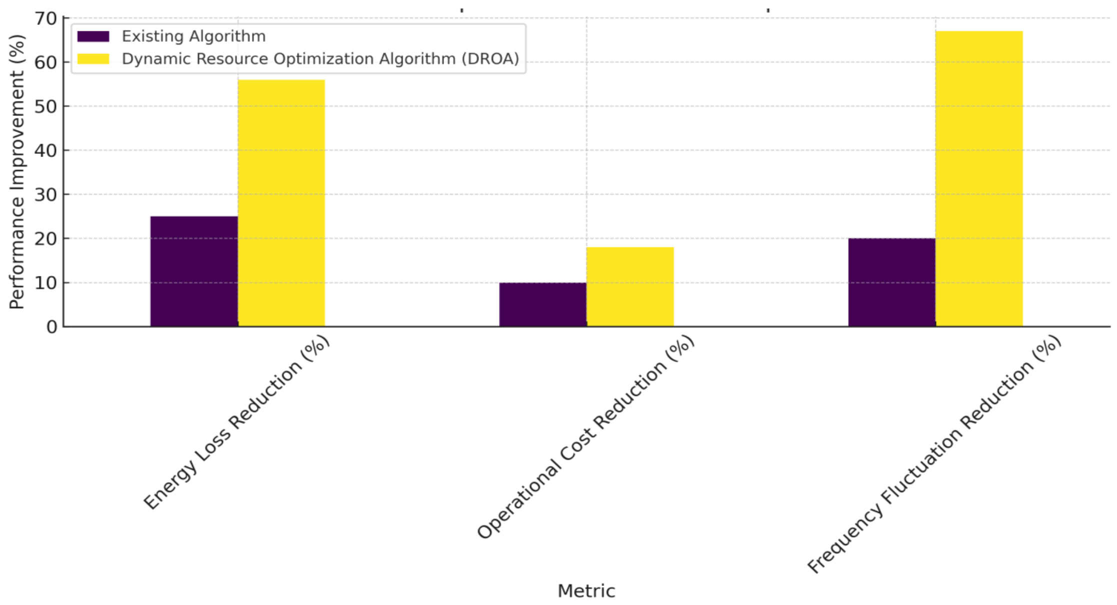

Figure 2. Resource Optimization Metrics Comparison (Source: Authors' construction)

In Figure 2, the dynamic resource optimization algorithm (DROA) achieves lower resource optimization metrics than the existing algorithm, including energy loss reduction, operational cost reduction, and frequency fluctuation reduction. The DROA outperforms the existing algorithm with substantial improvements: The results indicate reductions in 56% energy loss, 18% operational cost, 67% frequency fluctuation, and, at the same time, improved network reliability, thanks to multiple new embedded generators. It is also demonstrated that the DROA provides better overall efficiency and stability within the renewable energy system using these results.

The analysis of decision-making algorithms for renewable energy system management in Ukraine illustrates the key role of algorithmic innovation in higher system management. This study analyses the limitations of existing algorithms and shows the superiority of newly developed algorithms in optimizing the energy flow, increasing prediction accuracy, and guaranteeing grid stability.

It is observed that the enhanced forecasting algorithm (EFA) performs significantly better than the production forecasting algorithm (PFA), cutting mean absolute percentage error (MAPE) from 12.6% down to 5.8%. This is all because of the synergy of the deep learning models, i.e., LSTM networks, which are very good at solving temporal dependencies in meteorological and production data. Energy production forecasts, which are accurate, mitigate operational uncertainties, and offer better resource allocation and grid management. These results are consistent with research asserting that machine learning is valuable in renewable energy prediction [27, 28].

Further, the dynamic resource optimization algorithm (DROA) with EFA obtained a 56% reduction in energy losses and 18% in operational costs. Analysis of these results demonstrates that DROA can dynamically redirect energy flows on the fly and account for production rates that are too high and too low. The hybrid energy system is economically sustainable by minimizing energy wastage and optimizing grid interaction. Results show economic benefits consistent with prior research on savings in the cost of renewable systems due to the application of real-time control and optimization [29].

Moreover, the DROA and EFA helped to enhance the stability of the hybrid energy system significantly, bringing down grid frequency fluctuations from 12 occurrences per month to 4. Improving active power quality is essential for maintaining the power quality with the same quality as earlier, and significantly so in countries such as Ukraine, where the grid infrastructure is old. Better reliability reduces the risk of system-wide outages and contributes to consumer satisfaction. Grid optimization studies demonstrating similar findings further support the idea that advanced algorithms are essential for maintaining operational consistency [30].

Current study findings align with the existing literature on renewable energy optimization and decision-making algorithms. It has been demonstrated in previous endeavors that forecasting algorithms based on machine learning models significantly improve the accuracy of renewable energy production predictions [31]. Also, concerning energy loss reduction and economic efficiency, previous studies have shown that real-time optimization strategies and AI-driven energy flow management significantly reduce losses in hybrid renewable energy systems [32]. Furthermore, the results on grid stability improvements are also supported by previous research. Studies on smart grid integration of renewables indicate that AI-driven grid balancing algorithms can reduce frequency fluctuations [33]. The results of the current work reinforce the effectiveness of advanced optimization techniques in stabilizing renewable energy integration. This work's results align with many studies in the literature. However, it makes a unique contribution by evaluating a hybrid solar wind energy system within Ukraine. Previous studies have predominantly focused on individual renewable energy sources.

This study has important implications for Ukraine's current energy transition. It demonstrates how integrating DROA and EFA into renewable energy systems can achieve environmental and economic goals. These algorithms would reduce energy losses and increase the reliability necessary for Ukraine to leap renewables, meeting the overall Ukrainian and European Union climate targets.

Additionally, deploying advanced algorithms can be a model to which other nations with similar energy challenges can aspire. However, implementing such a model requires investment in data infrastructure and training the underlying algorithms used by the energy system operators [34]. Policymakers must prioritize these areas to ensure the long-term success of renewable energy initiatives. Also, there is a pressing need to explore management strategies that are financially viable and cost-cutting [35, 36].

Although the algorithms have advantages, they are highly dependent on good-quality data. The need for comprehensive data integration in real-time across all regions hampers the scalability of such solutions in Ukraine. These limitations can only be overcome by developing standardized data collection and sharing protocols [37]. Also, the current research focus is the economic and mathematical modeling of innovative agglomeration development based on information technologies [38]. This can also be considered in future studies. Moreover, the computational demands of the EFA and DROA algorithms require infrastructure upgrades, most prominently in areas with negligible technological capacity [39].

4. Conclusions

The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results section.

The potential of algorithmic improvements in decision-making for renewable energy management in Ukraine is illustrated in this study. Results demonstrated that the EFA and the DROA improved substantially over existing forecasting algorithms regarding forecasting accuracy, economic efficiency, and system stability. Advancements in these areas help to decrease energy losses, lower operational costs, and increase grid reliability, all of which are critical components of sustainable energy systems.

The results emphasize the importance of incorporating the latest technologies into Ukraine's power system if the country moves faster toward renewable power. These algorithms address operational inefficiencies and optimize energy resource management to enable energy security and climate goals consistent with national and international commitments.

4.1. Limitations and future research directions

This study has many significant contributions but has few limitations. The algorithms developed require robust computational infrastructure that may not be uniformly available across all regions of Ukraine. Also, the limited access to high-performance computing resources could hinder the real-time implementation of these algorithms. So, investments in grid modernization and deploying edge computing solutions will be necessary to enhance scalability and real-time processing capabilities and cover this gap.

Additionally, the current work considers the critical performance metrics of forecasting accuracy, economic efficiency, and grid stability. However, it does not incorporate other crucial factors like cybersecurity risks, environmental impacts, and stakeholder acceptance. In future endeavors, this aspect can be explored. Further, this study focuses only on solar-wind hybrid systems. However, other renewable energy combinations, such as solar-battery, wind-hydrogen, or multi-source microgrid systems, can be explored in future research. Moreover, it can also be evaluated how decision-making algorithms perform under different renewable energy configurations to improve scalability and adaptability across diverse energy infrastructures.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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