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METHOD AND CYBER-PHYSICAL SYSTEM FOR FORECASTING AND OPTIMIZING ELECTRICITY CONSUMPTION IN RESIDENTIAL DISTRICTS BASED ON MACHINE LEARNING ALGORITHMS

The development of cyber-physical systems combined with machine learning algorithms opens new opportunities for forecasting and optimizing electricity consumption in residential districts. This study examined existing technologies and solutions for energy consumption management, identifying their advantages and disadvantages. The analysis showed that modern commercial systems are primarily designed either for industrial use or individual consumption, lacking a comprehensive approach for residential districts. The proposed forecasting and optimization method is based on hybrid machine learning algorithms. For energy consumption forecasting, a combination of recurrent neural networks (RNN) and XGBoost was used, allowing for the consideration of both temporal dependencies and nonlinear factors. For energy consumption optimization, a combination of genetic algorithms (GA) and particle swarm optimization (PSO) was implemented, ensuring efficiency in finding optimal solutions. The developed cyber-physical system includes sensors for data collection, microcontrollers (Raspberry Pi) for data processing, and intelligent systems for controlling electrical appliances. This enables real-time energy consumption analysis and management, improving the energy efficiency of residential districts. Experimental results confirmed the effectiveness of the proposed approach, demonstrating high accuracy in energy consumption forecasting and the potential for reducing electricity costs through optimized usage. The proposed method has significant potential for scaling and implementation in large residential complexes, contributing to sustainable development and reducing the load on energy grids. Thus, the results of this study can be used for further improvement of energy management systems, promoting efficient electricity use, reducing consumer costs, and minimizing the environmental impact of energy systems.

Keywords: electricity consumption forecasting, cyber-physical system, machine learning, energy consumption optimization, artificial intelligence, smart grids, sensors, microcontrollers, energy efficiency, optimization algorithms

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МЕТОД І КІБЕРФІЗИЧНА СИСТЕМА ПРОГНОЗУВАННЯ ТА ОПТИМІЗАЦІЇ ЕЛЕКТРОСПОЖИВАННЯ ЖИТЛОВИХ КВАРТАЛІВ НА ОСНОВІ АЛГОРИТМІВ МАШИННОГО НАВЧАННЯ

Розвиток кіберфізичних систем у поєднанні з алгоритмами машинного навчання відкриває нові можливості для прогнозування та оптимізації споживання електроенергії в житлових районах. У цьому дослідженні було проаналізовано існуючі технології та рішення для управління енергоспоживанням, визначено їхні переваги та недоліки. Аналіз показав, що сучасні комерційні системи в основному призначені або для промислового використання, або для індивідуального споживання, не маючи комплексного підходу для житлових районів. Запропонований метод прогнозування та оптимізації базується на гібридних алгоритмах машинного навчання. Для прогнозування енергоспоживання використано комбінацію рекурентних нейронних мереж (RNN) та XGBoost, що дозволяє враховувати як часові залежності, так і нелінійні фактори. Для оптимізації енергоспоживання реалізовано комбінацію генетичних алгоритмів (ГА) та оптимізації рою частинок (PSO), що забезпечило ефективність пошуку оптимальних рішень. Розроблена кіберфізична система включає датчики для збору даних, мікроконтролери (Raspberry Pi) для обробки даних та інтелектуальні системи для керування електроприладами. Це дозволяє в режимі реального часу аналізувати енергоспоживання та керувати ним, підвищуючи енергоефективність житлових районів. Експериментальні результати підтвердили ефективність запропонованого підходу, продемонструвавши високу точність прогнозування енергоспоживання та потенціал зниження витрат на електроенергію за рахунок оптимізації її використання. Запропонований метод має значний потенціал для масштабування та впровадження у великих житлових комплексах, сприяючи сталому розвитку та зменшенню навантаження на енергетичні мережі. Таким чином, результати цього дослідження можуть бути використані для подальшого вдосконалення систем енергоменеджменту, сприяння ефективному використанню електроенергії, зниження витрат споживачів та мінімізації впливу енергетичних систем на навколишнє середовище.

Ключові слова: прогнозування електроспоживання, кіберфізична система, машинне навчання, оптимізація енергоспоживання, штучний інтелект, розумні мережі, сенсори, мікроконтролери, енергоефективність, алгоритми оптимізації.

Introduction

Electricity is an essential resource in the modern world, indispensable in various human activities, including industry, medicine, transportation, and daily life. The growing demand for electricity and the need for its efficient use have led to the necessity of implementing new technologies for monitoring, forecasting, and optimizing electricity consumption.

One of the promising solutions in this field is the use of cyber-physical systems, which combine hardware and software to collect, analyze, and manage energy resources [1]. Such systems consist of sensors, microcomputers, and software algorithms that enable real-time decision-making and functionality.

With the advancement of artificial intelligence and machine learning, an increasing number of solutions are integrating these technologies into energy management. These systems are becoming accessible not only to industrial enterprises but also to individual users aiming to optimize their electricity consumption and reduce energy costs.

As a result, companies are actively developing their own innovative solutions to improve electricity efficiency, ensuring sustainable development and reducing the load on power grids.

For example, Google offers its Google Nest system, which employs machine learning technologies to optimize energy usage in homes, particularly for temperature control and reducing energy consumption. The system learns users' habits and adjusts accordingly, reducing heating and cooling costs [2]. Tesla's Powerwall system ensures efficient energy storage and optimal utilization under variable tariffs and peak loads, using machine learning algorithms to optimize consumption based on demand forecasts [3]. Additionally, Schneider Electric has developed the EcoStruxure platform for energy management and building automation, which uses machine learning to forecast energy consumption and automatically adjust heating, ventilation, and air conditioning systems [4,5].

Although these systems contribute to energy savings and enhance user convenience, they are expensive and do not provide simultaneous forecasting and optimization of electricity consumption. Moreover, these products are designed for homes or industrial applications, lacking a comprehensive approach for residential districts.

Thus, the goal of this research is to develop and implement a method and a cyber-physical system for forecasting and optimizing electricity consumption in residential districts. This system will use machine learning algorithms to ensure high forecasting accuracy and effective energy management.

Selection of algorithms for forecasting electricity consumption in residential districts

Electricity consumption forecasting is a complex task that involves processing large volumes of data, such as air temperature, humidity levels, past energy consumption patterns, and socio-economic factors. Machine learning enhances forecast accuracy by utilizing historical data and various algorithmic approaches. Therefore, it is essential to select the most suitable algorithms for developing a forecasting and optimization method for residential electricity consumption [6].

Supervised Learning:

Supervised learning algorithms are the most widely used for electricity consumption forecasting.

- Linear regression is one of the simplest algorithms used to forecast electricity consumption based on multiple parameters.
- Decision trees classify data based on decisions made at each stage and are effective in handling large datasets.
- Support Vector Machines (SVM) can be used for both regression and classification, ensuring high accuracy in cases of non-linear dependencies.
- XGBoost is employed for electricity consumption forecasting due to its capability to process large datasets and effectively handle non-linear relationships [11].

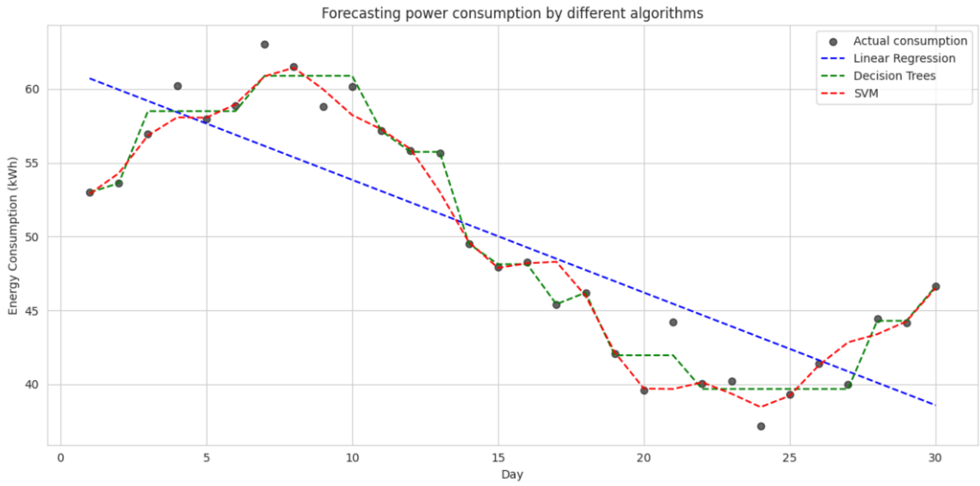

Fig. 1. Results of electricity consumption forecasting

Figure 1 illustrates the results of electricity consumption forecasting using supervised learning algorithms, namely linear regression, decision trees, and SVM.

Deep Learning:

For more complex and non-linear models, deep learning methods are used, particularly recurrent neural networks (RNNs) and Long Short-Term Memory (LSTM), which are well-suited for time series analysis. LSTM models can capture long-term dependencies in data, enabling longer-term electricity consumption forecasts. Figure 2 presents forecasting results using the LSTM algorithm.

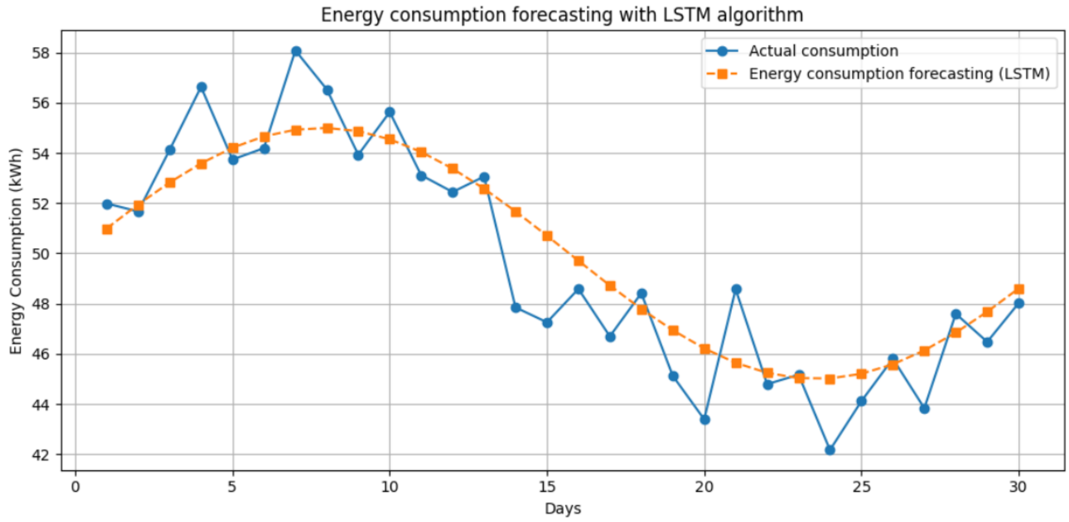

Fig. 2. Results of electricity consumption forecasting using the LSTM algorithm

Unsupervised Learning:

Unsupervised learning can help identify hidden patterns in data, which may be valuable for future forecasting. Clustering algorithms, such as k-means, can detect groups of consumers with similar energy consumption habits, aiding in consumption optimization. The application of k-means is shown in Figure 3.

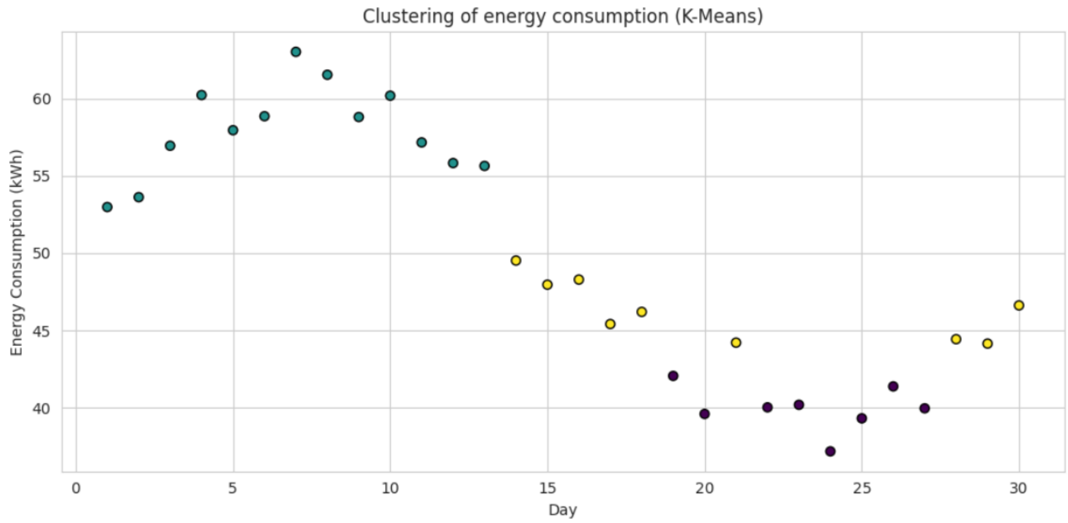

Fig. 3. Results of electricity consumption clustering using the k-means algorithm

The presented results indicate that a hybrid algorithm combining the advantages of different approaches is required. The best solution for electricity consumption forecasting is the hybrid model (RNN + XGBoost), which captures both temporal dependencies (e.g., consumption variations throughout the day) and non-linear factors.

Figure 4 presents the forecasting results using XGBoost, RNN, and their hybrid combination.

Selection of algorithms for optimizing electricity consumption in residential districts

Electricity consumption optimization in residential districts involves identifying optimal energy usage strategies while minimizing costs. Various optimization algorithms can be used for this purpose:

- Genetic algorithms (GA) simulate evolutionary processes to generate new solutions based on the best previous ones [9].
- Particle Swarm Optimization (PSO) is an optimization technique that mimics the behavior of particles seeking the best solution in a multi-dimensional space [10].

The results of electricity consumption optimization using the aforementioned algorithms relative to actual consumption are shown in Figure 5.

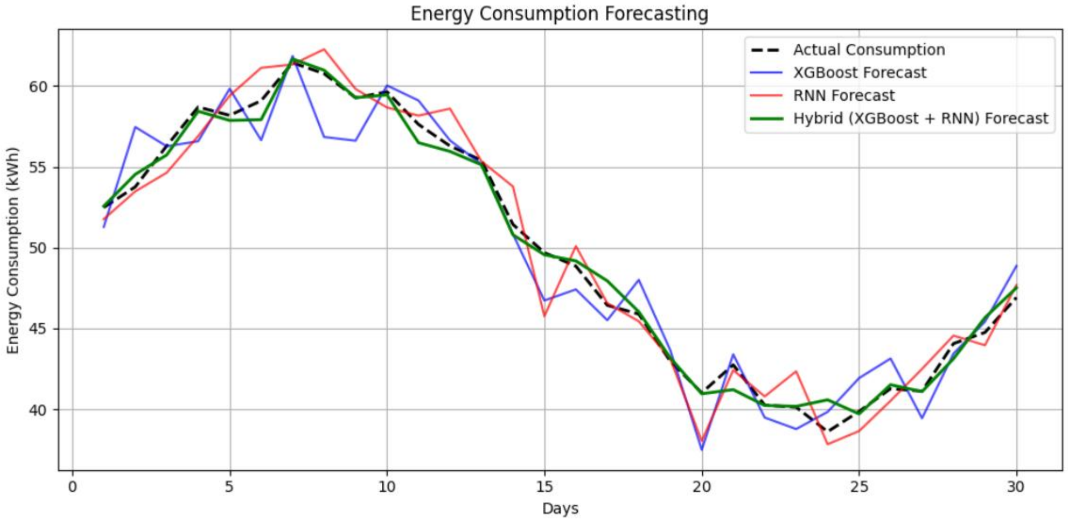

Fig. 4. Results of electricity consumption forecasting using XGBoost, RNN, and a hybrid approach

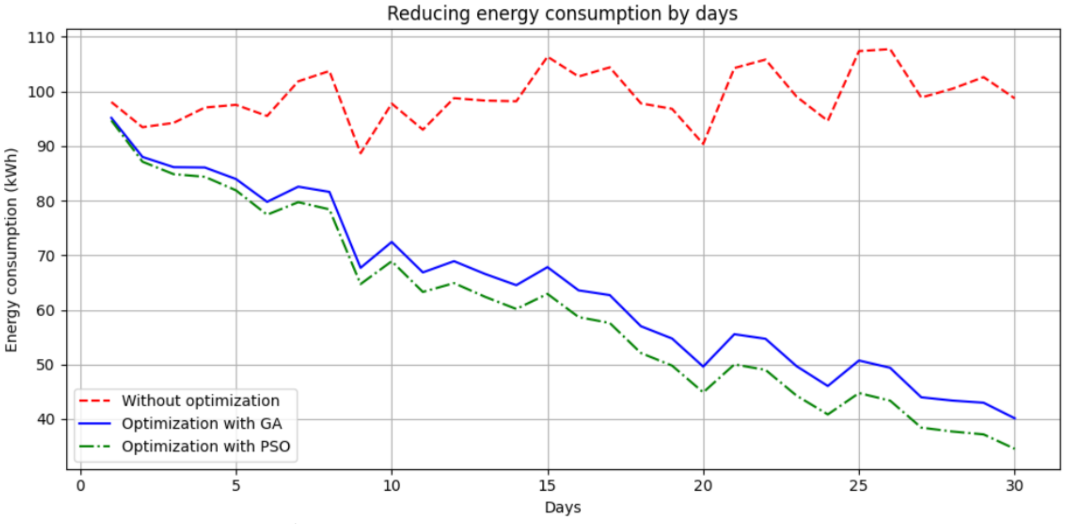

Fig. 5. Results of electricity consumption optimization using PSO and GA algorithms

To enhance optimization, a hybrid approach combining the speed of PSO and the reliability of GA is preferred. Its effectiveness is demonstrated in Figure 6.

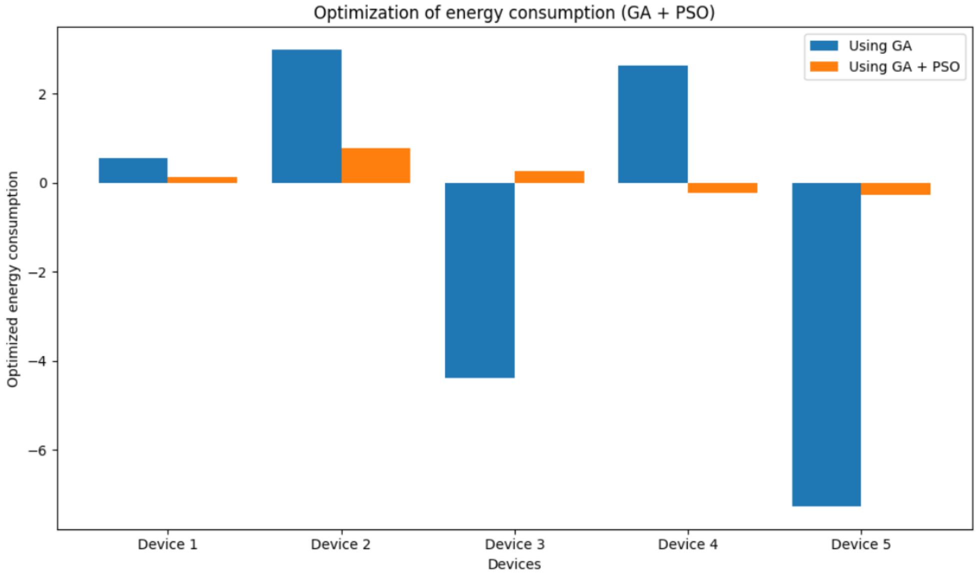

Fig. 6. Results of applying the hybrid optimization algorithm (GA + PSO)

As a result, the method for forecasting and optimizing electricity consumption in residential districts utilizes hybrid algorithms (RNN + XGBoost) and (GA + PSO), respectively.

Development of a method and cyber-physical system for forecasting and optimizing energy consumption

The hardware component plays a crucial role in the method for forecasting and optimizing electricity consumption in residential districts. The type of sensors and available connections determine the data used for developing machine learning models. For example, Figure 7 illustrates the logic behind the creation and operation of an electricity consumption forecasting model [6].

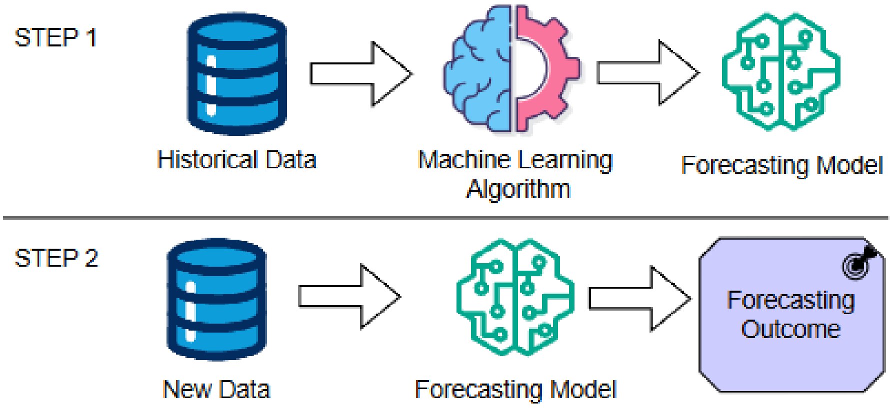

Fig. 7. Logic of creating and operating an electricity consumption forecasting model

The architecture of the cyber-physical system consists of the following components:

- Sensors for measuring environmental parameters (temperature, humidity, CO2 concentration) and monitoring energy consumption status.
- Microcontrollers (e.g., Raspberry Pi or Arduino) that collect and transmit data to the central system for analysis. Raspberry Pi is preferable in development, as it supports machine learning applications.
- Systems for controlling electrical appliances, such as smart plugs, which can be connected to sensor networks to regulate energy consumption in real time.

The interaction with machine learning algorithms is as follows: the data collected by sensors is processed using machine learning algorithms to predict energy consumption and optimize its use. Forecasting models determine expected energy consumption, while optimization algorithms adjust the operation of electrical devices. The operation of the method and cyber-physical system is shown in Figure 8.

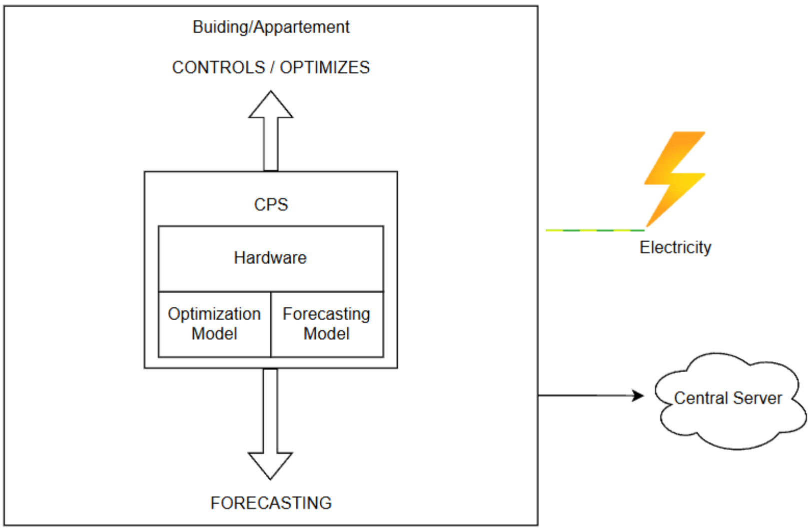

Fig. 8. Method and cyber-physical system for forecasting and optimizing electricity consumption in residential districts

Conclusions

The development of cyber-physical systems combined with machine learning algorithms opens new opportunities for forecasting and optimizing electricity consumption in residential districts. This study examined existing technologies and solutions for energy consumption management, identifying their advantages and disadvantages. The analysis showed that modern commercial systems are primarily designed either for industrial use or individual consumption, lacking a comprehensive approach for residential districts.

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Experimental results confirmed the effectiveness of the proposed approach, demonstrating high accuracy in energy consumption forecasting and the potential for reducing electricity costs through optimized usage. The proposed method has significant potential for scaling and implementation in large residential complexes, contributing to sustainable development and reducing the load on energy grids.

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