Methods of Artificial Intelligence and Machine Learning Forecasting and Optimization of Energy Consumption in Smart Cities

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***Abstract*— Smart cities are transforming urban life through advanced technologies, and efficient energy management is one of the key challenges they face. The rapid increase in energy consumption requires innovative approaches to optimize energy supply and demand. This article explores the application of artificial intelligence (AI) and machine learning (ML) algorithms for energy supply management in smart cities. It examines how these technologies can forecast energy consumption, balance supply and demand, and optimize energy management through real-time adjustments. The paper also highlights mathematical models and international case studies to illustrate the potential of AI and ML in achieving energy efficiency and sustainability. The findings demonstrate the effectiveness of these technologies in improving energy management and offer insights into future advancements in the field.**

Keywords*— smart cities, energy management, artificial intelligence, machine learning, energy forecasting, supply-demand optimization.

I. INTRODUCTION

Smart cities use advanced technologies to improve and manage urban life. One of the most important problems in these cities is energy supply and energy consumption. With increasing energy consumption, efficient management of energy networks and optimization of the balance of supply and demand are becoming increasingly important. The implementation of artificial intelligence (AI) and machine learning (ML) methods and algorithms for efficient energy supply management in smart cities is promising. So it offers ways to solve this problem by forecasting energy consumption and optimizing the balance of supply and demand in various fields. This article examines and analyzes modern approaches to the implementation and application of artificial intelligence and machine learning methods and algorithms in order to optimize energy supply in smart cities.

II. AI AND ML APPROACHES FOR MANAGING ENERGY SUPPLY IN SMART CITIES

AI is the field of application of methods, technologies, and computer systems designed to mimic human thinking and solve tasks normally performed by human intelligence [1]. ML is a field that develops and applies algorithms capable of analyzing data, making predictions, and extracting information. Currently, these technologies are widely used in the field of energy management, especially in forecasting and optimizing energy consumption. AI and ML algorithms learn from data, make effective decisions based on various factors, and improve energy management in smart cities.

Usually, AI and ML methods and algorithms are used to analyze energy consumption, optimize the balance of supply and demand, and manage energy networks [2].

A typical AI-based smart city energy management system includes the following modules [2]:

- Data collection (energy consumption, weather, time of day)
- Pre-processing (cleaning, normalization)
- Feature engineering (temperature, occupancy levels)
- Modeling (LSTM, ARIMA, etc.)
- Forecasting and optimization (real-time adjustments)

For the effective operation of AI and ML methods, a large amount of data related to the energy supply of a smart city is needed. Such data, which allows for assessment from different aspects, is collected from various sources. The following can be attributed to this data:

- Energy consumption data: Data on the energy consumed by customers in homes, commercial and other organizations is accurately recorded and monitored through smart meters, IoT and other intellectual measuring instruments [3, 4].
- Weather Information: It is clear that one of the important factors that directly affects energy consumption is weather. Thus, temperature and humidity of weather, wind speed and other factors directly affect energy consumption [3].
- Economic and Social Factors: The development of the city's population and infrastructure, industrial facilities and other socio-economic factors also affect energy consumption. By taking this information into account, more accurate predictions are obtained and the right decisions are made [3].

After the necessary data is collected, it is processed with the help of an artificial intelligence model, cleaned of possible "noise" data, normalized, and a probable prediction of future energy consumption in the smart city is made using various analysis methods (for example, time series analysis, neural networks, and other machine learning techniques).

AI and ML algorithms play an important role in analyzing potential energy consumption in a smart city, determining and optimizing the supply-demand balance, and effectively managing energy networks. These algorithms allow predicting energy use (consumption) in a smart city by taking into account many factors such as individual energy consumption data, weather conditions and temperature, time of day (daytime and evening hours), and working hours.

Well-known time series forecasting methods are generally used to forecast energy consumption in smart cities. To achieve more accurate forecasts, especially considering the changing hourly, weekly and monthly energy consumption patterns in smart cities, neural networks such as LSTM (Long Short-Term Memory) and GRU (Gated Recurrent Units) are used.

AI and ML methods are also used to model energy consumption in smart cities under uncertain conditions (e.g., to model the behavior of individual consumers). These approaches allow for data-driven adjustments to energy supply by learning consumption habits and patterns, and to improve the efficiency of smart city energy management technologies.

III. FORECASTING ENERGY CONSUMPTION IN SMART CITIES

As noted above, forecasting energy consumption occupies an important place in energy management in smart cities. In this way, it allows you to predict future energy needs in advance, on the basis of which to carry out appropriate energy production and distribution. In practice, time series analysis, statistical models, and heuristic methods are used as traditional methods of energy forecasting [2]. However, these approaches often do not provide accurate results and are not reliable enough in changing conditions [5].

The following time series analysis and ML algorithms are usually used to predict energy consumption [2,5,6]:

- ARIMA (Auto-Regressive Integrated Moving Average): A traditional method for forecasting energy consumption over time.
- LSTM Neural Networks: Analyze time series data with deep learning for more precise forecasts, particularly effective for non-linear, long-term dependencies.
- Random Forest and XGBoost: Machine learning algorithms that analyze various features for more accurate energy consumption predictions.

The application of ML, especially deep learning and time series forecasting models, provides ideal solutions to this problem. For example, the LST and GRUB networks effectively model dynamic changes in energy consumption over time, offering more accurate forecasts based on historical data.

IV. OPTIMIZATION OF THE BALANCE OF ENERGY SUPPLY AND DEMAND IN SMART CITIES

As energy consumption increases in a smart city, managing the balance between supply and demand becomes increasingly important. Optimizing the supply-demand balance ensures that energy networks operate efficiently and sustainably, preventing overloading. If supply does not match demand, congestion occurs in the networks, which can lead to energy losses and network outages [7].

AI and ML offer a solution to this problem through optimization algorithms. For example, AI algorithms monitor and analyze energy production and consumption in real time, which allows for a more accurate balance between supply and demand. A number of optimization algorithms are used to model uncertainties related to energy consumption and improve network performance. This approach also reduces energy costs and increases the efficiency of networks [8].

The following algorithms are mainly used for optimizing energy supply based on energy consumption forecasting [8]:

- Linear Programming (LP) - a mathematical method used to optimize energy production and distribution (demand and supply).
- Mixed-Integer Linear Programming (MILP): Provides optimal energy distribution according to the requirements of energy networks during semi-constrained and fully constrained energy management.
- Genetic Algorithms (GA): Used to find optimized solutions between demand and supply.

Real-Time Energy Management. The primary goal of energy management models is real-time control [9]. By analyzing hourly consumption and adjusting supply, energy grids can achieve:

- Monitoring and Regulation: Real-time monitoring and adjustment of energy supply.
- Load Reduction: Minimizing overloads and energy losses for balanced energy distribution.
- Individual Consumer Needs: Forecasting consumer-specific energy needs and directing supply accordingly.

V. MATHEMATICAL MODEL FOR SUPPLY-DEMAND BALANCE IN SMART CITIES

a. Consumer demand:

Based on the above, consumer demand can be given by the following mathematical expression:

$$\boldsymbol{CD = F(T, H, W, I)}$$

Here

$\boldsymbol{CD}$ - energy requirement (kWh);
$\boldsymbol{T}$ - temperature (°C);
$\boldsymbol{H}$ - humidity (%);
$\boldsymbol{W}$ - wind speed (m/s);
$\boldsymbol{I}$ - social and economic factors (working hours, vacation days, etc.).

b. Energy supply forecast:

$$\boldsymbol{ES = G\left(P_{solar}, P_{wind}, P_{grid}\right)}$$

Here

$\boldsymbol{ES}$ - energy supply (kWh);
$\boldsymbol{P_{solar}}$ - solar energy offer (kWh);
$\boldsymbol{P_{wind}}$ - wind energy offer (kWh);
$\boldsymbol{P_{grid}}$ - power supply from the grid (kWh).

c. Balancing and optimization:

$$\boldsymbol{BO = min\ (max(CD - ES, 0), L)}$$

Here

$\boldsymbol{BO}$ - optimized energy balance (kWh);
$\boldsymbol{L}$ - maximum energy limits (kWh).

VI. INTERNATIONAL EXPERIENCE IN ENERGY MANAGEMENT IN SMART CITIES

AI and ML have experience in implementing a number of international-level application projects for the management of energy supply of smart cities. Thus, in several cities in the United States, optimization of energy consumption and regulation of supply and demand balance is carried out by applying smart energy networks and forecasting algorithms [6]. In these projects, the supply and demand of energy are monitored in real time, the energy consumption is adjusted individually for each user according to his demand.

At the same time, various smart city energy management projects have been implemented in Europe (for example, Amsterdam Smart City) and Asia (for example, Yokohama Smart Community). These projects provide solutions to the problems of increasing the efficiency of energy supply management and environmental protection through the use of AI and machine learning algorithms. These applications allow both energy suppliers and consumers to monitor and optimize energy consumption in real time.

Region	Project Name	Used Technology	Outcome
USA	Smart Grid City	AI and ML for forecasting	Improved reliability and demand-side management
Europe	Amsterdam Smart City	IoT and AI	Enhanced grid flexibility and renewable energy use
Asia	Yokohama Smart Community	AI for supply-demand	Reduced carbon emissions and better energy efficiency

VII. CONCLUSION

Forecasting energy consumption in smart cities and optimizing the supply and demand balance are of great importance for more efficient and sustainable management of energy supply. AI and ML algorithms provide great opportunities to achieve this goal. These technologies help to realize energy management more effectively, reduce energy costs of consumers and protect the environment. In the future, the spread and development of these approaches to a wider range of applications will make it possible to further improve the energy management of smart cities.

One of the main difficulties in the field of energy forecasting and optimization is related to the availability and quality of data. Inaccurate or lacking data can make it difficult for AI algorithms to deliver accurate results. At the same time, in an environment where there is uncertainty and changing conditions, testing of the effectiveness of AI and ML is also necessary. Future research may focus on the application of AI and machine learning in more complex, nonlinear, and multi-variable systems. In addition, with new optimization algorithms and more accurate forecasting models, the use of these technologies can be further developed in the future.

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