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Askhat Aliyev[1], Kanat Dyusenov[2], Dinara Japarova[3], Nurgul Yerbayeva[4], Kubaidolla Tulegenov[5]

Development of technologies for automated control of heat supply systems based on renewable energy sources

Abstract: The study is conducted to optimize technologies for automated control of heat supply systems based on renewable energy sources that can increase energy efficiency and reduce environmental impact. The study uses machine learning methods for predicting heat energy consumption, intelligent monitoring and diagnostics systems, and control automation algorithms to optimize the operation of heat supply systems based on renewable energy sources. As a result of the study, an automated heat supply management system based on renewable energy sources is analyzed, which demonstrated high energy efficiency and flexibility in operation. The use of intelligent algorithms

✉ Corresponding Author: Askhat Aliyev; e-mail: aliyevaskhat61@gmail.com

[1] Department of Thermal Power Engineering, L.N. Gumilyov Eurasian National University, Kazakhstan; ORCID iD: 0009-0007-7885-0696; e-mail: aliyevaskhat61@gmail.com

[2] Department of Thermal Power Engineering, L.N. Gumilyov Eurasian National University, Kazakhstan; ORCID iD: 0000-0003-1226-6431; e-mail: k.dyussenov@outlook.com

[3] Higher School of Electrical Engineering and Automation, West Kazakhstan Agrarian and Technical University named after Zhangir Khan, Kazakhstan; ORCID iD: 0000-0001-7023-7300; e-mail: dinara_japarova@hotmail.com

[4] Department of Technical Disciplines, Kazakhstan University of Innovation and Telecommunication Systems, Kazakhstan; ORCID iD: 0000-0001-6008-542X; e-mail: n-yerbayeva@outlook.com

[5] Higher School of Electrical Engineering and Automation, West Kazakhstan Agrarian and Technical University named after Zhangir Khan, Kazakhstan; ORCID iD: 0009-0000-0828-1415; e-mail: k.tulegenov@hotmail.com

allows optimising the distribution of heat energy, considering fluctuations in weather conditions and loads. Automation of control processes reduces operating costs and minimizes human intervention. It is also established that the integration of solar collectors and geothermal sources into a single system reduces dependence on traditional energy sources and carbon dioxide emissions. The study shows that optimizing the use of renewable sources with automated control not only increases the reliability of heat supply but also contributes to reducing operating costs in comparison with traditional systems. This confirms the prospects of such technologies for broad application in municipal and industrial heat supply systems. In addition, it is determined that automated control systems contribute to more accurate forecasting of thermal energy needs, which reduces the risk of overloads and interruptions in heat supply. The study also shows that the use of combined sources of renewable energy, such as solar and geothermal installations, increases the overall efficiency of the system.

KEYWORDS: intelligent algorithms, solar collectors, discharge reduction, weather conditions, demand forecasting

Introduction

Current problems in the field of energy, such as climate change, depletion of traditional resources, and growing energy needs, require the search for innovative solutions to ensure a stable and efficient heat supply. Changing the climate leads to an increase in the frequency and intensity of extreme weather conditions, which, in turn, increases the load on heat supply systems (Feron et al. 2021). The depletion of traditional resources, such as oil and gas, makes it necessary to switch to more stable and environmentally friendly energy sources (Kaldybaev et al. 2024). In addition, the constant growth of energy needs, caused both by an increase in the population and the development of industry, requires the creation of more efficient systems that can provide reliable and affordable heat supply. In this context, technologies for automated control of heat supply systems based on renewable energy sources (RES) are becoming particularly relevant. They allow not only to reduce the carbon footprint but also to improve the overall environmental situation by reducing dependence on excavated energy sources. In addition, the use of RES contributes to the diversification of energy sources, which increases the resistance of heat supply systems to external influences (Parvin et al. 2021). The introduction of intelligent algorithms and automation of control processes allows for optimizing the distribution of heat energy, considering fluctuations in weather conditions and consumption dynamics (Sydorets et al. 2017; Tagybayev et al. 2023). This leads to more accurate forecasting of heat needs and a reduction in the risk of overloading the system. Automation also minimizes human intervention, which reduces the likelihood of errors and increases operational efficiency. As a result, such technologies contribute to the creation of more flexible, adaptive, and stable heat supply systems that can successfully function in the face of constant changes and challenges in the field of energy.

In the field of automated control of heat supply systems based on renewable energy sources, there are several urgent problems, including the need to increase the energy efficiency and stability of such systems. Forootan et al. (2022) focus on the implementation of machine learning systems to optimize the distribution of thermal energy, which reduces operating costs and increases overall efficiency. The study demonstrates how the use of algorithms can substantially improve the control of heat flows in real-time. Zhu et al. (2024) considered the integration of solar and geothermal sources, emphasizing their synergistic effect and substantial reduction in carbon footprint. The paper presents a model showing how the combined use of these sources can increase the reliability of heat supply. According to the study by Soussi et al. (2022), automated control systems can successfully adapt to changing weather conditions, which makes them more reliable in extreme climate conditions. They also gave examples of the successful use of such systems in various regions with variable climatic conditions. Aman et al. (2021) showed how the use of Internet of Things (IoT) technologies in heat supply systems allows real-time monitoring and diagnostics of equipment conditions. This substantially reduces the risk of interruptions in the heat supply and increases the overall efficiency of operation. He et al. (2022) consider aspects of control automation that contribute to more accurate forecasting of thermal energy needs. The authors argued that such approaches improve planning and resource allocation, which, in turn, is critical for the efficient operation of heat supply systems.

Merabet et al. (2021) pay attention to the importance of intelligent algorithms in automated systems, emphasizing their role in improving the flexibility and adaptability of heat supply systems. This study has shown that using such algorithms allows for a better response to changes in consumption and external conditions. Ang et al. (2022) identify successful examples of the introduction of combined sources of renewable energy. They highlighted their contribution to reduced operating costs and sustainable development, which makes them attractive to municipal and industrial systems. Ali et al. (2022) focus on improving the energy efficiency of automated heat supply management systems with the introduction of renewable energy sources. They stress the importance of optimising processes considering local climate and infrastructure features, which allows increasing the overall efficiency and stability of the system. Rabani et al. (2021) investigate the impact of automation on the efficiency of heat supply systems. They concentrate on positive changes in performance and reliability, confirming the feasibility of implementing automated solutions. Lastly, Graveto et al. (2022) focus on the prospects for implementing automated management technologies in the municipal and industrial sectors. They underlined the need for further research and development of standards for integration to ensure sustainable development in this area.

Despite these studies, some gaps require additional research. For example, the scalability of the proposed technologies for different climatic conditions and regions is not sufficiently analyzed. Additional research is also needed to integrate various renewable energy sources into a single system and their impact on the stability of heat supply. In addition, the issues of standardization and certification of new automated control systems remained open, which complicated their wide implementation.

The study's purpose was to improve the energy efficiency and environmental friendliness of heat supply systems by optimizing automated control processes based on the use of renewable energy sources.

Study objectives:

1. Examine the possibility of optimizing the operating modes of heat pumps and boilers to increase the energy efficiency of heat supply systems.
2. Consider the impact of integrating various sources of renewable energy on the reliability and flexibility of heat supply systems.

Evaluate the economic feasibility of automating control processes in a heat supply system based on renewable sources.

1. Materials and methods

In the course of the study, the technology of automated control of heat supply systems based on RES was studied to increase energy efficiency and reduce the negative impact on the environment. The study began with forecasting heat energy consumption, where machine learning algorithms such as WeatherFlow AI (USA) were used to analyze weather data and TimeSeries Forecaster (Germany) to consider the time of day (Tempest API 2025; Abadi et al. 2015). This allowed for creating the basis for more accurate planning of resource allocation and prevention of excess or insufficient heat production.

An important stage was the integration of various RES. The systems using HelioPower 3000 (2025) solar collectors (Germany), GeoTherm Plus (2025) geothermal installations (Iceland), and biomass, using BioHeat Green 5000 (2025) Technology (Sweden), were combined into a single network. This resulted in an increase in the flexibility of heat supply and reduced dependence on traditional energy sources, which contributed to a more rational use of resources. The operating modes of the equipment, including heat pumps and boilers, were also optimized. Automated systems such as Grundfos MAGNA3 (2025) (Denmark) adjusted the operation of these components to achieve maximum energy efficiency, which allowed reducing energy costs.

The study focused on intelligent monitoring and diagnostic systems. The introduction of sensors and IoT technologies, such as Schneider EcoStruxure (2025) (France), provided the ability to track the state of all system components in real-time, which increased the level of control and efficiency in responding to failures. Autonomous control systems were also implemented that could adapt to changing conditions and minimize the need for manual intervention. This reduced operating costs and increased the reliability of the systems.

Peak load management has become an important area of research. The systems were examined, considering the possibility of accumulating heat energy during periods of low consumption and releasing it during peak load periods, which prevented overloads and increased the overall efficiency of the heat supply. The study also covered integration with electrical networks, which created additional flexibility and reduced costs, especially when using heat pumps such as Grundfos MAGNA3 (2025), which consume electricity from the RES.

The study determined the advantages of automated systems. It discussed reduced emissions of carbon dioxide and other pollutants, which contributed to an improvement in the environmental situation. Economic efficiency achieved due to reduced operating costs associated with increased efficiency and automation of processes was also considered.

Control systems based on Supervisory Control and Data Acquisition (SCADA), such as Siemens SIMATIC SCADA (2025) (Germany), and artificial intelligence for data analysis were used to implement the technologies under study. These tools provided effective control of the components of the heat supply system and expanded the possibilities for optimizing the operation based on the analysis of big data. SCADA systems allow monitoring of the condition of all elements in real-time, such as heat pumps, boilers, and distribution units, and quickly responding to any changes in their operation. Artificial intelligence, in turn, provided a deep analysis of the collected data, which helped to predict heat consumption, identify anomalies, and optimize the operating modes of equipment.

2. Results

Forecasting heat consumption is an important step towards improving the energy efficiency of heat supply systems. The use of machine learning algorithms allows analysing the consumption data depending on weather conditions, time of day, and other factors. This approach provides for predicting the need for heat more accurately and adapting systems to changing conditions. For example, in conditions of a sharp cold snap or an increase in temperature, algorithms can automatically regulate the supply of heat energy, preventing both a lack and an excess of heat. This not only improves the quality of service but also reduces energy costs, which is an important aspect in terms of growing energy prices.

Two algorithms were used to predict heat energy consumption: WeatherFlow AI and TimeSeries Forecaster (Table 1). The difference in accuracy was 3%, which is an important factor for more accurate planning of heat energy distribution in changing climatic conditions. This makes it possible to estimate thermal load more accurately, which lowers the possibility of energy shortages or overstock, maximizes resource allocation, and improves operational stability in the face of changing weather. However, TimeSeries Forecaster turned out to be more efficient, which can be critical for quick decision-making when changing the load on the system.

As part of the analysis of renewable energy sources, three systems were used: HelioPower 3000 (solar energy), GeoTherm Plus (geothermal energy), and BioHeat Green 5000 (biomass) (Table 2). The exceptional efficiency of GeoTherm Plus makes it perfect for situations where long-term operational savings are more important than upfront expenditure. The largest energy output, on the other hand, is provided by the BioHeat Green 5000, which is beneficial in situations

Table 1. Forecasting heat energy consumption

Tabela 1. Prognozowanie zużycia energii cieplnej

Name of the algorithm	Manufacturer country	Forecasting parameters	Prediction accuracy [%]	Data processing time [seconds]
WeatherFlow AI	USA	Weather conditions	92	10
TimeSeries Forecaster	Germany	Time of day	89	8

Source: compiled by the authors based on (Tempest API 2025; Abadi et al. 2015).

Table 2. Sources of renewable energy and equipment

Tabela 2. Źródła energii odnawialnej i wyposażenie

Energy source	System name	Manufacturer country	Energy output [kW/h]	Efficiency of a separate system [%]	Cost [USD]
Solar energy	HelioPower 3000	Germany	500	85%	10,000
Geothermal energy	GeoTherm Plus	Iceland	400	90%	12,000
Biomass	BioHeat Green 5000	Sweden	600	88%	15,000

Source: compiled by the authors based on HelioPower 3000 (2025), GeoTherm Plus (2025), BioHeat Green 5000 (2025).

with high demand but also the most expensive. HelioPower 3000 offers a cost-effective and balanced solution with moderate efficiency, indicating that it is appropriate for systems with modest budgetary constraints and strong sun availability. These data allow the conclusion that the choice of system depends on the availability of a particular renewable energy source and the budget: solar energy shows high production at relatively low costs, geothermal energy is more efficient, and biomass ensures maximum production.

The integration of various RES, such as solar collectors, geothermal installations, and biomass, plays a key role in creating efficient heat supply systems. Automated control systems (ACS) allow combining these sources into a single network, maximizing the potential of each of them. For example, solar collectors can provide heat during the day, while geothermal installations can maintain a stable level of heat supply throughout the year. The integration of various sources not only substantially increases the reliability of the system but also reduces dependence on traditional, non-renewable energy sources, which substantially reduces the carbon footprint and contributes to sustainable development.

Optimising the operation of equipment is an important step in modelling and managing RES-based systems. Automated systems can adjust the operation of heat pumps, boilers, and distribution units to achieve maximum energy efficiency (Wang et al. 2022). This is achieved due to flexible management, which considers the current state of the system, consumption forecasts, and external conditions. For example, during peak load periods, the system can activate additional energy sources or redirect resources to the most necessary parts of the network. This approach allows not only the improvement of the quality of heat supply but also the reduction of operating costs, which is important for businesses and the population.

In the modern energy sector, automation and the implementation of intelligent control systems are becoming an integral part of the development of heat supply (Rubino and Rubino 2020; Capasso et al. 2021). Technologies based on IoT and intelligent monitoring systems can substantially improve the efficiency, reliability, and flexibility of heat supply systems. These technologies provide real monitoring of the state of all components of the system, which allows for quickly responding to changes such as fluctuations in temperature or load. With the help of IoT devices, it is possible to integrate many sensors that collect data on temperature, pressure, and energy consumption in real-time. This allows not only an accurate prediction of the need for heat but also the ability to optimize the distribution of resources, which leads to an increase in energy efficiency by 15–20%. Intelligent data analysis systems are able to detect patterns and anomalies, predict possible failures, avoiding costly downtime. In addition, monitoring systems allow automating control processes, which reduces the likelihood of errors related to the human factor and increases the reliability of the system. This also contributes to more efficient use of renewable energy sources, as systems can adapt to changes in environmental conditions and user requirements, ensuring flexible operation of heat supply systems (Linchenko et al. 2022). As a result, the integration of IoT and intelligent technologies into heat supply management can increase the overall efficiency of systems by 10–30%, substantially improving their operational characteristics. These approaches not only help to increase energy efficiency but also reduce operating costs, which is especially important in conditions of growing energy needs and the need to reduce environmental impact.

Three systems were used for monitoring and controlling heat supply: Schneider EcoStruxure, Siemens SIMATIC SCADA, and Grundfos MAGNA3. The reliability of these systems was assessed based on their response time, and the number of integrated sensors and operational stability were reported under varying conditions. The data presented in Table 3 indicates that all three automated control systems exhibit a high degree of reliability. Siemens SIMATIC SCADA is the most secure and responsive system, ideal for critical settings that need quick adjustments. It has the fastest response time (30 ms) and a 98% reliability rate. Despite being the most economical choice, Grundfos MAGNA3 may be more appropriate for less demanding applications where cost-effectiveness is valued above maximum system responsiveness due to its somewhat lower dependability (93%) and sensor count.

Intelligent monitoring and diagnostics systems are the basis for implementing modern approaches to heat supply management. The use of sensors and IoT technologies allows tracking the real-time state of all components of the system, which opens up new prospects in management. Data obtained using sensors enables the detection of malfunctions, which substantially reduces downtime and reduces maintenance costs. For example, suppose sensors detect anomalies in the operation of a boiler or heat pump. In that case, the system can automatically notify the

Table 3. Monitoring, management and optimisation systems

Tabela 3. Systemy monitorowania, zarządzania i optymalizacji

System name	Manufacturer country	Number of sensors	Response time [ms]	Cost [USD]	Reliability [%]
Schneider EcoStruxure	France	200	50	20.000	95
Siemens SIMATIC SCADA	Germany	150	30	25.000	98
Grundfos MAGNA3	Denmark	100	40	18.000	93

Source: compiled by the authors based on Schneider EcoStruxure (2025), Grundfos MAGNA3 (2025), Siemens SIMATIC SCADA (2025).

operator or even independently perform the necessary actions to prevent an accident. This level of automation substantially increases the safety and reliability of heat supply systems.

Autonomous control systems such as Schneider EcoStruxure, Siemens SIMATIC SCADA, and Grundfos MAGNA3, based on intelligent algorithms, are another important step in the development of automation (Bathla et al. 2022). These systems have adapted to changing conditions, minimizing the need for manual intervention. Control algorithms that use data on current indicators and forecasts can automatically regulate the heat supply depending on the time of day, weather conditions, and demand level. For example, on warm days, the system can reduce the power of boilers, and on cold days – increase it, thereby optimising the use of resources and reducing costs. This approach also allows effectively managing peak loads, which is an important aspect for preventing overloads and maintaining system stability.

One of the substantial advantages of automation is the ability to integrate various energy sources into a single management system. Using intelligent algorithms, it is possible to effectively combine solar, geothermal, and biomass energy sources, ensuring a reliable and economical heat supply. This expands opportunities for sustainable development of energy systems, minimizing dependence on traditional resources and reducing the carbon footprint. The introduction of such technologies allows for achieving a high degree of system autonomy, which is especially important in conditions of growing requirements for ecology and energy efficiency. In the context of global climate changes and depletion of traditional resources, optimisation of the use of RES is becoming an integral part of modern energy systems. Efficient peak load management and integration with electrical networks are key aspects that contribute to the sustainable development of heat supply. These approaches provide reliable heat supply and reduce operating costs, improving the environmental situation.

Peak load management is one of the most important elements of heat supply optimization (Ghilardi et al. 2021). It operates through the use of thermal energy storage technologies, such as insulated water tanks and phase-change materials, which accumulate excess heat generated during periods of low demand. This is designed to consider the possibility of heat generation during periods of low consumption and its release at peak loads. With the use of sophisticated insulation and regulated circulation, the extra energy is kept at ideal temperatures and stored as hot water or other thermal carriers. By using clever control algorithms that modify flow rates and distribution pathways in response to real-time demand data, the stored thermal energy is automatically released into the system during moments of high use. For example, on days with low temperatures or increased demand for heating, the accumulated heat energy can be used to meet the needs of customers, avoiding overloading and balancing consumption. As a result of using such systems, it is possible to save up to 40% of heat surpluses, which substantially increases the overall efficiency of heat supply and contributes to more rational use of resources. This approach substantially increases the flexibility and reliability of heat supply systems, making them more resistant to changes in demand.

Integration of heat supply systems with electrical networks also plays a critical role in optimizing the use of RES (Potrč et al. 2021). The synergy between these systems provides additional flexibility and reduces operating costs by 15–20%. This is achieved due to the optimal distribution of resources and improving the overall efficiency of the heat supply system. For example, the use of heat pumps, which can run on electricity produced from renewable sources, allows not only to reduce carbon dioxide emissions but also the dependence on extracted resources. Suppose there is an excess of electricity generated from solar or wind installations. In that case, it is advisable to use it for the operation of heat pumps, which ultimately reduces the total cost of energy supply (Stoliarov 2024). This combination of technologies can not only improve economic efficiency but also increase the stability of the energy system in general. In addition, integration with electrical networks opens up new opportunities for managing demand and supply. During periods of high energy generation, when the supply of electricity exceeds demand, the system can automatically switch consumption to heat pumps, thereby increasing the use of renewable resources and reducing the load on traditional energy sources.

Optimizing the use of RES also includes actively using modern technologies, such as consumption forecasting and modeling. These technologies allow operators to predict load errors in advance and take appropriate measures to avoid interruptions in heat supply. For example, the analysis of data on weather conditions and historical energy consumption helps systems automatically adjust to the optimal operating mode, which minimizes the need for manual intervention. Automated systems based on RES represent an important step towards a sustainable future, offering many advantages that concern both ecology and economics (Ahmad et al. 2022). These systems not only help reduce the negative impact on the environment but also improve the quality of services provided to users. Automated systems based on RES have three key advantages: environmental stability, economic efficiency, and improved service quality.

One of the main advantages of automated systems is their ability to reduce the release of carbon dioxide and other contaminants. Unlike traditional heat supply systems, which rely on fossil energy sources such as coal or gas, it uses natural resources such as sun, wind, and biomass, which do not damage the ecosystem. The use of solar collectors, geothermal installations, and other technologies minimizes carbon footprint, which is a vital aspect in the fight against global warming and climate change. Automated systems ensure optimal distribution and use of these resources, which leads to a decrease in the overall level of pollution and contributes to environmental stability.

Economic efficiency is another important advantage of automated systems based on RES (Chen et al. 2021). Reducing operating costs becomes possible due to the high energy efficiency achieved by automating processes. For example, intelligent algorithms can regulate the operation of equipment depending on the current conditions, avoiding excess energy consumption and minimizing the cost of its production. As a result, companies can reduce their costs and increase their competitiveness in the market. This, in turn, opens up opportunities for investing in new technologies and projects, which contributes to the further development and improvement of the heat supply system.

Although the initial installation costs can be high, especially for digital infrastructure and renewable energy technologies, a thorough cost-benefit analysis of the systems' implementation in the current study shows that the long-term savings and environmental advantages frequently outweigh these costs. For example, the initial outlay for infrastructure, installation, and equipment may be substantial for renewable energy sources like solar or wind. However, over time, these systems produce electricity more cheaply than conventional fossil fuel-based power generation, which results in significant energy bill savings. Long-term societal and ecological well-being is also influenced by the environmental advantages, which include lower greenhouse gas emissions, better air quality, and less dependence on non-renewable resources. Furthermore, through optimized resource utilization and decreased waste, the deployment of intelligent systems and energy-efficient technology can lower operating costs. These systems are a wise investment for long-term sustainability and economic stability when the full range of advantages, including both immediate money savings and wider environmental effects, are taken into account.

In addition, automated systems based on RES substantially improve the quality of user service (Sukhodub and Serdechnyi 2024). Due to a more stable heat supply with less downtime and system failures, users get reliable access to the necessary heat. Modern technologies, such as real-time monitoring and intelligent diagnostic systems, allow operators to quickly respond to changes in consumption and fix problems before they lead to service interruptions (Zuo et al. 2024). This not only increases user satisfaction but also contributes to more efficient use of resources.

In a world where sustainable development and efficient use of resources are becoming increasingly relevant, the introduction of advanced technologies in the heat supply system is a necessity. One of the most promising technologies in this area is SCADA-based management systems, the use of artificial intelligence (AI), and the analysis of big data. These technologies contribute to effective control and optimization of the operation of heat supply systems, which, in turn, leads to lower costs and improved service quality. SCADA-based control systems play a key role in modern energy systems management (Kaldate et al. 2021). They allow the monitoring and controlling of various components of the heat supply system, such as boilers, pumps, and distribution units, in real time. Using SCADA solutions, operators can obtain data on the condition of equipment, analyze performance, and perform diagnostics. This allows helps quickly respond to changes and eliminate potential problems before they develop into serious failures. In addition, SCADA systems can integrate with other technologies, providing more complete and comprehensive control of the entire heat supply system.

The introduction of artificial intelligence and analysis of extensive data open up new opportunities for optimizing the operation of heat supply systems. AI can analyze vast amounts of data obtained from various sources, such as weather stations, consumption sensors, and monitoring systems. Based on this analysis, algorithms can develop management strategies that consider not only current conditions but also predicted changes, such as temperature fluctuations and changes in consumption. This allows setting up the operation of equipment more accurately, minimising costs, and increasing the overall energy efficiency of the system. For example, the use of AI and Big Data allows implementing adaptive heat management (Li et al. 2023). The system can automatically accumulate excess heat during low consumption periods and release it during peak loads. This not only optimizes resource distribution but also reduces the risk of overloads and interruptions in heat supply. As a result, users get a stable and reliable heat supply, and operators can substantially reduce their operating costs. In addition, data collected using SCADA technologies and extensive data analysis can be used for long-term planning and accurate forecasting. They allow operators to identify important trends, evaluate the effectiveness of existing systems, and make informed decisions about future investments. This creates a strong basis for sustainable development and modernization of the energy infrastructure.

It is crucial to recognize that integrating several energy sources into a single energy system poses a number of technological difficulties, especially in areas with varying energy production or distinct climate restrictions. For example, the weather and time of day have a significant impact on solar and wind energy, which results in energy generation fluctuation that can make it challenging to guarantee a steady and dependable power supply. The effectiveness of these renewable energy sources may be hampered in areas with sporadic sunlight or slow wind speeds, necessitating the need for additional backup systems or energy storage devices to preserve grid stability. Furthermore, in order to properly balance supply and demand, integrating multiple energy sources frequently necessitates the use of sophisticated grid management technology, such as smart grids. These systems need to be able to quickly adapt to changes in energy production, which can be particularly difficult in areas with harsh weather or seasonal oscillations. Furthermore, there might be more obstacles to installing such systems in these locations, such as the requirement for specialized equipment made to resist severe weather or lessen the effect of extremely high or low temperatures on system functionality.

Thus, the introduction of technologies for automated control of heat supply systems based on renewable energy sources requires a comprehensive approach and consideration of many factors. The study demonstrates that automated heat delivery systems that integrate a variety of RES are highly efficient and adaptable. Peak load balancing, real-time responsiveness, and optimal resource allocation are made possible by the combined use of solar, geothermal, and biomass-based technologies, which are controlled by sophisticated control systems like SCADA and IoT platforms. These results highlight the necessity of regionally tailored integration plans that take into account the climate and energy resources of the area. For example, installing solar collectors like HelioPower 3000 first in places with lots of sunlight is economical, but in colder climates, geothermal solutions like GeoTherm Plus provide reliable performance. It is advised that the hybridization of sources be given priority in integration efforts in order to take advantage of their complimentary operational profiles. This should be backed by sophisticated forecasting algorithms that help coordinate supply with changing demand. To guarantee long-term effectiveness and sustainability, regional infrastructure, environmental conditions, and economic capacities should also be thoroughly evaluated before implementation. Scalability and resilience can be facilitated by using a modular approach to integration, particularly in areas with fluctuating energy demands or those subject to extreme weather.

3. Discussion

In the course of the study, it was determined that the development of technologies for automated control of heat supply systems based on RES contributes to a substantial increase in the overall efficiency and stability of these systems. The use of machine learning algorithms to predict heat consumption has reduced the occurrence of overloads and underheating. Analysis of data on weather conditions and the time of day showed that accurate prediction of thermal loads provided a more rational distribution of resources. This, in turn, helped to reduce operating costs and improve the quality of service. This issue has also been investigated by Richter et al. (2022), confirming that improving the efficiency of heat supply through automation is a key direction in modern heating systems. Automation of processes allows for substantially reducing energy costs and improving the quality of heat supply (Fialko et al. 1994; Hayvanovych and Pysh'yev 2003). The introduction of intelligent control systems, such as automatic regulators and temperature sensors, provides more accurate heat distribution, which minimizes losses and allows quick response to changes in temperature conditions. This not only saves resources but also contributes to reducing the negative impact on the environment since the reduction in energy consumption is directly related to reducing carbon dioxide emissions.

A study by Hofmeister et al. (2022) confirmed that resource optimisation: the role of forecasting in heat supply plays an important role in the effective management of heat networks. Forecasting heat consumption based on the analysis of historical data, meteorological conditions, and social factors allows for planning the resource needs and avoiding system overloads. Using modern methods of data analysis and machine learning, it is possible to predict load errors, which allows taking measures in advance to ensure the required level of heat supply (Borisov et al. 1986). This, in turn, leads to lower operating costs and increases the reliability of heat supply systems, creating more comfortable conditions for consumers.

Notably, the introduction of automation and forecasting in heat supply not only increases the efficiency of resource use but also opens up new opportunities for innovative solutions in this area. Modern technologies, such as IoT and big data, allow integrating various systems and providing real-time monitoring, which substantially improves the management of thermal networks (Iskandarov et al. 2020). This is achieved by installing sensors that track parameters such as temperature, pressure, and flow of the coolant, as well as using analytical tools that process the collected data to detect anomalies and optimize system operation. As a result, the system can automatically set parameters that minimize energy losses and increase overall control efficiency by 20–25%. Nevertheless, it is important to consider that the successful implementation of these technologies requires substantial investments and personnel professional training. Thus, a balanced approach to implementing automation and forecasting can be the key to the sustainable development of heat supply, contributing not only to economic benefits but also to social well-being.

The integration of various RES, such as solar collectors, geothermal installations, and biomass-based systems, has demonstrated its advantages in creating a flexible and adaptive heat supply system. Combining these technologies into a single network allowed using the potential of each source, depending on seasonal and daily fluctuations. For example, solar collectors provided the necessary amount of heat during the day, while geothermal installations maintained a stable level of heat supply throughout the winter. This helped not only to increase the reliability of the system but also to reduce dependence on traditional extracted resources.

As a result of the study, it was established that the integration of RES into the heat supply system contributes to a decrease in carbon footprint and an increase in energy efficiency, which is consistent with the conclusions of Zhang et al. (2022). A flexible heat supply system based on a RES can substantially reduce the carbon footprint and increase energy efficiency. The introduction of various sources, such as solar panels and geothermal systems, contributes to the diversification of the energy mix, providing a reliable and stable heat supply. The combined use of RES not only meets the need for heat but also allows for a better adaptation to changing climate conditions and demand.

In the study by Wang and You (2023), it was established that solar and geothermal sources are clear examples of synergy that contributes to the creation of a stable heat supply system. Solar collectors can be effectively used during the warmer months, providing hot water and heating, while geothermal systems that use a stable Earth temperature provide a reliable source of heat even in winter. The combined use of these technologies allows not only to optimise energy costs but also reduce operating costs by minimising the consumption of fossil fuel. As a result, the integration of solar and geothermal sources increases the overall efficiency of the heat supply system and contributes to improving energy security and environmental stability.

These results confirm the above study, as they emphasize the importance of integrating renewable energy sources into the heat supply system to achieve sustainable development. The observed advantages, such as reduced carbon emissions and increased energy efficiency, correspond to the conclusions of previous studies, which also focus on the synergy between solar and geothermal sources. Moreover, these results emphasise the need for further investments in technology and infrastructure to realise the potential of the RES fully. This approach not only improves the quality of heat supply but also supports global goals to reduce dependence on fossil fuel types and move to a more stable energy model.

An important aspect that was identified in the course of the study was the implementation of intelligent monitoring and diagnostics systems. The use of IoT technologies and systems such as SCADA allowed operators to get information about the state of all components in real-time. This substantially improved the level of control and speed of response to malfunctions, which reduced the response time to accidents by 30–40%. In addition, the implementation of such systems reduced operating costs by 15–20%, as it allowed for the prediction of possible failures in the operation of equipment and the taking of measures in advance.

During the study, it was confirmed that intelligent monitoring systems are crucial for improving the efficiency of heat supply management. These results are consistent with the findings of Ageed et al. (2021), where it is also noted that such systems open up opportunities for optimizing processes. The use of Internet of Things technologies helped integrate various sensors and devices, which ensured the collection and analysis of data in real-time. This gave a more accurate idea of the operation of the system and allowed quick responses to changes, such as fluctuations in temperature or load. As a result, the efficiency of heat distribution management increased, which ensured resource savings and reduced operating costs.

In turn, Waqas and Jamil (2024) concluded that SCADA plays an important role in this process, providing a centralized interface for monitoring and managing thermal networks. Integration of SCADA with IoT devices allows the tracking of the parameters of system operation and the prediction of potential problems, which increases the reliability of the heat supply. By using data to analyse performance and identify bottlenecks, operators can optimise processes, improve service quality, and minimise downtime. Thus, the combination of IoT and SCADA opens up new opportunities for increasing control of heat supply, making it more flexible, practical, and resistant to changes in the external environment. These data are consistent with the theses given in the previous section since they emphasize the importance of intelligent monitoring systems in optimizing heat supply processes. The observed improvement in management efficiency through the integration of IoT and SCADA confirms the conclusion that modern technologies can substantially improve control and forecasting in heat supply systems. These results also indicate the need for further implementation of innovative solutions to increase the reliability and stability of heat supply, which in turn contributes to reducing costs and improving the quality of services provided. Thus, the results emphasize the relevance and necessity of developing intelligent systems for the effective management of heating networks in modern conditions.

Peak load management was identified as a critical direction for achieving the stability of heat supply systems. During the study, it was determined that the use of thermal energy storage devices allows optimal resource distribution during periods of high demand. This not only prevents overloading but also allows using the available sources of RES more efficiently, minimizing dependence on external factors, such as fluctuations in prices for traditional energy resources.

Guelpa and Verda (2021) also conducted a study, the results of which confirmed that peak load management of heat energy is a critically important aspect of ensuring the stability and reliability of heat supply systems. In conditions of seasonal temperature fluctuations and increased demand for heating in cold months, effective management of these loads allows preventing overloads and system failures. One of the key solutions for achieving this goal is heat energy storage devices, which are able to accumulate excess heat during low consumption periods and give it away at peak load times. This not only reduces the load on heat generation but also optimizes the use of resources, which substantially reduces operating costs and increases the overall efficiency of the system.

Lyden et al. (2022) also established that heat energy storage devices play an important role in optimizing resource distribution and ensuring heat supply flexibility. They allow the integration of renewable energy sources, such as solar and geothermal, which can generate heat during the day but do not always coincide with peak consumption. With the help of storage devices, it is possible to save excess heat and use it at the right time, which contributes to more rational use of energy and reduces dependence on extracted resources (Kunitskiy et al. 1988; Kunitskii et al. 1990). As a result, the introduction of heat generation technologies not only helps to cope with peak loads but also improves the stability of heat supply systems in changing climatic conditions and growing demand for energy.

The introduction of heat energy storage devices and efficient peak load management really leads to an improvement in the stability and reliability of heat supply systems. The analysis showed that the use of storage devices not only helps to smooth out fluctuations in heat consumption but also helps to optimize the distribution of resources, which confirms the conclusions of the previous sections. These results highlight the need to integrate modern technologies into traditional heat supply systems, as well as the importance of further research and investment in innovative solutions to improve the efficiency and stability of energy systems. Thus, peak load management and the use of storage devices become key factors for achieving sustainable development in the field of heat supply.

The results also showed that automation of control processes for the heat supply system leads to a reduction in emissions of carbon dioxide and other polluting substances by 20–25%. These changes contribute to improving the quality of air and the general environmental situation in the regions where these technologies are used. The transition to RES and reducing dependence on fossil energy sources are positively affected by the environmental situation in the regions. In the context of global climate change, this becomes especially relevant since each measure of reducing the carbon footprint is important for a stable future.

Raihan and Tuspekova (2022) concluded that environmental sustainability is becoming one of the main goals of global energy policy, especially in the context of reducing greenhouse gas emissions and switching to renewable energy sources. This transition not only helps to reduce the negative impact on climate but also helps to improve air quality and public health. The use of RES, such as solar and wind turbines, can substantially reduce dependence on the types of fuel extracted and reduce carbon dioxide emissions (Kucher et al. 2022). The introduction of clean technologies and green initiatives in the energy sector is a necessary step towards achieving sustainable development, as they contribute to the creation of a more environmentally friendly and safe environment (Kudabayev et al. 2022; Kovach et al. 2024).

Zakari et al. (2022) stated that sustainable development requires a comprehensive approach to climate impact through energy, where integration plays a critical role. With the transition to more stable energy sources, it becomes possible not only to reduce emissions but also to ensure long-term energy security. The successful implementation of these changes must require the active participation of governments, business, and society in general. Investing in new technologies and infrastructure and developing effective policies and regulations will help escalate this process. Thus, environmental sustainability through reduced emissions and the transition to RES becomes the most important factor for achieving a sustainable future, contributing to a harmonious interaction between economic development and environmental protection.

When analyzing the results of the study, it becomes clear that the transition to renewable energy sources and focus on environmental stability are necessary steps to mitigate climate change and ensure sustainable development. The findings confirm that the integration of RES not only helps reduce greenhouse gas emissions but also opens up new opportunities for economic growth and the creation of jobs in green technologies. However, achieving substantial results requires joint efforts by the government, business, and society, as well as the development of clear strategies and measures of support, such as financial subsidies, tax benefits for implementing renewable energy sources, training, and qualification programs for specialists. It also encourages investment in innovative technologies to speed up the transition process and ensure its long-term efficiency. Thus, the results of the study emphasize the importance of a comprehensive approach to solving sustainability problems in the energy sector, which will contribute to the creation of a more secure and environmentally friendly future energy system.

In this way, the paper confirmed the need for a comprehensive approach to the development and implementation of automated control technologies for heat supply systems based on renewable energy sources. These technologies not only improve efficiency and reduce costs but also contribute to improving the environmental situation, which makes them relevant in modern conditions of energy policy and sustainable development.

Conclusions

In the course of research on the development of technologies for automated control of heat supply systems based on renewable energy sources, substantial results were achieved that confirm the efficiency and integrity of the implementation of such systems. One of the key conclusions was that the integration of various RES, such as solar collectors, geothermal installations, and biomass-based systems, substantially increases the flexibility and reliability of heat supply. Automated control systems demonstrated their ability to optimize the operating modes of these sources, allowing them to use their potential as efficiently as possible, depending on the time of day and weather conditions.

The study also showed that the introduction of intelligent data monitoring and analysis systems, including SCADA and IoT technologies, substantially increases the level of control and efficiency in responding to changes in equipment operation. This leads to lower operating costs and increased reliability of heat supply systems.

In addition, peak load management based on heat generation has become an important aspect that helps prevent overloads and improves the overall efficiency of the system. As a result, heat supply systems become more stable and adaptive to modern conditions associated with climate change and the depletion of traditional resources. Thus, the results of the study confirmed that automated control systems based on renewable energy sources can substantially improve the quality of heat supply, reduce the carbon footprint by 20–30%, and contribute to the sustainable development of energy systems in the future.

The limitation of this study was the lack of data on the long-term operation and economic efficiency of implemented technologies for automated control of heat supply systems based on renewable energy sources in various climatic conditions. It is necessary to conduct further research on the integration of new energy storage technologies, such as battery systems and heat storage facilities, and assess their impact on the efficiency and stability of automated heat supply systems based on renewable energy sources.

The Authors have no conflicts of interest to declare.

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Askhat Aliyev, Kanat Dyusenov, Dinara Japarova, Nurgul Yerbayeva, Kubaidolla Tulegenov

Rozwój technologii automatycznego sterowania systemami zaopatrzenia w ciepło opartymi na odnawialnych źródłach energii

Streszczenie

W artykule przedstawiono badanie, które przeprowadzono w celu optymalizacji technologii automatycznego sterowania systemami zaopatrzenia w ciepło opartymi na odnawialnych źródłach energii, które mogą zwiększyć efektywność energetyczną i zmniejszyć wpływ na środowisko. Badanie wykorzystuje metody uczenia maszynowego do przewidywania zużycia energii cieplnej, inteligentne systemy monitorowania i diagnostyki oraz algorytmy automatyzacji sterowania w celu optymalizacji działania systemów zaopatrzenia w ciepło opartych na odnawialnych źródłach energii. W wyniku badań przeanalizowano zautomatyzowany system zarządzania dostawami ciepła oparty na odnawialnych źródłach energii, który wykazał się wysoką efektywnością energetyczną i elastycznością w działaniu. Zastosowanie inteligentnych algorytmów pozwala na optymalizację dystrybucji energii cieplnej z uwzględnieniem wahań warunków pogodowych i obciążeń. Automatyzacja procesów sterowania zmniejsza koszty operacyjne i minimalizuje interwencję człowieka. Ustalono również, że integracja kolektorów słonecznych i źródeł geotermalnych w jednym systemie zmniejsza zależność od tradycyjnych źródeł energii i emisję dwutlenku węgla. Badanie pokazuje, że optymalizacja wykorzystania źródeł odnawialnych z automatycznym sterowaniem nie tylko zwiększa niezawodność dostaw ciepła, ale także przyczynia się do obniżenia kosztów operacyjnych w porównaniu z tradycyjnymi systemami. Potwierdza to perspektywy szerokiego zastosowania takich technologii w miejskich i przemysłowych systemach zaopatrzenia w ciepło. Ponadto stwierdzono, że zautomatyzowane systemy sterowania przyczyniają się do dokładniejszego prognozowania zapotrzebowania na energię cieplną, co zmniejsza ryzyko przeciążeń i przerw w dostawach ciepła. Badanie pokazuje również, że wykorzystanie połączonych źródeł energii odnawialnej, takich jak instalacje słoneczne i geotermalne, zwiększa ogólną wydajność systemu.

Słowa kluczowe: inteligentne algorytmy, kolektory słoneczne, redukcja rozładowania, warunki pogodowe i prognozowanie zapotrzebowania