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ARTIFICIAL INTELLIGENCE FOR ENVIRONMENTAL RISK MANAGEMENT IN AUTOMATED BOILER SYSTEMS

INTELIGÊNCIA ARTIFICIAL PARA GESTÃO DE RISCOS AMBIENTAIS EM SISTEMAS DE CALDEIRAS AUTOMATIZADOS

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Abstract

This paper examines the application of artificial intelligence in automated boiler systems with the aim of improving environmental risk management and reducing emissions generated during combustion processes. The study focuses on the use of neural network models as intelligent

Resumo

Este artigo examina a aplicação da inteligência artificial em sistemas automatizados de caldeiras com o objetivo de melhorar a gestão de riscos ambientais e reduzir as emissões geradas durante os processos de combustão. O estudo concentra-se no uso de modelos de redes monitoring and predictive control tools in industrial heating systems. The main objective of the research is to evaluate how artificial intelligence can support safer and more efficient operation of automated boilers while contributing to lower fuel consumption and reduced environmental impact. The research methodology is based on experimental data collected from an automated boiler system of the OZON 55 type equipped with sensor-based monitoring devices. Operational parameters such as temperature, air supply, fuel characteristics, and gas emissions were recorded and analyzed using recurrent neural network models designed to predict deviations in combustion behavior. The obtained results indicate that neural network–based predictive monitoring can detect anomalies in operational parameters at an early stage and enable timely adjustments of combustion conditions. Such improvements contribute to increased operational safety, improved fuel efficiency, and lower emissions of harmful gases. The findings suggest that the integration of artificial intelligence into automated boiler systems represents an effective technological approach for enhancing environmental protection, improving risk management, and supporting more sustainable energy use in industrial heating systems.

Keywords: Neural Networks. Risk Management. Automated Boiler Systems. Environmental Protection.

neurais como ferramentas inteligentes de monitoramento e controle preditivo em sistemas industriais de aquecimento. O principal objetivo da pesquisa é avaliar de que forma a inteligência artificial pode contribuir para uma operação mais segura e eficiente de caldeiras automatizadas, ao mesmo tempo em que promove a redução do consumo de combustível e dos impactos ambientais. A metodologia de pesquisa baseia-se na análise de dados experimentais coletados a partir de um sistema de caldeira automatizada do tipo OZON 55, equipado com sensores de monitoramento. Parâmetros operacionais como temperatura, fornecimento de ar, características do combustível e emissões gasosas foram registrados e analisados por meio de modelos de redes neurais recorrentes desenvolvidos para prever desvios no comportamento da combustão. Os resultados obtidos indicam que o monitoramento preditivo baseado em redes neurais permite detectar anomalias nos parâmetros operacionais em estágio inicial e possibilita ajustes oportunos nas condições de combustão. Essas melhorias contribuem para maior segurança operacional, melhor eficiência no uso do combustível e redução das emissões de gases nocivos. Os resultados sugerem que a integração da inteligência artificial em sistemas automatizados de caldeiras representa uma abordagem tecnológica eficaz para fortalecer a proteção ambiental, aprimorar a gestão de riscos e promover o uso mais sustentável da energia em sistemas industriais de aquecimento.

Palavras-chave: *Redes Neurais. Gestão de Riscos. Sistemas Automatizados de Caldeiras. Proteção Ambiental.*

1 INTRODUCTION

The increasing integration of artificial intelligence into industrial systems is transforming the way complex technological processes are monitored and controlled. In energy systems that rely on combustion processes, maintaining stable operating conditions is essential for ensuring safety, efficiency, and environmental sustainability. Automated boiler systems represent an important component of modern heating infrastructure, but their operation involves multiple technical parameters whose variations may influence both system reliability and emission levels. In this context, artificial intelligence offers new possibilities for improving the monitoring and control of industrial combustion systems. By analyzing large volumes of operational data, intelligent models can identify patterns in system behavior and support predictive management of combustion processes. Such approaches enable earlier detection of operational deviations and allow more precise control of key parameters that influence fuel consumption and emission levels. The growing use of automated heating technologies also raises broader questions related to environmental protection, energy efficiency, and risk management. Improving the performance of combustion systems is not only a technical challenge but also an important aspect of sustainable energy use. The application of artificial intelligence in automated boiler systems therefore represents a promising approach for improving operational reliability while simultaneously supporting environmental protection and responsible energy management.

2 RISK MANAGEMENT AND INTELLIGENT MONITORING IN AUTOMATED BOILER SYSTEMS

Risk management in industrial systems is a key factor in ensuring the safety, efficiency, and reliability of their operation. Boilers with automatic firing represent complex electro-mechanical energy systems in which operational stability depends on the coordinated functioning of multiple technical components and control processes (POPOVIĆ et al., 2024). Due to the high temperatures, pressures, and continuous combustion processes involved, the operation of such systems inherently carries certain safety and environmental risks (POPOVIĆ et al., 2023). Consequently, effective risk management becomes particularly important in order to prevent system failures, ensure safe operation, and maintain optimal performance (JEVTIC et al., 2025).

Improving boiler efficiency through controlled operation can lead to significant energy savings and a reduction in pollutant emissions (POPOVIĆ et al., 2025). Regular maintenance procedures contribute to the stability of system performance and help reduce operational costs. However, the recommended maintenance intervals differ depending on the type of boiler and operational conditions. For this reason, the implementation of advanced early-detection systems based on intelligent algorithms has become increasingly important for improving operational efficiency, system reliability, and overall safety (MENG et al., 2021).

Boiler systems operate under high temperatures and pressures, and inadequate control of these parameters can lead to serious technical failures or accidents. Risk management in such systems therefore involves the early identification of potential hazards, including overheating caused by equipment malfunctions or irregularities in fuel quality and supply. In this context, artificial intelligence technologies, particularly neural network models, provide new possibilities for improving risk management in automated boiler systems. By analyzing large volumes of data generated by monitoring sensors, neural networks can detect anomalies, predict potential failures, and enable timely preventive interventions (POPOVIĆ et al., 2025). Furthermore, the application of intelligent models in combustion optimization and temperature control can significantly reduce the likelihood of improper operation while simultaneously improving system efficiency. Such improvements contribute to lower energy consumption and reduced environmental impact.

Recent research increasingly emphasizes the role of machine learning and deep learning methods in fault detection and predictive maintenance of industrial energy systems. These approaches enable earlier diagnosis of system failures, improved operational planning, and reduced downtime (GUO et al., 2018). In order to minimize interruptions in operation and decrease maintenance costs, modern boiler manufacturers have introduced advanced fault detection and diagnosis techniques. These techniques can generally be classified into three categories: model-based methods (CHEN; PATTON, 2012) (DING, 2008), data-driven approaches (XU et al., 2019), and statistical methods (GANGSAR; TIWARI, 2020) (KHALID et al., 2023). Model-based techniques can provide reliable solutions for relatively simple systems but often become difficult to apply to complex industrial processes due to the high computational resources required. As a result, data-driven and statistical approaches have gained increasing attention. These methods include the use of machine learning algorithms (KHALID et al., 2020), artificial neural networks (ANN) (ALI et al., 2015), and multivariate statistical techniques such as principal component analysis (PCA) (ZHOU et al., 2020). Such methods rely on real-time data obtained from monitoring and data acquisition systems to detect irregularities and diagnose operational faults. Boiler installations are typically equipped with acoustic emission sensors (CHEMWENO; PINTELON, 2020) (RAZMI-FAROOJI et al., 2019) and various process monitoring instruments (SOHAIB; KIM, 2019), which generate large datasets suitable for intelligent analysis and predictive control (RANDJELIVIC et al., 2025).

In parallel with technological development, the global community has adopted numerous international instruments aimed at environmental protection and climate change mitigation. Under the framework of the United Nations, several international agreements have been established to regulate environmental protection policies and reduce greenhouse gas emissions. One of the key approaches identified in the Kyoto Protocol to the United Nations Framework Convention on Climate Change is the continuous research and development of renewable energy sources, carbon sequestration technologies, and other advanced environmentally friendly technologies (UNITED NATIONS, 1998). Within this context, innovative digital and intelligent management systems are increasingly recognized as important components of environmentally sustainable technological solutions (UNITED NATIONS, 2004).

The application of intelligent control models in industrial combustion systems contributes to more efficient fuel utilization and reduced consumption of pellets or fossil fuels. Consequently, the overall quantity of combustion products is reduced, leading to lower emissions of carbon dioxide and other greenhouse gases. Advanced environmentally friendly technologies therefore do not include only physical infrastructure but also digital systems capable of optimizing combustion processes and improving operational efficiency. Artificial intelligence applied to industrial combustion systems represents a modern ecological technology that enables emission reduction directly at the source. By improving combustion efficiency and enabling predictive operational control, such systems reduce the need for additional carbon capture technologies while simultaneously supporting compliance with environmental protection regulations.

3 APPLICATION OF NEURAL NETWORKS IN OZON 55 TYPE BOILERS

Neural networks have a wide range of applications, including complex security systems, everyday technological solutions that improve quality of life, and various industrial processes (SOHAIB; KIM, 2019). Among the different neural network architectures, recurrent neural networks (RNNs) are particularly suitable for analyzing time-series and sequential data because they retain information about previous states of the system (SOHAIB et al., 2019) (POPOVIĆ et al., 2023a) (GROSSBERG, 2013) (MEDSKER; JAIN, 2001) (YU et al., 2019). This characteristic makes them especially useful for monitoring and controlling industrial processes in which system behavior depends on previous operational conditions.

In automated boiler systems, RNN models can be used to control combustion parameters by analyzing sequences of operational data (ALVES, 2024). The basic architecture of a recurrent neural network consists of recurrent nodes that receive both the current input signal and feedback from the previous hidden state. This mechanism enables the network to capture temporal dependencies and adapt its predictions based on previously observed data. However, standard RNN architectures encounter limitations when dealing with long-term dependencies due to the vanishing gradient problem during training (STAUDEMEYER; MORRIS, 2019) (MOHD NOOR et al., 2026).

To overcome this limitation, Long Short-Term Memory (LSTM) networks were introduced as an advanced form of recurrent neural networks. LSTM architectures include specialized memory cells that allow the network to retain information over longer time periods (SHERSTINSKY, 2020). The main components of an LSTM network include input gates, which regulate what new information is stored in the memory cell; forget gates, which determine what information should be discarded; and output gates, which control what portion of the stored information is used as output at a given time step (SAK et al., 2014). Such mechanisms allow LSTM models to maintain relevant information from previous states of the system. This capability is particularly valuable in complex combustion processes where variations in fuel quality, air supply, or pressure conditions can significantly influence system performance (BIANCHI et al., 2017).

In this research, RNN and LSTM models were applied to predict key combustion parameters in automated boiler systems. The predictive models analyze sequences of sensor-generated data, including temperature, pressure, air flow, and fuel supply parameters. Based on these predictions, the system can dynamically adjust operational settings in real time, ensuring efficient combustion even when fuel quality or environmental conditions vary.

To investigate these possibilities, experimental data were collected from an OZON 55 type automated boiler. For this purpose, an Arduino Uno microcontroller platform was used as the central data acquisition unit. The system was connected to several sensors, including type K thermocouples, humidity sensors, and gas detection sensors. Temperature probes were installed at key monitoring points, including the combustion chamber area, the smoke channel approximately one meter above the exhaust outlet, and locations measuring both internal and external air temperature. Humidity sensors were used to monitor the relative humidity of ambient air and pellet fuel, while gas sensors installed in the chimney measured the concentration and composition of combustion gases.

By May 2022, the experimental system underwent several hardware and software modifications in order to improve measurement accuracy and ensure more reliable data acquisition. After these improvements were implemented, systematic experimental measurements for the research were conducted starting in October 2022 (POPOVIĆ et al., 2024a).

In parallel with the construction of the measuring system, the invention of the mathematical model began. By searching for possible mathematical models, we came to the conclusion that, the model to be used is multivariate and non-linear. On the other hand, the nature of the collected data in the form of time series imposes a dynamical discrete time model for this system. For this reason, the required model is of the following form

$$y(x) = f\big(Y(t, D_y), X_1(t, D_1), X_2(t, D_2) \ldots\big) \tag{1}$$

where

> $f: \mathbb{R}^{D_y + D_{x_1} + D_{x_2} + \cdots} \rightarrow \mathbb{R}$ is a continuous non-linear map representing the required model. The problem solved initially is the determination of the dimensions of vectors $Y, X_1, X_2, \ldots$ $i.e. D_Y, D_1, D_2, \ldots$which are the orders of the models autoregressive and transregressive dependencies of the system. The method used for this has been described in Djukic work (ĐUKIĆ, 1997). The essence of this method consists in computation of probability that the collected data are produced by a system whose model is a linear map.

The synaptic weights and activation parameters of the neural network, represented by matrices, were optimized using the back-propagation algorithm based on the gradient of the error function. This optimization process enables the network to adjust its internal parameters in order to minimize prediction errors and improve model performance. The system is structured as a recurrent neural network designed to process sequential data. In this architecture, measured values obtained from the monitoring sensors are introduced as input data, and the network processes the sequence step by step. At each time step, the model receives the current input vector together with the hidden state generated in the previous step. Based on these inputs, a new hidden state is computed through linear transformations defined by the network weight matrices (POPOVIĆ et al., 2022) .

An activation function is then applied to the resulting values, producing the updated hidden state of the network. This hidden state serves as an internal representation of the system's previous operational conditions and enables the network to capture temporal dependencies within the data sequence. When new measurements are introduced, the same transformation process is repeated: the network combines the new input data with the current hidden state, applies the corresponding transformations and activation functions, and generates an updated internal state. Through this iterative process, the recurrent neural network gradually processes the entire sequence of measured values. At each step, the hidden state can be used to generate output values, which represent the predicted operational parameters of the combustion system.

4 ANALYSIS OF THE OBTAINED VALUES

The discussion of the obtained results requires a brief overview of the training configuration used for the neural network model. The training phase incorporates several parameters that influence the stability, convergence, and predictive accuracy of the model. The number of epochs defines how many times the entire dataset passes through the neural network during training. In this study, the number of epochs was set to 100 in order to allow sufficient learning while avoiding excessive computational cost. The batch size determines the number of samples processed before updating the model parameters. Due to the large amount of collected operational data, the batch size was set to 256, enabling efficient processing and stable gradient estimation (POPOVIĆ et al., 2023a).

In order to improve model convergence and prevent overfitting, two optimization strategies were implemented. The first is the learning rate reduction callback, which dynamically decreases the learning rate when model performance stagnates, enabling more stable weight updates. The second is the early stopping mechanism, which terminates the training process when no improvement is observed over seven consecutive epochs. In such cases, the weights from the best-performing epoch are restored and used for further model evaluation. This training configuration ensured stable convergence and reliable parameter estimation. After the training phase, the model predictions were compared with experimentally measured values obtained from the sensor-based monitoring system installed on the boiler. The results demonstrate that the predicted values closely follow the trends of the measured operational parameters, although minor deviations are present.

As shown in Figure 1, a comparison between measured and predicted CO emission values obtained using three different models indicates that all models are capable of capturing the overall trend of CO emissions. However, differences in prediction accuracy are noticeable. Among the analyzed approaches, the neural network–based model demonstrates superior performance, providing more consistent and reliable tracking of emission variations, particularly under dynamically changing operating conditions.

Figure 1

Comparison between measured and predicted CO emission values obtained using three different models

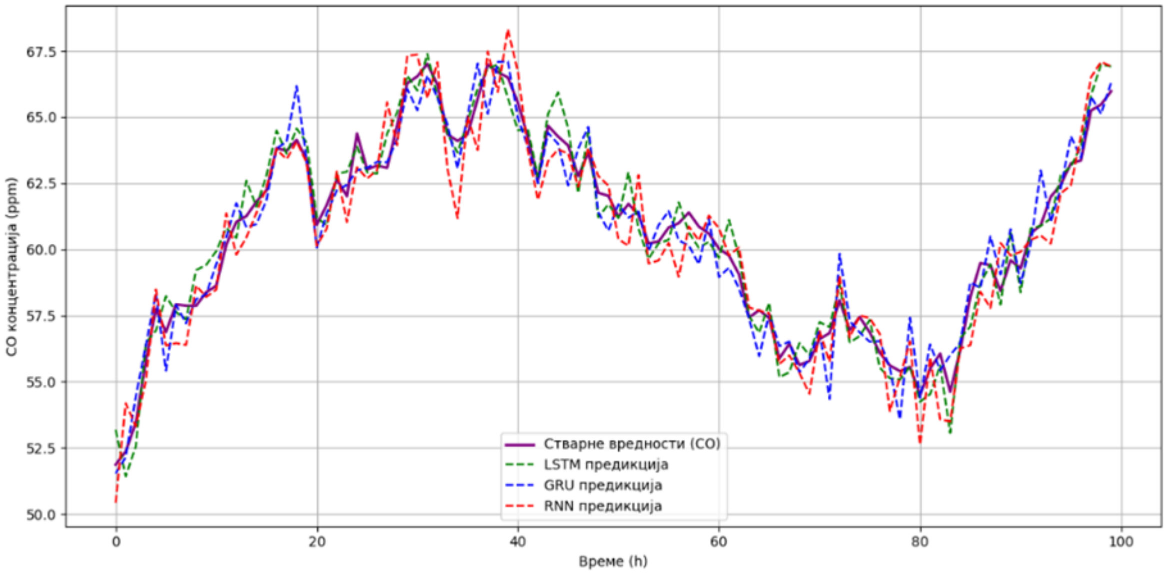
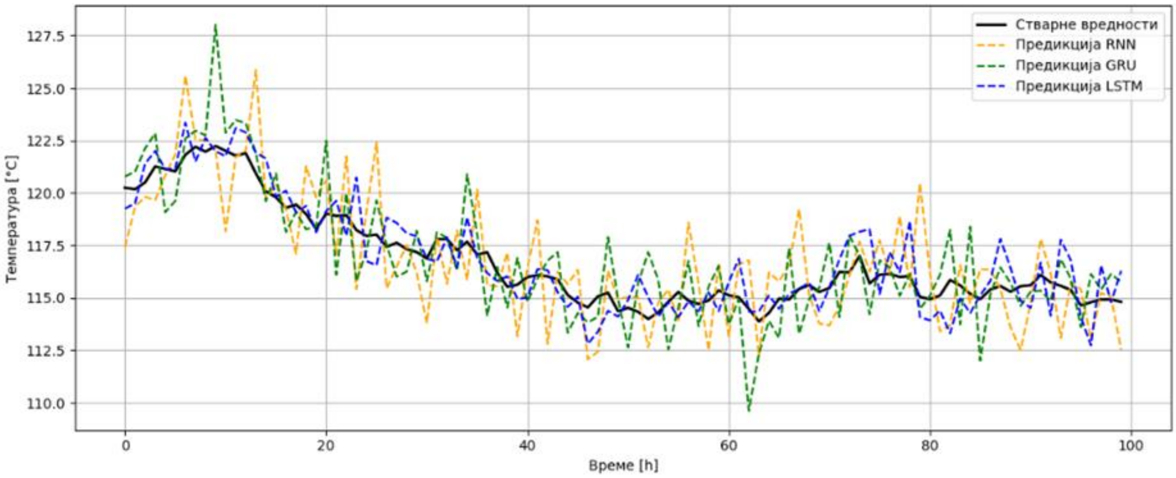


Figure 2

Comparative analysis of actual and predicted flue gas temperature values



As shown in Figure 2, a comparative analysis of actual and predicted flue gas temperature values indicates that the predicted values closely follow the measured data, confirming the model's ability to capture the dynamic behavior of the combustion process. Although minor discrepancies are present, these deviations can be attributed to external factors such as variations in fuel quality and environmental conditions.

Furthermore, the analysis shows that as the number of measurement points increases, the prediction error decreases, indicating that model performance improves with larger datasets. Overall, the obtained results confirm that the neural network model is capable of accurately representing key combustion parameters and supporting reliable predictive monitoring of automated boiler systems.

One of the main challenges in developing the predictive model is the relatively short operational period of the boiler during the experimental phase. This limitation is primarily caused by variable weather conditions, which affect the frequency and duration of boiler operation. Future improvements of the model should therefore include additional parameters related to climatic and environmental conditions in the microregion where the measurements are conducted. From a practical perspective, the implementation of intelligent control systems requires certain hardware and software modifications of conventional boilers. However, for boilers of the OZON series, which typically operate within a power range between 25 kW and 75 kW, the implementation of such systems can be economically justified. The required investment is relatively modest and can be offset by the annual energy savings achieved through improved combustion efficiency.

OZON boilers are already equipped with a microcontroller and a set of sensors that monitor key operational parameters such as exhaust air temperature and flue gas temperature. Therefore, only minimal additional hardware is required for implementing the proposed monitoring system. For example, the installation of a humidity and temperature sensor inside the pellet storage tank (such as the DHT11 sensor) and a particulate matter sensor (PM2.5) can significantly improve data collection. Once the additional sensors are integrated, the system can operate using upgraded control software that incorporates neural network–based predictive models.

The results obtained in this study demonstrate that the integration of artificial intelligence into automated boiler systems can contribute to more stable operation, improved predictive monitoring, and enhanced efficiency of combustion processes. By enabling earlier detection of anomalies and more precise control of operational parameters, such systems can support both safer industrial operation and reduced environmental impact through improved fuel utilization and lower emissions.

5 ENVIRONMENTAL AND REGULATORY IMPLICATIONS OF ARTIFICIAL INTELLIGENCE IN AUTOMATED BOILER SYSTEMS

The results obtained in this research demonstrate that artificial intelligence can significantly improve the monitoring and control of automated boiler systems. By analyzing operational data collected from sensor-based monitoring systems installed on the OZON 55 boiler, neural network models were able to identify patterns in combustion behavior and predict operational deviations. Such predictive capabilities enable earlier detection of anomalies in key combustion parameters, including temperature, air supply, and fuel flow, allowing corrective actions to be implemented before critical failures occur. In this way, predictive monitoring contributes to increased operational safety, system reliability, and more stable control of combustion processes. In addition to improving system reliability, the predictive model developed in this research enables more efficient adjustment of combustion parameters. By continuously analyzing sensor data and adapting system responses in real time, the artificial intelligence model helps maintain optimal combustion conditions even when fuel quality or environmental conditions vary. Improved combustion efficiency leads to reduced fuel consumption and a decrease in the total volume of combustion by-products released into the atmosphere. These technological improvements are directly relevant to contemporary environmental protection policies. In accordance with the Kyoto Protocol to the United Nations Framework Convention on Climate Change, technological innovation plays a key role in reducing greenhouse gas emissions (UNITED NATIONS, 1998) (UNITED NATIONS, 2004). Intelligent monitoring and control systems, such as the neural network model developed in this research, can therefore be considered a form of advanced environmentally sound technology that contributes to emission reduction through improved energy efficiency and optimized industrial processes.

The proposed method is also consistent with the principles of modern regulatory frameworks governing artificial intelligence and industrial safety. Within the European Union, the Artificial Intelligence Act establishes a risk-based regulatory framework that requires AI systems used in industrial infrastructure to ensure reliability, transparency, and effective risk management (EUROPEAN UNION, 2016). Predictive monitoring approaches such as the one presented in this study contribute to these requirements by enabling continuous supervision of system performance, early detection of anomalies, and preventive risk mitigation. Similarly, the Machinery Regulation (EU) 2023/1230 highlights the importance of ensuring predictable and safe behavior of automated machines, particularly in cases of malfunction or unexpected operational conditions(EUROPEAN UNION, 2023) (EUROPEAN UNION, 2024a). By providing early warnings and predictive insights into system behavior, neural network–based monitoring systems can support safer operation of industrial equipment and reduce the probability of hazardous events. In addition, the improved monitoring, documentation, and traceability of operational data enabled by artificial intelligence systems may contribute to greater transparency and accountability in industrial processes. Such capabilities are increasingly relevant within emerging legal frameworks concerning artificial intelligence liability and product responsibility, where detailed operational data may play an important role in assessing system performance and determining potential liability (EUROPEAN UNION, 2024b) (EUROPEAN COMMISSION, 2022).

These considerations illustrate that the integration of artificial intelligence into automated boiler systems has implications that extend beyond purely technical improvements, touching upon broader issues of environmental protection, industrial safety, and regulatory governance.

6 CONCLUSION

The growing expansion of automated boiler systems, combined with increasing concerns regarding environmental pollution and energy efficiency, highlights the importance of developing intelligent technological solutions for safer and more sustainable industrial energy systems. Improving the efficiency of fuel utilization in combustion processes not only reduces the consumption of biomass and fossil fuels but also significantly decreases the emission of harmful gases released into the atmosphere. In this way, more efficient combustion management contributes to environmental protection and to improving overall living conditions. The results presented in this research demonstrate that the integration of artificial intelligence, particularly neural network models, can significantly enhance the monitoring and control of automated boiler systems. By analyzing operational data obtained from sensor-based monitoring systems, neural networks enable predictive identification of anomalies in combustion parameters and allow timely adjustments of system operation. Such predictive capabilities improve operational stability, reduce the probability of system failures, and support more efficient fuel utilization.

One of the key advantages of the proposed approach lies in the ability of neural network models to predict critical operational parameters, including combustion chamber temperature, pellet energy value, and oxygen concentration in the air–fuel mixture. Accurate prediction of these parameters enables more precise control of the combustion process, leading to improved heating system performance and reduced fuel consumption. At the same time, the optimization of combustion parameters contributes to lowering greenhouse gas emissions and minimizing the environmental impact of heating systems. Beyond its technical contribution, the proposed approach also has broader implications for environmental risk management and regulatory compliance. Intelligent monitoring and predictive control systems support the objectives of international climate policies aimed at reducing greenhouse gas emissions, while also aligning with emerging regulatory frameworks governing artificial intelligence, industrial safety, and environmental protection.

In this context, artificial intelligence–based monitoring systems should not be viewed solely as technological tools for automation, but as instruments for improving environmental sustainability, operational safety, and responsible risk management in industrial energy systems. The integration of such technologies represents an important step toward more efficient, safer, and environmentally responsible operation of automated boiler systems. Future research should focus on expanding the dataset used for model training, incorporating additional environmental and climatic parameters, and further improving predictive accuracy in order to enhance the reliability and practical applicability of intelligent control systems in industrial combustion processes.

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REFERENCES

ALI, J. B.; FNAIECH, N.; SAIDI, L.; CHEBEL-MORELLO, B.; FNAIECH, F. Application of empirical mode decomposition and artificial neural network for automatic bearing fault diagnosis based on vibration signals. *Applied Acoustics*, v. 89, p. 16–27, 2015.

ALVES, F. L. T. T. O direito ao meio ambiente e a litigância climática no ordenamento jurídico brasileiro. 2024.

BIANCHI, F. M.; MAIORINO, E.; KAMPFFMEYER, M. C.; RIZZI, A.; JENSSEN, R. Recurrent neural network architectures. In: Recurrent neural networks for short-term load forecasting. 2017. p. 23–29.

CHEMWENO, P. K.; PINTELON, L. Towards e-maintenance: an exploration approach for aircraft maintenance data. In: Applications and challenges of maintenance and safety engineering in Industry 4.0. Hershey: IGI Global, 2020. p. 189–212.

CHEN, J.; PATTON, R. J. Robust model-based fault diagnosis for dynamic systems. Berlin: Springer, 2012.

DING, S. X. Model-based fault diagnosis techniques: design schemes, algorithms, and tools. Berlin: Springer, 2008.

ĐUKIĆ, D. Modelisation des systemes non lineaires. Lausanne: EPFL, 1997.

EUROPEAN COMMISSION. Proposal for a directive on adapting non-contractual civil liability rules to artificial intelligence (AI Liability Directive). Brussels, 2022. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022PC0496. Access on: Mar. 24, 2026.

EUROPEAN UNION. Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016. Official Journal of the European Union, 2016. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0679. Access on: Mar. 24, 2026.

EUROPEAN UNION. Regulation (EU) 2023/1230 of the European Parliament and of the Council of 14 June 2023. Official Journal of the European Union, 2023. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1230. Access on: Mar. 24, 2026.

EUROPEAN UNION. Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024. Official Journal of the European Union, 2024. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401689. Access on: Mar. 24, 2026.

EUROPEAN UNION. Directive (EU) 2024/2853 on liability for defective products. Official Journal of the European Union, 2024. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202402853. Access on: Mar. 24, 2026.

GAO, Z.; CECATI, C.; DING, S. X. A survey of fault diagnosis and fault-tolerant techniques—part I. *IEEE Transactions on Industrial Electronics*, v. 62, p. 3757–376, 2015.

GANGSAR, P.; TIWARI, R. Signal based condition monitoring techniques for fault detection and diagnosis of induction motors. *Mechanical Systems and Signal Processing*, v. 144, p. 106908, 2020.

GROSSBERG, S. Recurrent neural networks. *Scholarpedia*, v. 8, n. 2, p. 1888, 2013.

GUO, Y.; TAN, Z.; CHEN, H.; LI, G.; WANG, J.; HUANG, R.; AHMAD, T. Deep learning-based fault diagnosis. *Applied Energy*, v. 225, p. 732–745, 2018.

IOFFE, S.; SZEGEDY, C. Batch normalization: accelerating deep network training. arXiv preprint, 2015. Available from: https://arxiv.org/abs/1502.0367. Access on: Mar. 24, 2026.

JEVTIĆ, R.; VUČKOVIĆ, D.; RANĐELOVIĆ, M.; JANKOVIĆ, I.; LUKIĆ, J.; NIČKOVIĆ, J. Simulation of evacuation as a consequence of Industry 4.0. Belgrade, 2025.

KHALID, S.; LIM, W.; KIM, H. S.; OH, Y. T.; YOUN, B. D.; KIM, H. S.; BAE, Y. C. Intelligent steam power plant boiler waterwall tube leakage detection. *Sensors*, v. 20, p. 6356, 2020.

KHALID, S.; SONG, J.; RAOUF, I.; KIM, H. S. Advances in fault detection and diagnosis. *Mathematics*, v. 11, n. 8, p. 1767, 2023.

MEDSKER, L. R.; JAIN, L. Recurrent neural networks: design and applications. Boca Raton: CRC Press, 2001.

MENG, Y.; WU, X.; OLADEJO, J.; DONG, X.; ZHANG, Z.; DENG, J.; PANG, C. H. Application of machine learning in industrial boilers. *ChemBioEng Reviews*, v. 8, n. 5, p. 535–544, 2021.

MOHD NOOR, N. A. W.; ABD. RAHMAN, N.; MOHD ALI, J.; YUSUP, S. Advancing sustainability and efficiency in coal-fired boilers. *International Journal of Energy Research*, 2026.

POPOVIĆ, S.; DENIĆ, N.; STOJANOVIĆ, J.; ĐUKIĆ, D.; POPOVIĆ, S. Đ. Innovations in risk management: integration of neural networks in boilers with automatic firing. PaKSoM 2024, 2024.

POPOVIĆ, S.; ĐUKIĆ, D.; ĐUKIĆ POPOVIĆ, S.; KOPANJA, L. Preliminary research on neural networks in combustion control. In: Virtual International Conference on Science Technology and Management in Energy, 2023. Proceedings… p. 299–303.

POPOVIĆ, S.; POPOVIĆ, S. D.; DENIĆ, N.; ĐUKIĆ, D.; STOJANOVIĆ, J. Risk management innovations through neural network integration. *Journal of Soft Computing and Decision Analytics*, v. 3, n. 1, p. 129–135, 2025.

POPOVIĆ, S.; VIDUKA, D.; BAŠIĆ, A.; DIMIĆ, V.; ĐUKIĆ, D.; NIKOLIĆ, V.; STOKIĆ, A. Optimization of artificial intelligence algorithm selection. *Electronics*, v. 14, n. 3, p. 562, 2025.

RANĐELOVIĆ, M.; JEVTIĆ, R.; NIČKOVIĆ, J.; VUČKOVIĆ, D. The model of smart education system. Belgrade, 2025.

RAZMI-FAROOJI, A.; KROPSU-VEHKAPERÄ, H.; HÄRKÖNEN, J.; HAAPASALO, H. Data management in e-maintenance. *Journal of Quality in Maintenance Engineering*, v. 25, p. 378–396, 2019.

SAK, H.; SENIOR, A. W.; BEAUFAYS, F. Long short-term memory recurrent neural network architectures. 2014.

SHERSTINSKY, A. Fundamentals of recurrent neural networks. *Physica D*, v. 404, p. 132306, 2020.

SOHAIB, M.; ISLAM, M.; KIM, J.; JEON, D. C.; KIM, J. M. Leakage detection of a spherical water storage tank. *Applied Sciences*, v. 9, p. 196, 2019.

SOHAIB, M.; KIM, J. M. Data driven leakage detection. *Applied Sciences*, v. 9, p. 2450, 2019.

STAUDEMEYER, R. C.; MORRIS, E. R. Understanding LSTM. arXiv preprint, 2019. Available from: https://arxiv.org/abs/1909.09586. Access on: Mar. 24, 2026.

UNITED NATIONS. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Kyoto, 1998. Available from: https://unfccc.int/resource/docs/convkp/kpeng.pdf. Access on: Mar. 24, 2026.

UNITED NATIONS. Buenos Aires programme of work on adaptation and response measures. Buenos Aires, 2004. Available from: https://unfccc.int/sites/default/files/resource/docs/cop10/l16.pdf. Access on: Mar. 24, 2026.

XAVIER, J. V. B.; MOURA, E. P.; BARRETO, G. Data-driven prediction of silicon content. Available from: https://ssrn.com/abstract=6293241. Access on: Mar. 24, 2026.

XU, G.; LIU, M.; WANG, J.; MA, Y.; WANG, J.; LI, F.; SHEN, W. Data-driven fault diagnostics. In: IEEE Conference, 2019. Proceedings… p. 103–108.

YU, Y.; SI, X.; HU, C.; ZHANG, J. A review of recurrent neural networks. *Neural Computation*, v. 31, n. 7, p. 1235–1270, 2019.

ZHOU, P.; ZHANG, R.; XIE, J.; LIU, J.; WANG, H.; CHAI, T. Data-driven monitoring of furnace conditions. *IEEE Transactions on Industrial Electronics*, v. 68, p. 622–631, 2020.

Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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