Machinery & Energetics
Vol. 15, No. 3. 2024

Journal homepage:
https://technicalscience.com.ua/en

UDC 662.6/.9:504.06
DOI: 10.31548/machinery/3.2024.84

Taras Kravets*

PhD in Technical Sciences, Associate Professor
Lviv Polytechnic National University
79000, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0002-7186-926X

Mykhailo Semerak

Doctor of Technical Sciences, Professor
Lviv Polytechnic National University
79000, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0002-7582-6398

Igor Galyanchuk

PhD in Technical Sciences, Senior Lecturer
Lviv Polytechnic National University
79000, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0001-6242-1749

Oksana Yurasova

PhD in Technical Sciences, Senior Lecturer
Lviv Polytechnic National University
79000, 12 Stepan Bandera Str., Lviv, Ukraine
https://orcid.org/0000-0001-9930-9152

Andrii Kharchuk

Associate Professor
Lviv State University of Life Safety
79007, 35 Kleparivska Str., Lviv, Ukraine
https://orcid.org/0009-0000-8783-0522

Analytical study on improving the efficiency and environmental friendliness of solid organic fuels

Abstract. The purpose of this study was to analyse methods of increasing the efficiency and environmental friendliness of the use of solid organic fuels (SOF) in electricity generation. This study employed a comprehensive approach to the analysis and optimisation of technological processes, operational systems, and environmental aspects of the use of SOF. The study found that the use of modern technologies, such as gasification and pyrolysis, considerably increases the efficiency of converting SOF into electricity. Optimisation of boiler and turbine designs and automation of fuel supply systems helps to reduce energy losses and improve overall system efficiency. It was found that the use of new materials for boilers increases their resistance to corrosion and erosion, which extends the service life of the equipment. The study also showed that the introduction of gas cleaning and secondary combustion systems significantly reduces emissions of harmful substances, which improves environmental performance. An analysis of ash utilisation opportunities showed that

Article's History: Received: 29.03.2024; Revised: 12.07.2024; Accepted: 15.08.2024.

Suggested Citation:
Kravets, T., Semerak, M., Galyanchuk, I., Yurasova, O., & Kharchuk, A. (2024). Analytical study on improving the efficiency and environmental friendliness of solid organic fuels. *Machinery & Energetics,* 15(3), 84-93. doi: 10.31548/machinery/3.2024.84.

*Corresponding author

its use as a fertiliser or construction material is a promising area. The study proved that an integrated approach to the use of SOF can substantially increase their efficiency and environmental friendliness. The findings of the study suggest that the use of innovative methods of combustion process control allows achieving more stable and efficient power generation. It was proved that the introduction of automated monitoring and control systems reduces operating costs and increases the reliability of equipment. The study also found that the use of advanced analytical tools to predict equipment wear and tear allows for prompt preventive maintenance, which further increases the efficiency and duration of uninterrupted operation of energy systems

Keywords: solid organic fuels; gasification; pyrolysis; electricity; corrosion; erosion; ecology

INTRODUCTION

In the context of global climate change, accompanied by an increase in the average global temperature, melting glaciers, and an increase in the frequency of extreme weather events, the global community is facing serious challenges in reducing the adverse environmental impact. One of the main tasks in this context is to ensure a stable supply of energy necessary to support the vital activity of society, industry, and transport, while minimising greenhouse gas emissions that cause climate change. Considering this, the search for efficient and environmentally friendly energy sources has become particularly important. Solid organic fuels (SOF), including wood, pellets, straw, and other biomass, have gained considerable attention as promising alternative energy sources that can partially replace fossil fuels such as coal, oil, and natural gas (Sivabalan *et al.*, 2021). Biomass, being a renewable resource, can be reproduced in a relatively short time, making it a more environmentally friendly alternative to fossil fuels, which are limited and declining. The use of SOF not only reduces dependence on conventional energy resources, but also helps to reduce greenhouse gas emissions, as the plants that serve as a source of biomass absorb carbon dioxide from the atmosphere as they grow (Palianytsia *et al.*, 2014). The need for this study is driven by current challenges in the energy sector, such as growing global energy demand, limited fossil fuel resources, and the need to reduce greenhouse gas emissions. Due to their renewable characteristics, SOF can play a key role in the transition to more environmentally friendly energy sources. However, the efficient use of SOF requires the improvement of existing processing and combustion technologies, as well as the optimisation of mechanical systems to achieve maximum environmental and economic benefits.

An analysis of the problem of increasing the efficiency and environmental friendliness of the use of SOF points to numerous studies that cover various aspects of this topic. Z. Hameed *et al.* (2021) showed that innovative gasification methods can significantly increase the calorific value of fuel and reduce pollutant emissions. They also investigated how these methods contribute to a more complete utilisation of biomass energy, increasing the overall efficiency of the process. G. Mong *et al.* (2022) reviewed pyrolysis technologies, focusing on reducing waste and improving the quality of end products. Their study also highlighted the significance of temperature control to achieve best results in pyrolysis plants. M. Soleh *et al.* (2023) highlighted the impact of different types of biomass on the efficiency of the combustion process, emphasising the significance of proper fuel preparation. Furthermore, their results showed that biomass preparation influences the reduction of harmful emissions during combustion. L. Martinez-Valencia *et al.* (2021) focuses on the automation of fuel supply systems, which reduces maintenance costs and increases process stability. They also noted that automation contributes to more accurate fuel dispensing, which reduces energy losses. Further research by C. Tang *et al.* (2022) revealed the benefits of using new materials for boiler structures that considerably increase their durability and efficiency. They also pointed to the reduction of corrosion processes due to the use of these materials, which extends the service life of the equipment. A. Islam *et al.* (2023) made a significant contribution to the development of gas purification methods that reduce emissions of harmful particles and improve environmental performance. Their research also focused on the effectiveness of different filter media in cleaning processes. J. Odzijewicz *et al.* (2022) focused on ash utilisation technologies, showing how these by-products can be used as fertilisers or construction materials. They also investigated the economic benefits of such approaches, which help reduce waste. F. Mustafa *et al.* (2023) considered aspects of combustion monitoring and control, focusing on the significance of automated systems to improve efficiency and reduce costs. The researchers also stressed that these systems ensure prompt detection and elimination of deviations in the operation of plants. L. Peiró *et al.* (2022) showed the promise of innovative approaches to integrating biomass into existing energy systems, which can improve their overall efficiency and environmental performance. They also noted that such approaches can contribute to greater flexibility of energy systems in the use of different fuels. Overall, while these studies make a valuable contribution to understanding the efficiency and environmental friendliness of using SOF, there are gaps that need to be further explored, particularly in terms of the impact of various fuels on technological processes, the long-term performance of new materials, and the economic aspects of biomass integration.

The purpose of this study was to analyse methods of increasing the efficiency and environmental friendliness of using SOF in electricity generation. Research objectives:

- to investigate modern technologies for SOF processing, such as gasification and pyrolysis, to assess their impact on the efficiency of electricity production;
- to analyse the mechanical systems used for combustion of SOF and to identify opportunities for their optimisation to improve energy efficiency;
- to evaluate the environmental aspects of the use of SOF, including the reduction of harmful substances and ash disposal, to determine their impact on the environment.

MATERIALS AND METHODS

The present study analysed the aspects of using SOF for electricity generation. Various types of SOF, such as wood, pellets, straw, and other types of biomass, which are widely used in the energy sector, were considered. Significant attention was paid to the examination of each type of biomass in terms of its availability, energy potential, environmental impact, and the possibility of integration into modern energy systems.

Methods for analysing the physical and chemical properties of biomass were also used, including determining moisture content, ash content, calorific value, and composition of volatile substances. The moisture content of the biomass was determined to assess its impact on combustion efficiency and energy costs for grinding and drying the fuel before combustion. The ash content was analysed to determine the amount of residual material after combustion, which can cause problems with equipment maintenance. The calorific value was assessed to determine the amount of energy that can be obtained during combustion, which is a key indicator of fuel efficiency in power plants. The study of the composition of volatile substances helped to assess their impact on the formation of harmful emissions during combustion.

Furthermore, the energy potential of various types of biomass was assessed, considering the possibility of their mass production and market availability. As the efficient use of biomass for energy purposes requires a stable supply of raw materials, the study addressed the regional specifics of biomass cultivation and harvesting. The environmental impact, including emissions of harmful substances during combustion, and the fuel's ability to recover were also considered. The main technologies used for converting SOF into electricity, specifically gasification and pyrolysis, were considered. The study analysed their advantages and disadvantages, process efficiency, and the potential for reducing emissions of harmful substances.

The operational mechanical systems, such as boilers, turbines, and fuel preparation and supply systems used for combustion of the SOF were analysed. Particular attention was paid to the design features of these systems, their reliability, and upgrade capabilities. The possibilities of using new materials and engineering solutions that increase the efficiency of heat transfer, reduce heat loss, and improve the overall performance of energy systems were investigated.

The environmental impacts of the use of SOF, including emissions of harmful substances such as CO_2, NO_x, and slag and ash particles occurring from the combustion process, were also investigated. Methods of reducing these emissions, such as the use of flue gas cleaning systems and secondary combustion technologies, were analysed. Furthermore, the study considered the issue of utilisation of ash, which can be used as fertiliser or construction material.

RESULTS

SOF play an important role in electricity generation, especially in the context of renewable energy sources. The use of SOF, such as wood, agricultural waste, and other biomass, can considerably reduce greenhouse gas emissions if used efficiently. SOF occupy a special place among alternative energy sources due to their availability and potential for sustainable development (Angulo-Mosquera *et al.*, 2021). SOF includes various types of biomass, such as wood, pellets, straw, husks, husks, and other organic waste generated by agricultural and industrial activities. These materials are renewable resources that can be used to produce heat and electricity with minimal environmental impact. Each type of SOF has its unique characteristics that determine their efficiency and environmental friendliness. Wood, as one of the most common SOF, has a high energy potential due to its calorie content. At the same time, its efficiency largely depends on the level of humidity – the lower the humidity, the more energy can be obtained by burning it. Pellets produced by pressing wood waste have a stable calorific value and low moisture content, which makes them one of the most efficient types of SOF.

Straw, peelings, and husks, which are agricultural wastes, are also widely used as a SOF. Although these materials have a lower calorific value than wood, their availability and low cost make them attractive for energy needs, especially in rural areas. However, the use of such fuels is accompanied by certain difficulties, specifically, high ash content and the possibility of harmful emissions during combustion. This requires the implementation of special flue gas cleaning and ash disposal technologies to minimise the negative impact on the environment. Thus, the SOF represent a diverse group of materials, each of which has its characteristics that affect the efficiency of their use in the energy sector. The choice of the suitable type of SOF and its processing technology depends on the concrete conditions and requirements for energy efficiency and environmental friendliness. Therefore, research and development of technologies aimed at optimising the use of SOF is crucial for the transition to cleaner energy sources. Technologies for generating electricity from SOF are key to the development of renewable energy sources (Wang & Wright, 2022).

With the growing demand for environmentally friendly energy solutions, it is important to consider modern methods that enable efficient conversion of biomass into electricity (Table 1). These include combustion, gasification, and pyrolysis, each of which has its unique advantages and challenges.

Table 1. Technologies of electricity generation from the SOF

Technology	Working principle	Advantages	Disadvantages
Combustion	Conversion of fuel into a gaseous coolant for steam production	High enough efficiency, proven technology	CO_2 emissions, reduced efficiency when used in intermediate modes
Gasification	Conversion of solid and liquid fuels into gaseous fuels	Reduced emissions, high efficiency	Complexity of equipment, need for additional gas cleaning systems
Pyrolysis	Heat treatment of fuel in the absence of oxygen	Possibility of obtaining several types of fuel	Complexity of the process, need for special systems to handle the output products

Source: compiled by the authors of this study based on O. Corigliano *et al*. (2022)

Combustion is one of the most conventional and widespread technologies for generating electricity from SOF. The principle of operation of such systems is to use biomass to heat water, which leads to the formation of steam. This steam drives turbine generators that generate electricity. This method is efficient and reliable, but its effectiveness depends on the quality of the fuel used and the design of the equipment. An important aspect is the optimisation of the combustion process to minimise the production of harmful emissions, ash, and slag. Gasification is a more innovative approach, which involves converting SOF into gaseous fuel through partial oxidation at hot temperatures. The resulting synthesis gas consists primarily of hydrogen, carbon monoxide, and methane, and can be used for power generation or as a raw material for the chemical industry. Gasification reduces the amount of ash and harmful emissions, making this method more environmentally friendly than conventional combustion. At the same time, this process requires sophisticated equipment and strict control of parameters, which can increase the cost of implementing the technology.

Pyrolysis is a process of thermal treatment of SOF in the absence of oxygen, which results in the formation of solid, liquid, and gaseous products. These products can be used for further energy production or as raw materials for other industries. The solid residue (biochar) can be used as fuel or as fertiliser, the liquid fractions can be used as biofuels, while the gaseous products can be used to produce electricity or heat. Pyrolysis is a flexible technology that allows to produce various types of energy carriers but requires precise control of temperature conditions and the composition of the feedstock. Thus, technologies for generating electricity from SOF offer a wide range of opportunities for the efficient and environmentally friendly use of renewable resources. The choice of the suitable technology depends on specific conditions, including the type of biomass, availability of process equipment, and requirements for process efficiency and environmental friendliness. The integration of these technologies into the modern energy sector will help reduce dependence on fossil fuels and reduce the negative impact on the environment.

The analysis of mechanical systems used for combustion of SOF is a major step in improving the efficiency and reliability of power plants (Table 2). These systems include diverse types of boilers, turbines, and fuel preparation and feeding systems, each of which plays a critical role in ensuring efficient conversion of biomass to electricity (Chehrmonavari *et al*., 2023).

Table 2. Analysis of mechanical systems for the use of SOF

System	Description	Key features	Challenges and limitations
Solid fuel boilers	Boilers for SOF combustion	Heat output, materials, operating mode	Short service life, need for regular maintenance
Turbines	Turbines for converting thermal energy into electricity	Efficiency, type (steam, gas)	Dependence on steam/gas quality, maintenance costs
Fuel preparation and supply systems	Automatic systems for fuel preparation and delivery	Continuity of operations, automation	Installation costs, problems with fuel recycling

Source: compiled by the authors of this study based on J. Zhuang *et al*. (2022)

The design of boilers is one of the key elements in combustion systems for SOF. The main focus of boiler design is on heat transfer efficiency, which determines how fully and efficiently fuel is converted into heat. The materials used to make the boilers must be resistant to hot temperatures, corrosion and erosion that occur during the biomass combustion process. The choice of materials and optimisation of the boiler design increase their durability and reduce heat loss, which increases the overall efficiency of the energy system. Turbines, which are used to convert thermal energy into mechanical energy and then into electricity, also require careful analysis. The type of turbines and their design features determine the efficiency of energy conversion, which is a key factor in achieving high performance. The optimum operating conditions of the turbines depend on the parameters of the steam generated in the boilers, including pressure and temperature. Furthermore, it is necessary to consider the possibility of using different types of turbines to work with different types of biomass, which may require special adjustments and adaptations.

Fuel preparation and supply systems ensure uninterrupted and uniform supply of SOF to the boilers. These systems must be designed to minimise fuel losses during grinding, drying, transport, and storage, and to ensure that the fuel is delivered evenly to the combustion zone. Automation of fuel supply processes helps to optimise system performance, reduce operating costs, and improve equipment reliability. Modern fuel supply systems can include dosing mechanisms, conveyors, augers, and other elements that ensure the accuracy and stability of the process. Thus, the analysis of mechanical systems for the use of SOF is a vital component of improving the efficiency and environmental friendliness of power plants. Optimising the design of boilers, selecting the right turbines and automating fuel supply systems not only increases productivity but also reduces the adverse impact on the environment. These aspects are critical to ensuring the sustainable development of the energy sector and the transition to renewable energy sources. Optimising the design of energy systems to improve efficiency is a key area of development for modern energy systems using SOF (Wang *et al.*, 2021). This process included several key aspects aimed at improving the operation of boilers, turbines, and fuel supply systems, which would increase productivity and reduce energy losses.

The modernisation of boilers has become one of the crucial steps in improving heat exchange efficiency. The use of new materials that were highly resistant to corrosion and erosion considerably increased the boilers' service life and reduced heat losses. The use of advanced designs and the latest heat exchange technologies helped to optimise combustion processes, which increased the overall efficiency of the system. The use of combustion processes for combustion of SOF in oxygen or oxygen-enriched air is important in this area. Improvements to the turbines included the use of more efficient models capable of operating at lower temperatures, which helped reduce energy losses during the conversion of heat into mechanical work. The introduction of new types of turbines increased productivity and reduced energy costs, which had a positive impact on the overall efficiency of power plants. Automation of fuel preparation and supply systems was an essential element in optimising energy processes. The use of sensors and automatic control systems ensured the accuracy and stability of fuel supply, which reduced the cost of its transportation and ensured the smooth operation of the plants. This helped to increase the efficiency of fuel combustion and minimise losses, which had a positive impact on the overall performance of the system. Overall, optimisation of power system designs and technologies enabled a substantial increase in the efficiency of using SOF, which ultimately contributed to reducing energy costs and improving the environmental friendliness of electricity generation. These measures were critical to ensure the stable and efficient operation of modern power plants using renewable energy sources.

The use of SOF for electricity generation has valuable environmental aspects that directly affect the environment and the efficiency of energy systems (Table 3). Improvement of the environmental friendliness of the use of SOF includes reducing pollutant emissions, efficient ash disposal, and rational use of resources.

Table 3. Environmental aspects of using SOF

Environmental aspect	Description	Potential solutions
Reduction of emissions	The use of SOF can lead to emissions of CO_2, NO_x, SO_x, and other pollutants	Use of the latest combustion technologies, modern flue gas cleaning technologies, catalytic converters
Disposal of ash and slag	Ash and slag remaining after combustion of SOF may contain heavy metals and other harmful substances	Use of ash as fertiliser, in building materials or for land reclamation
Rational use of resources	Loss of thermal energy during combustion of SOF can reduce the efficiency of energy systems	Optimisation of the combustion process, introduction of high-efficiency boilers and turbines, utilisation of biomass residues

Source: compiled by the authors of this study based on M.A. Abdelkareem *et al.* (2021)

Reduction of emissions is one of the key tasks when using SOF. For this, gas purification technologies are actively used to reduce the concentration of harmful substances in exhaust gases. Secondary combustion systems provide additional combustion of the remaining particles in the flue gas, thereby reducing emissions of inorganic compounds and soot particles. Catalytic converters are used to convert toxic gases such as nitrogen and carbon oxides into less harmful compounds. The introduction of these technologies substantially reduces the negative impact on the environment, making the use of SOF more environmentally friendly. The disposal of ash and slag is another notable aspect of the environmental benefits of using SOF. The ash and slag produced during biomass combustion can be recycled and used as fertiliser or building material. Biomass ash contains a considerable amount of nutrients such as potassium, calcium, and phosphorus, which are useful for improving soil quality. It can also be used as an ingredient in the manufacture of building materials such as concrete or tiles, which reduces the need for virgin raw materials and reduces the environmental footprint of the construction industry.

Efficient use of resources includes reducing energy losses and using biomass residues. Improvement of the combustion efficiency and conversion of SOF helps to reduce the amount of unused fuel and reduce overall energy costs. Another major aspect is the use of biomass residues, such as husks, stalks, or wood waste, which are often overlooked. Reusing them as fuel or raw materials for new products reduces waste and improves overall system efficiency. Thus, the environmental aspects of using the SOF include reducing pollutant emissions, ash disposal, and efficient use of resources. The introduction of relevant technologies and practices helps to reduce the negative impact on the environment, increasing the environmental friendliness of electricity production from biomass, and ensuring the sustainable development of the energy sector (Al-Ghouti *et al.*, 2021). With the future challenges of the energy sector related to the need to reduce emissions and increase efficiency, the development of innovative technologies in the field of using SOF is becoming critically important. The key areas of this development include new materials for boilers and turbines, innovative methods of processing SOF, as well as automation and digitalisation of processes (Wang & Wright, 2021).

Modern research in the field of materials science focuses on the development of new alloys and coatings that can considerably improve heat resistance and reduce wear and tear on energy system components. New materials, such as ceramic composites and high-strength alloys, can withstand extreme temperatures and aggressive operating conditions. They ensure a longer service life for boilers and turbines, which reduces the frequency of repairs and replacements and increases the overall efficiency of power plants. The introduction of such materials can considerably reduce maintenance costs and improve system reliability. Innovative methods of processing SOF focus on integration with renewable energy sources and the development of innovative processing technologies. For instance, biomass can be combined with solar or wind energy to improve the efficiency of energy systems. Gasification and pyrolysis processes are becoming increasingly sophisticated, enabling the conversion of SOF into high-quality gaseous or liquid fuels with higher energy density. Integrating these technologies into a combined heat and power system can significantly improve overall efficiency and reduce emissions.

Automation and digitalisation of the SOF combustion process is another major area of development. Artificial intelligence (AI) and big data allow optimising management processes, improving the accuracy of system regulation and monitoring. Intelligent control systems can automatically adjust combustion parameters to achieve maximum efficiency and reduce emissions. For instance, AI-powered systems can predict energy needs, optimise fuel supply, and ensure more efficient integration with other energy sources. Digitalisation also facilitates maintenance by monitoring the condition of equipment in real time. The development of new materials, innovative methods of processing SOF, and automation of processes are key to improving the efficiency and environmental friendliness of SOF-based energy systems. These technological advances not only reduce the negative impact on the environment, but also provide economic benefits through reduced maintenance costs and improved overall system reliability. According to current research and innovations, the future use of SOF will be closely linked to the integration of innovative technologies, which opens new opportunities for sustainable energy development (Singh *et al.*, 2021).

Increasing the efficiency and environmental friendliness of using SOF for electricity generation requires a comprehensive approach, including technology improvement, design optimisation, and the use of modern mechanical systems. Efficient use of SOF can considerably reduce greenhouse gas emissions and promote the development of renewable energy sources.

DISCUSSION

The analysis of the results showed a significant potential for increasing the efficiency and environmental friendliness of the use of SOF in electricity generation. Modern technologies such as combustion in pure oxygen, gasification, and pyrolysis were found to considerably reduce emissions compared to conventional methods of use. However, these technologies required complex gas purification systems, which increased production costs. Optimisation of boiler and turbine designs and the introduction of the latest materials have helped to improve heat transfer efficiency and reduce energy losses. This was also investigated by V. Ashokkumar *et al.* (2022), where the findings confirmed that the introduction of technologies such as carbon capture and storage systems significantly reduced carbon dioxide emissions. The use of gasification and pyrolysis of solid fuels has contributed to cleaner combustion, thereby reducing emissions. Z. Xie *et al.* (2021) also showed that modern combustion technologies for combustion of SOF, such as particulate filters and desulphurisation systems, effectively reduce the concentration of harmful substances in emissions. Optimisation of combustion processes ensured more complete combustion of fuel, reducing the amount of residual emissions. Notably, the effectiveness of technologies largely depends on their proper application and integration into existing energy supply systems. Successful emissions reduction also requires constant monitoring and adaptation of technologies to changing operating conditions. Investing in innovative solutions and their adaptation can substantially improve the environmental impact of using SOF, making it more competitive with other energy sources (Chupa & Zhovtulia, 2023).

The study of mechanical systems for the use of SOF has demonstrated the significance of process automation, especially in the context of fuel supply systems. The use of automatic control systems has reduced fuel losses and ensured the stability of power plants (Stoliarov, 2024). On the other hand, the high complexity of such systems required considerable investment and regular maintenance, which raised the question of the feasibility of their implementation in a context of limited funding. A. Marot *et al.* (2022) concluded that automation in energy supply systems with SOF ensures stability and efficiency. Automated control systems help maintain optimised combustion parameters, reducing emissions and increasing efficiency. L. Angulo-Mosquera *et al.* (2021) found that research into mechanical systems for the use of SOF highlighted the significance of automation, especially in fuel delivery systems. Automatic control systems reduce fuel losses and increase the stability of power plants, which has a positive impact on their efficiency. However, the high complexity of such systems requires major investment and regular maintenance, which raises questions regarding their feasibility in a context of limited funding. These findings support the cited study, as they demonstrate that automation truly contributes to the efficiency and sustainability of power plants. At the same time, they emphasise the need for a thorough substantiation of the economic feasibility of such investments, especially for enterprises with limited financial resources. The introduction of automated systems must be balanced with the enterprise's ability to maintain and adapt them to ensure long-term sustainability and economic benefit.

Optimisation of boiler and turbine designs has proven to be effective in increasing the overall efficiency of systems using SOF. The use of new materials, such as high-temperature alloys and nanomaterials, has improved thermal conductivity and corrosion resistance (Orumbayev *et al.*, 2021). This helped to reduce maintenance costs and extend the life of the equipment. It is worth noting the study by M. Nemitallah *et al.* (2023), who also found that optimising boiler and turbine designs is key to improving the efficiency of power plants. Improvements in the geometry of heat exchange surfaces, turbine aerodynamics, and fuel combustion systems can reduce energy losses and increase efficiency. This also helps to reduce emissions, which increases the environmental sustainability of production. Y. Guo *et al.* (2023) concluded that new materials with high thermal conductivity, corrosion and temperature resistance allow for more efficient heat transfer and reduce energy losses. They also increase the equipment's resistance to stress, which extends its service life and reduces replacement costs, contributing to higher efficiency and lower operating costs. These data are in line with the theses presented in the previous section of this study, confirming the significance of both design optimisation and the use of innovative materials to achieve maximum efficiency. Improvements in boiler and turbine designs, together with the use of the latest materials, create a synergistic effect that increases the overall efficiency of power plants (Prypoten *et al.*, 2022). This demonstrates that innovative approaches in engineering and materials science are essential for achieving sustainable development and reducing operating costs in the modern energy sector.

From an environmental standpoint, improving the environmental friendliness of the use of SOF required a comprehensive approach, including both the modernisation of existing technologies and the introduction of innovative methods of reducing emissions. It was found that efficient ash utilisation can considerably reduce the environmental impact of electricity generation if the ash is used as fertiliser or in building materials. However, the issues of safety and economic feasibility of such disposal necessitated additional research. R. Permatasari & A. Sodri (2023) also conducted a study that confirmed that ash utilisation and emission reduction are critical for environmental safety when using SOF. Ash contains toxic substances, and therefore its efficient utilisation, for instance in construction materials, reduces the negative impact on the environment. Modern technologies, such as flue gas filtration, help to reduce emissions of harmful substances in line with environmental standards. N. Rajendran *et al.* (2021) also found that a comprehensive approach includes reducing pollutant emissions, optimising the combustion process to minimise ash, and upgrading equipment and using alternative energy sources. This helps to significantly reduce the environmental impact of using SOF. Comparing the data obtained during the study, it can be stated that an integrated approach to improving the environmental friendliness of the use of SOF has a substantial impact on reducing the environmental burden. The implementation of efficient ash utilisation methods and modern emission reduction technologies is proving to be effective in reducing toxic emissions and improving environmental quality (Mysak *et al.*, 2017). This data confirms that the integration of innovative solutions in the field of recycling and pollution control is the key to achieving sustainable and environmentally friendly use of the SOF.

Innovative developments in the use of SOF, such as integration with other renewable energy sources and the use of AI to optimise processes, have demonstrated the prospects for a considerable increase in the efficiency of energy systems. The use of these technologies would enable the creation of more sustainable and cost-effective SOF-based solutions for electricity generation. A. Shah *et al.* (2022) concluded that innovative technologies such as pyrolysis and gasification considerably increase the efficiency of SOF use, reducing pollutant emissions and lowering operating costs. Automation systems and new materials for flue gas cleaning make the use of the SOF more environmentally friendly and economical. M. Hasan *et al.* (2022) found that integrating SOF with renewable sources such as biomass or solar energy can ensure a stable energy supply, reduce dependence on fossil fuels, and lower greenhouse gas emissions. Combining SOF with renewable sources increases economic efficiency and reduces the environmental footprint of energy systems. When analysing the results of the study, it is clear that the introduction of innovative technologies in the use of SOF substantially increases their efficiency and reduces the negative environmental impact. Specifically, improved combustion processes and new methods of flue gas treatment provide a significant reduction in emissions and lower operating costs. At the same time, the integration of SOF with renewable energy sources opens prospects for more sustainable and economical use of energy resources, improving environmental performance, and reducing dependence on fossil fuels. Thus, a comprehensive approach to technology optimisation and integration with renewable sources is key to achieving sustainable energy.

Thus, the analytical study confirmed the need for further modernisation and optimisation of the systems that use SOF to achieve high efficiency and minimise negative environmental impact. The results also highlighted the significance of investing in innovative technologies and increasing automation to ensure sustainable and environmentally friendly electricity production in the future.

CONCLUSIONS

The analytical study revealed that the use of SOF for electricity generation can be efficient and environmentally friendly, provided that modern technologies and approaches are applied. It was found that the introduction of the latest technologies, such as combustion in pure oxygen, gasification, and pyrolysis, can reduce emissions of harmful substances, which has a positive impact on the environmental situation. However, these technologies require sophisticated gas purification systems, which considerably increases the cost of electricity production.

The optimisation of boiler and turbine designs using high-temperature alloys and nanomaterials has substantially improved heat transfer efficiency. High-temperature alloys increased operating temperature and corrosion resistance, while nanomaterials reduced heat loss and increased wear resistance. This helped to increase the overall efficiency and extend the service life of the equipment. Automation of fuel supply systems ensured the stability of power plants, reducing fuel losses and the risk of interruptions. Despite the high cost, the introduction of such systems has considerably increased the efficiency of electricity generation and reduced maintenance costs. Environmental aspects, such as ash and slag recycling and emissions reduction, have become key to improving environmental safety. The use of ash and slag as fertilisers or building materials reduced waste and provided additional economic benefits, while modern gas cleaning technologies reduced emissions of harmful substances into the atmosphere.

Thus, the study confirmed the significance of modernising and optimising SOF-based systems to achieve high efficiency and environmental safety in electricity generation. The economic feasibility and safety of utilising ash and slag from solid organic fuels as fertiliser or construction material should be further investigated. A limitation of this study was the lack of a detailed analysis of the economic efficiency of implementing modern gas cleaning technologies and automation of fuel preparation and supply systems.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

REFERENCES

[1] Abdelkareem, M.A., Elsaid, K., Wilberforce, T., Kamil, M., Sayed, E.T., & Olabi, A. (2021). Environmental aspects of fuel cells: A review. *Science of the Total Environment*, 752, article number 141803. doi: 10.1016/j.scitotenv.2020.141803.

[2] Al-Ghouti, M.A., Khan, M., Nasser, M.S., Al-Saad, K., & Heng, O.E. (2021). Recent advances and applications of municipal solid wastes bottom and fly ashes: Insights into sustainable management and conservation of resources. *Environmental Technology & Innovation*, 21, article number 101267. doi: 10.1016/j.eti.2020.101267.

[3] Angulo-Mosquera, L.S., Alvarado-Alvarado, A.A., Rivas-Arrieta, M.J., Cattaneo, C.R., Rene, E.R., & García-Depraect, O. (2021). Production of solid biofuels from organic waste in developing countries: A review from sustainability and economic feasibility perspectives. *Science of the Total Environment*, 795, article number 148816. doi: 10.1016/j.scitotenv.2021.148816.

[4] Ashokkumar, V., Flora, G., Venkatkarthick, R., SenthilKannan, K., Kuppam, C., Stephy, G.M., Kamyab, H., Chen, W.-H., Thomas, J., & Ngamcharussrivichai, C. (2022). Advanced technologies on the sustainable approaches for conversion of organic waste to valuable bioproducts: Emerging circular bioeconomy perspective. *Fuel*, 324, article number 124313. doi: 10.1016/j.fuel.2022.124313.

[5] Chehrmonavari, H., Kakaee, A., Hosseini, S.E., Desideri, U., Tsatsaronis, G., Floerchinger, G., Braun, R., & Paykani, A. (2023). Hybridizing solid oxide fuel cells with internal combustion engines for power and propulsion systems: A review. *Renewable and Sustainable Energy Reviews*, 171, article number 112982. doi: 10.1016/j.rser.2022.112982.

[6] Chupa, V., & Zhovtulia, L. (2023). Study of emissions into the atmosphere from the combustion of pellets and solid waste. *Ecological Safety and Balanced Use of Resources*, 14(2), 50-60. doi: 10.69628/esbur/2.2023.50.

[7] Corigliano, O., Pagnotta, L., & Fragiacomo, P. (2022). On the technology of solid oxide fuel cell (SOFC) energy systems for stationary power generation: A review. *Sustainability*, 14(22), article number 15276. doi: 10.3390/su142215276.

[8] Guo, Y., Ruan, K., Wang, G., & Gu, J. (2023). Advances and mechanisms in polymer composites toward thermal conduction and electromagnetic wave absorption. *Science Bulletin*, 68(11), 1195-1212. doi: 10.1016/j.scib.2023.04.036.

[9] Hameed, Z., Aslam, M., Khan, Z., Maqsood, K., Atabani, A.E., Ghauri, M., Shahzad Khurram, M., Rehan, M., & Nizami, A.S. (2021). Gasification of municipal solid waste blends with biomass for energy production and resources recovery: Current status, hybrid technologies and innovative prospects. *Renewable and Sustainable Energy Reviews*, 136, article number 110375. doi: 10.1016/j.rser.2020.110375.

[10] Hasan, M.Y., Monir, M.U., Ahmed, M.T., Abd Aziz, A., Shovon, S.M., Akash, F.A., Khan, M.F., Faruque, J., Rifat, S.I., Hossain, J., Kundu, P., & Ali, S. (2022). Sustainable energy sources in Bangladesh: A review on present and future prospect. *Renewable and Sustainable Energy Reviews*, 155, article number 111870. doi: 10.1016/j.rser.2021.111870.

[11] Islam, A., Teo, S.H., Ng, C.H., Taufiq-Yap, Y.H., Choong, S.Y., & Awual, M.R. (2023). Progress in recent sustainable materials for greenhouse gas (NO_x and SO_x) emission mitigation. *Progress in Materials Science*, 132, article number 101033. doi: 10.1016/j.pmatsci.2022.101033.
[12] Marot, A., Kelly, A., Naglic, M., Barbesant, V., Cremer, J., Stefanov, A., & Viebahn, J. (2022). Perspectives on future power system control centers for energy transition. *Journal of Modern Power Systems and Clean Energy*, 10(2), 328-344. doi: 10.35833/MPCE.2021.000673.
[13] Martinez-Valencia, L., Camenzind, D., Wigmosta, M., Garcia-Perez, M., & Wolcott, M. (2021). Biomass supply chain equipment for renewable fuels production: A review. *Biomass and Bioenergy*, 148, article number 106054. doi: 10.1016/j.biombioe.2021.106054.
[14] Mong, G.R., Chong, C.T., Chong, W.W., Ng, J.-H., Ong, H.C., Ashokkumar, V., Tran, M.-V., Karmakar, S., Goh, B.H., & Yasin, M.F. (2022). Progress and challenges in sustainable pyrolysis technology: Reactors, feedstocks and products. *Fuel*, 324, article number 124777. doi: 10.1016/j.fuel.2022.124777.
[15] Mustafa, F.E., Ahmed, I., Basit, A., Alvi, U.-E-H., Malik, S.H., Mahmood, A., & Ali, P.R. (2023). A review on effective alarm management systems for industrial process control: barriers and opportunities. *International Journal of Critical Infrastructure Protection*, 41, article number 100599. doi: 10.1016/j.ijcip.2023.100599.
[16] Mysak, Y., Lys, S., & Martynyak-Andrushko, M. (2017). Research on gasification of low-grade fuels in a continuous layer. *Eastern-European Journal of Enterprise Technologies*, 2(8-86), 16-23. doi: 10.15587/1729-4061.2017.96995.
[17] Nemitallah, M.A., Nabhan, M.A., Alowaifeer, M., Haeruman, A., Alzahrani, F., Habib, M.A., Elshafei, M., Abouheaf, M.I., Aliyu, M., & Alfarraj, M. (2023). Artificial intelligence for control and optimization of boilers' performance and emissions: A review. *Journal of Cleaner Production*, 417, article number 138109. doi: 10.1016/j.jclepro.2023.138109.
[18] Odzijewicz, J.I., Wołejko, E., Wydro, U., Wasil, M., & Jabłońska-Trypuć, A. (2022). Utilization of ashes from biomass combustion. *Energies*, 15(24), article number 9653. doi: 10.3390/en15249653.
[19] Orumbayev, R.K., Bakhtiyar, B.T., Umyshev, D.R., Kumargazina, M.B., Otynchiyeva, M.T., & Akimbek, G.A. (2021). Experimental study of ash wear of heat exchange surfaces of the boiler. *Energy*, 215, article number 119119. doi: 10.1016/j.energy.2020.119119.
[20] Palianytsia, B., Kulik, T., Dudik, O., Cherniavska, T., & Tonkha, O. (2014). Study of the thermal decomposition of some components of biomass by desorption mass spectrometry. *Springer Proceedings in Physics*, 155, 19-25. doi: 10.1007/978-3-319-05521-3_3.
[21] Peiró, L.T., Martin, N., Méndez, G.V., & Madrid-López, C. (2022). Integration of raw materials indicators of energy technologies into energy system models. *Applied Energy*, 307, article number 118150. doi: 10.1016/j.apenergy.2021.118150.
[22] Permatasari, R., & Sodri, A. (2023). Utilization of fly ash waste in the cement industry and its environmental impact: A review. *Jurnal Penelitian Pendidikan IPA*, 9(9), 569-579. doi: 10.29303/jppipa.v9i9.4504.
[23] Prypoten, Yu., Kotenko, V., Bashinsky, S., & Piskun, I. (2022). Study of the efficiency of solid fuel boilers of different configuration. *Modern Technologies, Materials and Structures in Construction*, 19(1), 73-78. doi: 10.31649/2311-1429-2022-1-73-78.
[24] Rajendran, N., Gurunathan, B., Han, J., Krishna, S., Ananth, A., Venugopal, K., & Priyanka, R.S. (2021). Recent advances in valorization of organic municipal waste into energy using biorefinery approach, environment and economic analysis. *Bioresource Technology*, 337, article number 125498. doi: 10.1016/j.biortech.2021.125498.
[25] Shah, A.V., Singh, A., Mohanty, S.S., Srivastava, V.K., & Varjani, S. (2022). Organic solid waste: Biorefinery approach as a sustainable strategy in circular bioeconomy. *Bioresource Technology*, 349, article number 126835. doi: 10.1016/j.biortech.2022.126835.
[26] Singh, M., Zappa, D., & Comini, E. (2021). Solid oxide fuel cell: Decade of progress, future perspectives and challenges. *International Journal of Hydrogen Energy*, 46(54), 27643-27674. doi: 10.1016/j.ijhydene.2021.06.020.
[27] Sivabalan, K., Hassan, S., Ya, H., & Pasupuleti, J. (2021). A review on the characteristic of biomass and classification of bioenergy through direct combustion and gasification as an alternative power supply. *Journal of Physics: Conference Series*, 1831, article number 012033. doi: 10.1088/1742-6596/1831/1/012033.
[28] Soleh, M., Ahmad, A.H., Juangsa, F.B., Darmanto, P.S., & Pasek, A.D. (2023). Impact of different kinds of biomass mixtures on combustion performance, interaction and synergistic effects in cofiring of coal and biomass in steam power plants. *Clean Energy*, 7(5), 1136-1147. doi: 10.1093/ce/zkad049.
[29] Stoliarov, O. (2024). Efficient electricity generation forecasting from solar power plants using technology: Integration, benefits and prospects. *Bulletin of Cherkasy State Technological University*, 29(1), 73-85. doi: 10.62660/bcstu/1.2024.73.
[30] Tang, C., Pan, W., Zhang, J., Wang, W., & Sun, X. (2022). A comprehensive review on efficient utilization methods of High-alkali coals combustion in boilers. *Fuel*, 316, article number 123269. doi: 10.1016/j.fuel.2022.123269.
[31] Wang, J., Dong, F., Ma, Z., Chen, H., & Yan, R. (2021). Multi-objective optimization with thermodynamic analysis of an integrated energy system based on biomass and solar energies. *Journal of Cleaner Production*, 324, article number 129257. doi: 10.1016/j.jclepro.2021.129257.
[32] Wang, Y., & Wright, L.A. (2021). A comparative review of alternative fuels for the maritime sector: Economic, technology, and policy challenges for clean energy implementation. *World*, 2(4), 456-481. doi: 10.3390/world2040029.

[33] Xie, Z., Wu, R., & Wang, S. (2021). How technological progress affects the carbon emission efficiency? Evidence from national panel quantile regression. *Journal of Cleaner Production*, 307, article number 127133. doi: 10.1016/j.jclepro.2021.127133.

[34] Zhuang, J., Tang, J., & Aljerf, L. (2022). Comprehensive review on mechanism analysis and numerical simulation of municipal solid waste incineration process based on mechanical grate. *Fuel*, 320, article number 123826. doi: 10.1016/j.fuel.2022.123826.

Тарас Кравець

Кандидат технічних наук, доцент
Національний університет «Львівська політехніка»
79000, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0002-7186-926X

Михайло Семерак

Доктор технічних наук, професор
Національний університет «Львівська політехніка»
79000, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0002-7582-6398

Ігор Галянчук

Кандидат технічних наук, старший викладач
Національний університет «Львівська політехніка»
79000, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0001-6242-1749

Оксана Юрасова

Кандидат технічних наук, старший викладач
Національний університет «Львівська політехніка»
79000, вул. Степана Бандери, 12, м. Львів, Україна
https://orcid.org/0000-0001-9930-9152

Андрій Харчук

Кандидат технічних наук, доцент
Львівський державний університет безпеки життєдіяльності
79007, вул. Клепарівська, 35, м. Львів, Україна
https://orcid.org/0009-0000-8783-0522

Аналітичне дослідження з підвищення ефективності та екологічності використання твердих органічних палив

Анотація. Метою дослідження було проаналізувати методи підвищення ефективності та екологічності використання твердих органічних палив (ТОП) у виробництві електроенергії. У цьому дослідженні було застосовано комплексний підхід до аналізу та оптимізації технологічних процесів, експлуатаційних систем та екологічних аспектів використання ТОП. В ході дослідження було встановлено, що використання сучасних технологій, таких як газифікація та піроліз, значно підвищує ефективність перетворення ТОП у електроенергію. Оптимізація конструкцій котлів та турбін, а також автоматизація систем подачі палива, сприяє зниженню втрат енергії та підвищенню загальної ефективності систем. Встановлено, що використання нових матеріалів для котлів підвищує їх стійкість до корозії та ерозії, що продовжує термін служби обладнання. Дослідження також показало, що впровадження систем очистки газів та вторинного спалювання значно зменшує викиди шкідливих речовин, що покращує екологічні показники. Аналіз можливостей утилізації золи показав, що її використання як добрива або будівельного матеріалу є перспективним напрямком. У результаті дослідження доведено, що комплексний підхід до використання ТОП може суттєво підвищити їх ефективність та екологічність. Результати дослідження показали, що застосування інноваційних методів управління процесами горіння дозволяє досягти більш стабільного та ефективного виробництва електроенергії. Доведено, що впровадження автоматизованих систем моніторингу та контролю знижує експлуатаційні витрати і підвищує надійність роботи обладнання. У ході дослідження було також встановлено, що використання передових аналітичних інструментів для прогнозування зношуваності обладнання дозволяє своєчасно проводити профілактичні ремонти, що додатково підвищує ефективність і тривалість безперебійної роботи енергетичних систем

Ключові слова: тверде органічне паливо; газифікація; піроліз; електроенергія; корозія; ерозія; екологія