UDC 628.47-026.562
DOI: 10.15587/1729-4061.2024.313823

PROSPECTS OF ELECTRICITY GENERATION THROUGH THE USE OF ALTERNATIVE SOURCES SUCH AS WASTE TIRES PROCESSING PRODUCTS

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The object of this study is a hybrid energy system that integrates the processes of recycling used tires with the use of alternative energy sources to design a sustainable and environmentally safe power generation system.

The problem addressed in this study is to find effective methods for recycling waste tires for electricity generation, as traditional recycling methods are energy-intensive and lead to the loss of valuable resources.

Three methods of tire processing have been considered: pyrolysis, thermal degradation, and mechanical grinding. The method of electricity generation using pyrolysis has demonstrated high environmental performance due to a significant reduction in greenhouse gas emissions and a high rate of renewable energy (80 %). According to the results of the study, the use of 5 MW pyrolysis furnaces in combination with 500 kW solar panels provides a reduction in dependence on fossil sources, reducing CO_2 emissions to 50.0 kg/year. The method has high capital costs (NPC USD 4.2 million), but the cost of energy production (COE USD 0.18/kWh) makes this method competitive in the long run. Thermal degradation provides a balanced approach in terms of energy efficiency (75 %) and environmental performance. Although its CO_2 emissions are higher than in pyrolysis, the method makes it possible to obtain additional products that could be used in other industries, thereby increasing economic efficiency. Mechanical shredding has the lowest average energy costs (USD 0.12/kWh) and the lowest CO_2 emissions (30.0 kg/year), making it ideal for cost-conscious businesses.

The study confirms the possibility of effective integration of renewable sources with tire recycling methods.

The practical use of the research results is possible during the implementation of grant projects for the recycling of used tires, and in the work of relevant government structures for devising a policy for the disposal of used tires

***Keywords:** tire recycling, pyrolysis, thermal degradation, mechanical grinding, renewable energy sources, chemotology*

Received date 12.08.2024
Accepted date 18.10.2024
Published date 30.10.2024

***How to Cite:** Boichenko, S., Kuberskyi, I., Shkilniuk, I., Danilin, O., Kryuchkov, A., Rozen, V., Khotian, A., Sokolovska, N., Yakovlieva, A., Pavlovskyi, M. (2024). Prospects of electricity generation through the use of alternative sources such as waste tires processing products. Eastern-European Journal of Enterprise Technologies, 5 (8 (131)), 6–21. https://doi.org/10.15587/1729-4061.2024.313823*

1. Introduction

The growing number of used tires is becoming a serious problem for the environment and society as a whole. Millions of car tires are produced every year in the world, which after the end of their service life become a heavy burden on ecosystems. Conventional disposal methods, such as landfilling or incineration, not only negatively affect ecosystems but also contribute to the loss of valuable resources. Waste processing could be a solution to the problem [1].

However, waste processing is an energy-intensive industry that requires significant resources and technological innovation to improve efficiency and reduce energy consumption.

In a situation where there is a shortage of electricity, it creates serious challenges for the economy and the livelihood of the population. Reducing dependence on external energy sources becomes a priority task. Failures in the supply of electricity not only stop production processes but also endanger the operation of critically important facilities. Under such conditions, the work of processing enterprises should be carried out exclusively autonomously. It is expedient to find a technological solution when production processes are reconfigured for additional electricity generation, which could significantly increase the energy security of the country. This approach would ensure the stability of energy supply and reduce vulnerability to external challenges.

One of the most promising directions in this context is the process of recycling tires with the production of energy from them. The use of tires to generate electricity has great potential, as it could not only help reduce the burden on the ecosystem but also provide valuable energy resources. The introduction of innovative technologies in the field of tire recycling could become the key to sustainable development of the country [2].

In this regard, the use of used tires as a source of energy is seen as a promising alternative to conventional methods of electricity production. Owing to this integration, it is possible to create a closed loop where waste is transformed into a resource, providing the energy needs of the country without additional burden on the environment.

Under today's conditions, issues of sustainable development are gaining special relevance, which increases the importance of scientific research in the field of waste processing. The issue of recycling car tires is one of the most complex and urgent environmental challenges today [3]. Solving this problem requires the use of innovative approaches that will make it possible not only to reduce the negative impact on the environment but also to ensure economic efficiency and energy security of the country [4, 5].

Of the total number of tires in the world, only about 23 % are recyclable, the majority of which is used to obtain energy through incineration or other thermal processing methods such as pyrolysis [6]. Other methods of processing, for example, mechanical grinding, make it possible to further use of used tires in road construction.

The issue of tire recycling is becoming even more urgent against the background of a constant increase in the amount of plastic and rubber waste [7, 8]. According to numerous scientific studies, polymer waste and used tires are considered the most dangerous waste [9, 10]. However, the huge volumes of these wastes, accumulated over decades, represent a significant energy potential [11]. They can be converted into energy by processing using pyrolysis methods or thermal degradation, which also makes it possible to reduce the burden on the environment.

According to estimates, the expected potential of obtaining fuel from waste tires ranges from 67.5 thousand tons/year [12] to 180 thousand tons/year [13].

The level of recycling and use of used tires in the world varies in a very wide range [14]: from 92 % in Japan to 45 % in the USA, and in the countries of Western Europe it reaches 50 % [15].

From the point of view of energy potential, methods of recycling used tires show different levels of efficiency. Mechanical grinding, although it is the most attractive from the point of view of obtaining high-quality secondary raw materials, has limited potential in the field of energy due to the lack of energy production [16]. However, the obtained rubber crumb can be used as a raw material for energy-efficient processes, for example, in the production of rubber asphalt or other construction materials [17].

Used tires, like plastic waste, have a significant potential for use in energy production due to their high resistance to corrosion in environmental conditions [18, 19]. This makes them attractive for processing in energy processes, in particular through pyrolysis and thermal degradation. In addition to the possibility of reducing the burden on the environment, these technologies make it possible to create alternative sources of energy [20, 21].

The results of such research have the potential for widespread implementation in practice because they could significantly reduce the vulnerability of the national economy to external challenges, ensure the stability of the functioning of critically important objects, and reduce the negative impact on ecosystems. In particular, when there is an urgent need to transition to renewable energy sources, the process of recycling tires to generate electricity could become a key element of an energy security strategy. The integration of methods will not only ensure the stability of energy supply but will also make it possible to create an economically profitable and environmentally safe cycle of resource use.

Scientific research aimed at devising technologies for processing used tires for energy generation is relevant and in demand both from the point of view of ecology and energy. It could not only contribute to sustainable development but also make it possible to solve important socio-economic problems, ensuring the stability and independence of the country's energy system.

2. Literature review and problem statement

There are numerous studies that consider the possibility of obtaining energy during the recycling of tires. In particular, work [22] reports the results of studies on the technical evaluation of gasification of used tires as an alternative technology for electricity generation. It is shown that a promising solution is the use of gas obtained as a result of gasification of tires in gas engines and turbines. The study proved that the combined use of a Bubbling Fluidized Bed Gasifier (BFBG), internal combustion engines, and gas turbines could be effective in producing both electrical and thermal energy. It has been investigated that the use of gas obtained as a result of gasification of tires when using an internal combustion engine (ICE-G) is more efficient in electricity production compared to the use of a gas turbine (GT-G). At the same time, it has been proven that a greater thermal effect occurs when using GT-G.

However, issues related to the efficiency and economic feasibility of these technologies under real operating conditions remained unresolved in the work. The reason for this are the difficulties associated with the need for high initial investments for the creation of the appropriate infrastructure and preparation of raw materials (shredding of tires, removal of metal, etc.). In addition, questions remain regarding the long-term stability of gasification systems and the impact on the environment due to emissions of harmful substances during the process.

An option to overcome related difficulties may be to conduct additional research on the optimization of gasification processes and the use of alternative gas purification technologies. It is also advisable to consider the construction of an economic model that would provide for the gradual introduction of such systems on an industrial scale, taking into account subsidies or state support to reduce the financial burden at the initial stage.

Study [23] considers the burning of used tires in a cogeneration plant using a circulating fluidized bed for electricity generation. The use of waste tires as fuel has been shown to increase boiler efficiency and lower electricity production costs compared to conventional fuels such as heavy fuel and coal. During peak hours, waste tire burning was found to generate 27.5 % more electricity per ton of fuel than heavy fuel and 42.3 % more than coal.

But the issues related to the high costs of implementing this technology, as well as the significant energy consumption of the tire burning process, remained unresolved. Utilization of a large amount of limestone for desulfurization of high-sulfur rubber fuel makes relevant research economically burdensome. In addition, the high cost of electricity produced from used tires under the conditions of fluctuations in the international fuel market may become another obstacle to the large-scale implementation of this technology. An option to overcome related difficulties may be the use of alternative energy sources, which would reduce costs and increase efficiency.

Work [24] reports the results of research on the energy utilization of used tires by gasification in modified reactors. It is shown that the gasification of used tires in modified reactors makes it possible to efficiently produce electricity and thermal energy. According to the authors, this could solve the problem of tire disposal in Brazil, reduce the negative impact on the environment, and contribute to the creation of new jobs.

However, questions related to the high costs of implementing gasification technology, especially at the initial stages of implementation, as well as the possibility of reducing the efficiency of gasification due to the formation of resins in the gasification process, remained open. In addition, the high energy consumption of the process and the cost of the electricity obtained in this way could become serious obstacles to the widespread adoption of this technology. The reason for this may be objective difficulties associated with the need to design and implement effective gas purification systems, which makes relevant research expensive and difficult.

It is possible to improve the structures of gasifiers to reduce the formation of resins in the gasification process and to optimize the gas purification processes, which would make it possible to reduce the energy consumption of the process and the cost of the received electricity.

An example of research at the local level is paper [25], which reports the results of research on the possibility of using used tires for electricity generation under the conditions of small islands, such as Puerto Rico. It is shown that pyrolysis is the most recommended technology for processing used tires, which makes it possible to obtain energy and simultaneously solve the problem of tire disposal. The study models the potential for energy production based on tire pyrolysis and suggests that the technology could provide about 7 % of Puerto Rico's total generating capacity.

However, issues related to the high initial costs of implementing pyrolysis technology, as well as the energy consumption of the process, which may complicate the economic feasibility of such projects, remain unresolved. A possible solution to these problems is the construction of a network of small pyrolysis plants that would work on used tires in combination with alternative energy sources. This could help reduce costs and increase the competitiveness of the generated electricity. This approach could be an important step towards the sustainable development of the energy system of small areas, which would contribute to reducing dependence on fossil fuels.

Similar is study [26], which reports the results from processing used tires by the pyrolysis method in order to obtain energy in Palestine. It is shown that the pyrolysis of used tires makes it possible to obtain such products as pyrolysis oil, pyrolysis carbon, and pyrolysis gas, which have high energy characteristics. In particular, pyrolysis oil can serve as a substitute for conventional liquid fuel, and pyrolysis gas can be used to meet the energy needs of the pyrolysis process itself.

However, the paper does not address issues related to the need to clean pyrolysis gas from hydrogen sulfide before burning it, which reduces the efficiency of the process and increases costs. In addition, a significant amount of chlorine and sulfur in pyrolysis carbon can cause environmental problems when it is used as a fuel. The reason for this may be technological limitations and the difficulty of cleaning pyrolysis products, which makes the process expensive and technically difficult.

Options for solving this tasks are the use of combined processing technologies and the application of heat recovery systems to increase energy efficiency. It is also advisable to consider the introduction of catalysts to reduce the reaction temperature and the modernization of filtration systems. These approaches could significantly improve the efficiency and cost-effectiveness of waste tire energy production, while reducing environmental risks and costs.

Paper [27] reports the results of research on the thermochemical processing of used tires for the purpose of obtaining energy. The authors investigated the processes of pyrolysis, combustion, and gasification of used tires, using thermogravimetric analysis together with mass spectrometry to determine the composition of the released gases.

Tire pyrolysis is shown to occur in two stages, with temperature ranges of approximately 250 to 500 °C for truck tires and 280 to 530 °C for passenger tires. The pyrolysis process leads to the release of hydrogen, methane, carbon oxides, and aromatic hydrocarbons. In particular, truck tires show a slightly higher calorific value of gases than passenger tires. The paper highlights the technical aspects of the processing methods; however, the issues related to the energy intensity of the pyrolysis and gasification processes remain unresolved, which significantly increases the overall cost of energy production. In addition, the non-uniformity of the composition of different types of tires complicates the standardization of processes, and also causes difficulties with the disposal of solid residues after thermochemical treatment, which contain harmful impurities. However, the integration of pyrolysis with other methods of waste treatment could increase the efficiency of disposal and reduce the negative impact on the environment.

Work [28] gives the results of a review of research on the possibilities of using pyrolysis gas obtained from used tires for energy production. It is shown that pyrolysis gas has a significant energy potential, in particular, with a calorific value of 30–40 MJ/m^3, which makes it a promising source of fuel for power plants. It is also stated that pyrolysis gas could be used to support the pyrolysis process itself and other energy purposes.

However, issues related to the high content of pollutants such as sulfur, chlorine, and heavy metals in pyrolysis gas remain unresolved. These components exceed the legally established norms and create serious environmental problems. The reason for this may be technological limitations associated with the need for expensive gas purification systems, which makes the pyrolysis process difficult and economically burdensome.

Options for overcoming these difficulties are the improvement of gas purification technologies, the development of new catalysts, as well as combining pyrolysis with other processing technologies. This will reduce cleaning costs and increase the overall efficiency of the process. The integration of pyrolysis with other innovative energy technologies could also help reduce production costs and increase the competitiveness of pyrolysis gas as an energy resource.

The cited studies are aimed at finding effective methods for the disposal of used tires for the purpose of electricity production. Research confirms that used tires could become a valuable source of energy that would help reduce the environmental burden and dependence on conventional fossil fuels.

Pyrolysis, incineration, and gasification are defined as the main promising technologies, which have common features, such as the possibility of obtaining energy from waste and solving the environmental problem of tire disposal. All studies emphasize that these processes could be efficient sources of energy, but significant questions remain that need to be resolved.

Scientists point to the high energy potential of pyrolysis gas and other processing products. At the same time, all methods are marked by the significant cost of equipment and processes, as well as the need to clean up harmful gases released during tire processing. It should be noted that existing methods are expensive, and the generated electricity is expensive, which makes such technologies less attractive from an economic point of view.

Therefore, issues related to the high cost of produced electricity and energy-intensive methods remain unresolved. These issues make the economic feasibility of such technologies limited.

This allows us to state that it is appropriate to conduct a study aimed at designing hybrid energy systems that integrate the processes of recycling used tires with the use of alternative energy sources. Such an approach will contribute to the creation of a cheap, sustainable, and ecologically safe electricity generation system.

The use of alternative energy sources in combination with the disposal of used tires could reduce the cost of electricity production and make it competitive in the market. This would reduce the energy consumption of the process and increase the economic feasibility of such technologies, which could ultimately contribute to their spread and integration into the energy system.

It is important to assess the possibility of integrating renewable energy sources into the processes of treating used tires, which could provide new perspectives in solving the problem of their utilization. In particular, the use of wind and solar energy can significantly reduce energy costs and environmental impact during tire recycling, increasing the technical and economic efficiency of this process. The use of such alternative energy sources would provide stable and ecologically clean power for all stages of processing, contributing to sustainable development and a significant reduction in greenhouse gas emissions.

Our study has the potential to be a useful tool for tire recycling businesses, enabling them to improve the efficiency of their processes. In addition, the results could be used by government structures to devise a more effective tire recycling policy that takes into account the use of renewable energy sources.

3. The aim and objectives of the study

The purpose of our study is to assess the technical and economic feasibility of electricity generation obtained by recycling used tires. The results will contribute to the development of new technologies for processing used tires using renewable energy sources, reducing dependence on fossil fuels, and improving the environmental situation in regions with high environmental protection requirements.

To achieve the goal, the following tasks were set:

– to evaluate the possibilities of integrating the electricity generated by recycling used tires into the general energy system;

– to carry out a comprehensive energy-ecological-economic evaluation of the methods for processing used tires;

– to carry out energy modeling of the processes of recycling used tires with the help of HOMERPro.

4. The study materials and methods

The object of our research is a hybrid energy system that integrates the processes of recycling used tires with the use of alternative energy sources to design a sustainable and environmentally safe power generation system.

The hypothesis of the research assumes that the operation of a hybrid energy system, which combines the energy obtained in the process of recycling used tires and the operation of alternative energy sources, could make it possible to develop a competitive system of electricity generation. This system would be able to effectively reduce the environmental impact of used tires and increase the stability of the energy system.

In the study, three hybrid energy systems were modeled, which integrate the processes of various tire waste processing methods: pyrolysis, thermal degradation, and mechanical grinding. Each of these systems is evaluated according to indicators of energy efficiency, economic feasibility, and environmental impact.

The Hybrid Optimization Model for Multiple Energy Resources (HOMERPro) software was used to evaluate and optimize the energy systems powering the tire waste recycling processes. The HOMERPro program made it possible to analyze 3 different scenarios for the use of renewable energy sources for powering technological processes and additional generation.

The pyrolysis method involves the thermochemical decomposition of organic materials in the absence of oxygen. The study was carried out by simulating the operation of a pyrolysis reactor operating at temperatures from 400 to 600 °C. That made it possible to evaluate the efficiency of the process, in particular the quantity and quality of the products obtained, such as pyrolysis oil, gases, and carbon residue. Energy costs were calculated on the basis of temperature conditions, heating rate, and holding time, and the obtained data were analyzed to determine the economic feasibility of using pyrolysis under industrial conditions.

Thermal degradation of tires is carried out at high temperatures in the presence of oxygen, which contributes to the decomposition of polymers and the formation of gaseous products and carbon residue. The process was simulated under a temperature regime of 600–800 °C to evaluate energy consumption and decomposition performance.

Mechanical shredding is the physical separation of tires into small particles to obtain granulated rubber and other materials. The modeling involved determining the optimal energy consumption required to grind the tires to a certain particle size. The energy costs and economic indicators associated with the realization of the obtained materials, such as granulated rubber, steel, and textile fibers, were estimated.

The characteristics of the equipment required for tire recycling have been taken into account in HOMERPro. These are the technical specifications of pyrolysis reactors, thermal units, and mechanical shredders, which made it possible to evaluate the overall efficiency of the system. With the help of the software package, the optimal dimensions of the components necessary to ensure the maximum productivity of the process with minimum energy consumption were selected.

To optimize the energy systems of each process, the most effective configuration parameters were found. Modeling was performed to find the best balance between energy efficiency and economic feasibility.

With the help of HOMERPro, equipment selection was carried out with a number of assumptions and uncertainties. The block diagram of modeling using HOMERPro is shown in Fig. 1.

For modeling the economic performance, the net present cost (*NPC*) and localized cost of energy (*LCOE*) of the system were estimated, and for the environmental aspect, the emission reduction and the renewable share were investigated in HOMERPro.

NPC is calculated from the following formula (1):

$$NPC = TAC/CRF, \quad (1)$$

where *TAC* is the total annual cost; *CRF* is the capital recovery factor.

To calculate the average cost of the usable electricity produced by the system in USD/kWh, HOMERPro uses the Localized Cost of Energy (*LCOE*) and it can be calculated from the following formula (2):

$$LCOE = Cann\ tot/E, \quad (2)$$

where *Cann tot* is the annual total cost, USD, and *E* is the total electricity consumption in kWh.

To quantify the contribution of renewable energy sources to the system, the share of renewable sources is used according to the following formula (3):

$$f = E/Eann_{tot}, \quad (3)$$

where $Eann_{tot}$ is the annual total energy production of the system, electricity production.

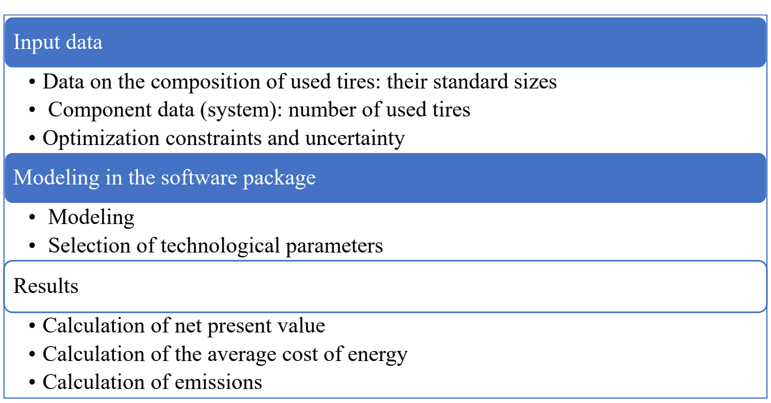

Fig. 1. Flow chart of the process using HOMERPro

The results of modeling and selection of technological parameters make it possible to compare three methods of tire waste processing and determine which of them is the most effective in terms of energy costs, economic benefit, and environmental safety. This made it possible to draw conclusions about the feasibility of implementing each of the methods under industrial conditions, taking into account their productivity, economic and environmental indicators.

5. Results of the study based on the assessment of prospects for electricity generation by recycling used tires

5. 1. Results of assessing the possibility of integration of electricity generated by recycling used tires

Under the conditions of growing demand for energy resources and the need to solve the problem of waste disposal, one should look for innovative approaches that would help ensure energy security and reduce the environmental burden. One of the promising areas is the use of used tires for electricity generation. Such a combined method, which combines tire recycling with the use of alternative energy sources (ASE), has significant potential for integration into the country's energy system.

A SWOT analysis of the electricity generation method based on a combination of used tire recycling methods and the use of alternative energy sources (ASE) was carried out. The results of constructing a SWOT analysis matrix are given in Table 1.

For a more in-depth analysis, a cross-point evaluation of the factors of the SWOT analysis was carried out, which makes it possible to determine the influence of each element on other aspects of the method. Evaluation on a scale from 1 to 5 points, where 5 is the highest impact, make it possible to clearly assess the significance of the interaction between strengths and weaknesses, opportunities and threats for the combined method of electricity generation using the recycling of used tires and alternative energy sources. The results of the cross-assessment of SWOT analysis factors are given in Table 2.

Our cross-assessment demonstrated how each element of the SWOT analysis affects other elements, creating a comprehensive view of the opportunities and threats of the power generation method.

Strengths are rated 3 points in the context of impact on weaknesses due to the possibility of compensating technological complexity with economic benefits and 4 points for synergy with new technologies, which increases the efficiency of the process.

Weaknesses received 5 points for their ability to minimize high initial costs through innovation, but also received 4 points for their impact on increasing competition and economic risks.

Opportunities received 4 points for their ability to enhance the strengths of the method and 5 points for reducing technological risks and costs, which is critical for the implementation of the combined approach, and 3 points for the likelihood of reducing economic threats through regulatory support.

Threats are rated 2 points because they can be partially neutralized by economic benefits, although competition and regulatory restrictions may negatively affect the profitability of the method, and 4 points for the potential negative effects of regulatory restrictions and competition.

Table 1

Matrix of SWOT analysis of electricity generation by recycling used tires and using ASE

Strengths	Weaknesses
– a comprehensive approach to waste disposal and energy generation: the use of used tire recycling methods together with ADE provides solutions to the problems of waste disposal and production of environmentally clean energy; – waste disposal: a significant amount of used tires is generated annually. Recycling methods can reduce the amount of used tires that often accumulate in unauthorized landfills; – diversification of sources of energy supply: for example, pyrolysis can provide the generation of about 1.5 MW of energy from 1 ton of tire, as well as obtaining up to 600 liters of pyrolysis oil and 300 kg of carbon. This energy can be supplemented by ADE, which provides a stable energy supply; – economic benefit: used tires as raw material can be obtained at a low price or for free. Solar and wind energy are also available resources	– technological complexity and high initial costs: The combined use of processing methods and ADE requires significant investments in equipment and technologies; – environmental risks: if the processing process is not properly controlled, harmful substances such as polyaromatic hydrocarbons and dioxins may be released; – intermittency of RES: the inconsistency of energy production from RES (for example, solar energy depends on the weather and time of day) requires reliable energy storage systems
Opportunities	**Threats**
– technological innovations: the introduction of new technologies can increase the efficiency and environmental cleanliness of the processing and use of ADE, increase the efficiency and reduce the costs of the combined method; – market expansion: there is a high demand for waste recycling solutions and alternative energy sources. The combined approach can become a promising direction for small and medium-sized enterprises; – regulatory incentives for enterprises: the possibility of subsidies and tax benefits from the state for enterprises engaged in waste processing and the use of ADE; – synergy: the interaction of different technologies (pyrolysis, solar and wind energy) can create a more sustainable and efficient energy supply system	– competition: other methods of waste processing and alternative energy sources are actively developing, which can compete with the combined method; – regulatory restrictions: strict environmental regulations can increase costs and complicate the licensing process; – economic factors: fluctuations in the prices of oil and traditional types of fuel can affect the profitability of the combined method; – public opinion: the likelihood of protests by local residents against the installation of pyrolysis and energy plants due to the danger of environmental risks

Table 2

Cross-assessment of factors in the SWOT analysis of electricity generation with the recycling of used tires and the use of ASE

–	Strengths	Weaknesses	Opportunities	Threats
Strengths	–	3 points: technological complexity can be compensated by a significant economic benefit	4 points: synergy with new technologies will increase the effectiveness of the method	2 points: threats from regulatory restrictions can be minimized by economic benefits
Weaknesses	3 points: the comprehensive approach of the method will level out the high initial costs of installing the technology	–	5 points: innovation will compensate for the high cost in the initial stages	4 points: high costs increase the impact of competition and economic factors
Opportunities	4 points: technological innovation can enhance strengths	5 points: innovation can reduce technological risks and costs	–	3 points: the risks of economic instability can be reduced by regulatory incentives
Threats	2 points: strengths can reduce regulatory barriers	4 points: competition will affect profitability due to the high complexity of implementation	3 points: economic threats will increase if innovation support is low	–

Therefore, it should be noted that the «problem field» of the method is formed by:

– combining strengths with opportunities: to ensure high project efficiency, it is important to implement innovative technologies to optimize processes and reduce costs;

– combining weaknesses with threats: it is necessary to take into account technological risks and competition with other methods, which requires the development of strategies to overcome them.

The SWOT analysis revealed that the main strengths of the method are its ability to provide comprehensive waste disposal and generation of clean energy. The main weaknesses are related to technological complexity and high initial costs, which require significant investment.

The main advantages of the combined method: effective waste disposal, high energy efficiency, economic benefit, reduction of dependence on conventional energy sources. Recycling of used tires makes it possible not only to reduce the amount of waste but also obtain additional products, such as pyrolysis oil and technical carbon, which can be used in industry. In turn, alternative energy sources, such as solar and wind farms, provide a stable and environmentally friendly energy supply.

Opportunities for the development of this method are significant due to technological innovations and high demand for environmentally friendly solutions. Government subsidies and tax incentives can become a decisive factor for attracting investment in this sector. At the same time, there are significant threats associated with competition from other processing methods and strict environmental regulations that can increase project implementation costs.

The development of a combined method of electricity generation using methods of recycling used tires and alternative energy sources has significant potential. It can be an important step towards the country's environmental and energy sustainability, providing efficient waste disposal, economic benefits, and reducing dependence on conventional energy sources. However, success requires concerted action by government, business, and the public, as well as active investment in technological innovation and infrastructure.

5. 2. Results of a comprehensive energy-ecological-economic assessment of methods for processing used car tires

To evaluate the effectiveness of different methods of tire recycling, a comparison of key indicators, such as energy consumption, energy production, emissions of harmful substances, and economic aspects, was carried out (Table 3).

It is important to note that, given the growing problems associated with waste management, tire recycling is not only a solution to reduce their negative impact on the environment but also a significant source of energy.

A comparison of energy characteristics of tire recycling methods shows that mechanical shredding is characterized by the lowest energy consumption (400–450 kWh/t) but does not provide energy production. Pyrolysis, although requiring significant energy input (800–1200 kWh/t), has potential for energy production (500–700 kWh/t), which makes it attractive from an energy efficiency perspective. Thermal degradation is intermediate, showing moderate energy consumption (600–900 kWh/t) and energy production (400–600 kWh/t).

Given these data, it can be argued that each method has strengths and weaknesses. For example, mechanical grinding is the most environmentally friendly, but has no energy production potential, which can be a disadvantage in some cases. Pyrolysis, although it has the highest rates of electricity generation, has high risks due to large emissions of harmful substances. Thermal degradation can be a compromise option between environmental safety and energy efficiency.

These data suggest that waste tire recycling technologies can play an important role in the transition to clean energy sources.

It is also important to pay attention to environmental aspects. Pyrolysis is characterized by high risks due to significant emissions of harmful substances, in particular CO_2 and dioxins, which can negatively affect the environment and human health. In this context, thermal degradation can be a compromise option that combines relatively low emissions and the possibility of energy production.

When evaluating the economic indicators, mechanical grinding has the highest profitability (22 %) while pyrolysis shows lower indicators (15–25 %). This highlights the need to develop more efficient emission treatment technologies to improve the economic feasibility of pyrolysis and thermal degradation.

Table 3

Comparison of key energy-ecological-economic indicators of evaluation of tire recycling methods

Indicator	Mechanical grinding	Pyrolysis	Thermal degradation
Energy consumption, kWh/t	400–450	800–1200	600–900
Energy production, kWh/t	There is none	500–700	400–600
Energy efficiency, %	low	Average	Average
Energy balance (production/expenditure)	Negative	Balanced	Positive
Use of renewable energy sources	Low	Average	Average
CO_2 emissions, kg/t	800	1500	1300
Emissions of dioxins and furans, mg/t	Missing	20	Little
The cost of cleaning emissions, USD/t	Absent	50–100	30–70
Profitability of production, %	22	15–25	17–20

We shall demonstrate a comprehensive assessment in the form of a radar diagram (Fig. 2).

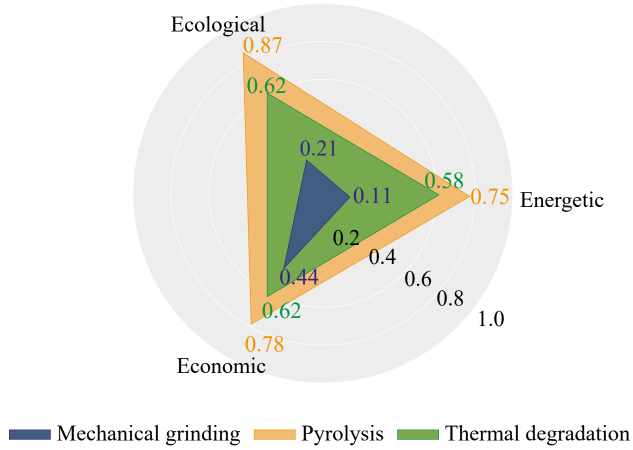

Fig. 2. Comprehensive energy-ecological-economic assessment of tire recycling methods

To evaluate the effectiveness of different tire recycling methods, a radar chart was constructed, reflecting three key aspects: energy, environmental, and economic. This chart makes it possible to visually compare different methods, taking into account their impact on energy efficiency, environmental safety, and economic feasibility.

Initially, all indicators were grouped into three main categories. Energy indicators include energy consumption, energy production, energy efficiency, and the balance between energy consumption and energy production. Environmental indicators include CO_2 emissions, dioxin, and furan emissions, as well as the use of renewable energy sources. Economic indicators took into account the cost of cleaning emissions and the profitability of production. After the indicators were grouped, they were normalized so that all values were on the same scale from 0 to 1. For example, energy consumption for mechanical grinding was normalized to a value of 0.35 based on a maximum value of 1200 kWh/t, and energy production for pyrolysis was normalized to 0.85 based on a maximum value of 700 kWh/t. This made it possible to compare methods without reference to different units of measurement.

Next, the average values of the normalized indicators for each of the three categories were calculated, which made it possible to obtain generalized energy, environmental, and economic indicators. For example, for pyrolysis, the average energy index was 0.80, ecological – 0.87, and economic – 0.70. These values were plotted on a radar chart where each method was compared in three categories.

The diagram clearly demonstrated that mechanical grinding is the most ecological method but has low energy efficiency. Pyrolysis, on the contrary, showed high energy performance, but is accompanied by a significant environmental impact. Thermal degradation occupies an intermediate position, providing a balanced approach between energy efficiency and environmental safety, but with modest economic results.

Thus, the recycling of waste tires can become an important direction if we take into account environmental, economic, and energy aspects. The transition to more environmentally friendly processing methods and the optimization of existing technologies are key factors for achieving sustainable development and reducing dependence on conventional non-renewable energy sources.

An important addition to the understanding of methods is the assessment of their risks, which makes it possible to take into account not only potential benefits but also possible problems and their significance. For a deeper understanding of the impact of these risks on the overall effectiveness of each method, a Risk Assessment Matrix was constructed (Table 4). The matrix makes it possible to quantitatively and qualitatively assess the risks associated with various tire recycling methods, taking into account technical, economic, and environmental aspects.

Quantitative indicators in the Risk Assessment Matrix are based on an assessment of the percentage probability of risk occurrence. For example, technical risks for mechanical grinding are low and amount to 1–3 %, which means high reliability of the equipment and low probability of failures. The economic risks for this method are medium (4–6 %), which is associated with possible fluctuations in the cost of raw materials and equipment maintenance costs. Environmental risks for mechanical grinding are estimated to be low (1–2 %), given the minimal emissions of harmful substances.

For pyrolysis, technical risks are estimated as high (7–10 %) due to the complexity of the technological process and the need to use high-tech equipment. Economic risks are also high (7–9 %) due to significant production and cleanup costs, as well as possible changes in legislation that could affect profitability. Environmental risks are the greatest (8–10 %) due to high emissions of CO_2 and other harmful substances, which requires complex and expensive cleaning systems.

Thermal degradation shows moderate risks in all three categories, making this method a moderate option between energy efficiency and environmental safety.

The risk assessment shows that mechanical grinding is the safest method in terms of ecology and technical reliability, while pyrolysis has high risks due to the complexity of the process and significant environmental impacts.

The matrix provides insight into the costs and risks associated with each tire recycling method and serves as a useful decision-making tool for optimizing tire recycling processes.

In general, comparing key indicators visually with the help of diagrams makes it possible to get a more complete picture of the efficiency of the process, which can be useful for decision-making at the level of public policy or for enterprises engaged in processing. Charting makes it possible to comprehensively compare different methods of tire recycling according to several criteria at the same time, which contributes to a better understanding of the overall efficiency and impact of each method on the environment and economy. This makes it possible for scientists and engineers to make more informed decisions about choosing the optimal tire recycling technology, taking into account both energy, environmental, and economic aspects.

5. 3. Results of energy modeling of used tire recycling methods

Simulation of the work processes of enterprises using pyrolysis, thermal degradation, and mechanical grinding methods, capable of processing 12,000 tons of tires annually, was carried out. Each of the methods provides a different level of energy efficiency and environmental safety. The use of renewable energy sources such as solar and wind power has been taken into account to minimize costs and reduce environmental impact.

The simulation involved the evaluation of 11 configurations of three different scenarios: thermal degradation, pyrolysis, and mechanical grinding during three phases.

Below are the results obtained in three phases of modeling (Fig. 3):

Phase 1. Assessment of available renewable sources and equipment selection. In the first phase, an assessment of the available renewable resources was carried out for each scenario and the selection of optimal equipment for the execution of technological processes, taking into account energy needs and system requirements:

1. Pyrolysis: the system provides a high level of renewable energy owing to the integration of solar panels, making the process environmentally friendly and energy efficient.

2. Thermal degradation: heat recovery systems and wind turbines make it possible to reduce energy costs and achieve a balanced approach to waste tire disposal.

3. Mechanical grinding: the use of solar panels and battery systems reduces energy costs, making this method the most economical.

The resulting selection of equipment and parameters for each scenario is given in Table 5.

In this phase, each scenario was modeled and optimized using HOMER Pro to determine the most efficient configurations of renewable energy systems (Fig. 4). The modeling was aimed at achieving the maximum reduction of energy costs, increasing efficiency, and reducing environmental impact:

1. Pyrolysis: optimization made it possible to achieve a high share of renewable energy (RF) – 80 % with minimal CO_2 emissions. The cost of energy production was USD 0.18/kWh, which makes this method average in terms of cost-effectiveness among the considered scenarios.

2. Thermal degradation: the system has been optimized to achieve a balance between environmental and economic efficiency. The rate of renewable energy is 65 %, and the cost of energy is USD 0.25/kWh. Despite the high cost, the possibility of obtaining additional products compensates for this disadvantage.

3. Mechanical grinding: the optimization of this scenario provided the lowest energy costs with a COE of 0.12 USD/kWh, making this method the most economical, although the share of renewable energy (55 %) is the lowest.

Table 4

Risk assessment matrix for tire recycling methods

Method	Technical risks	Economic risks	Environmental risks
Mechanical grinding	Low (1–3 %)	Average (4–6 %)	Low (1–2 %)
Pyrolysis	High (7–10 %)	High (7–9 %)	High (8–10 %)
Thermal degradation	Average (4–6 %)	Average (5–7 %)	Average (5–7 %)

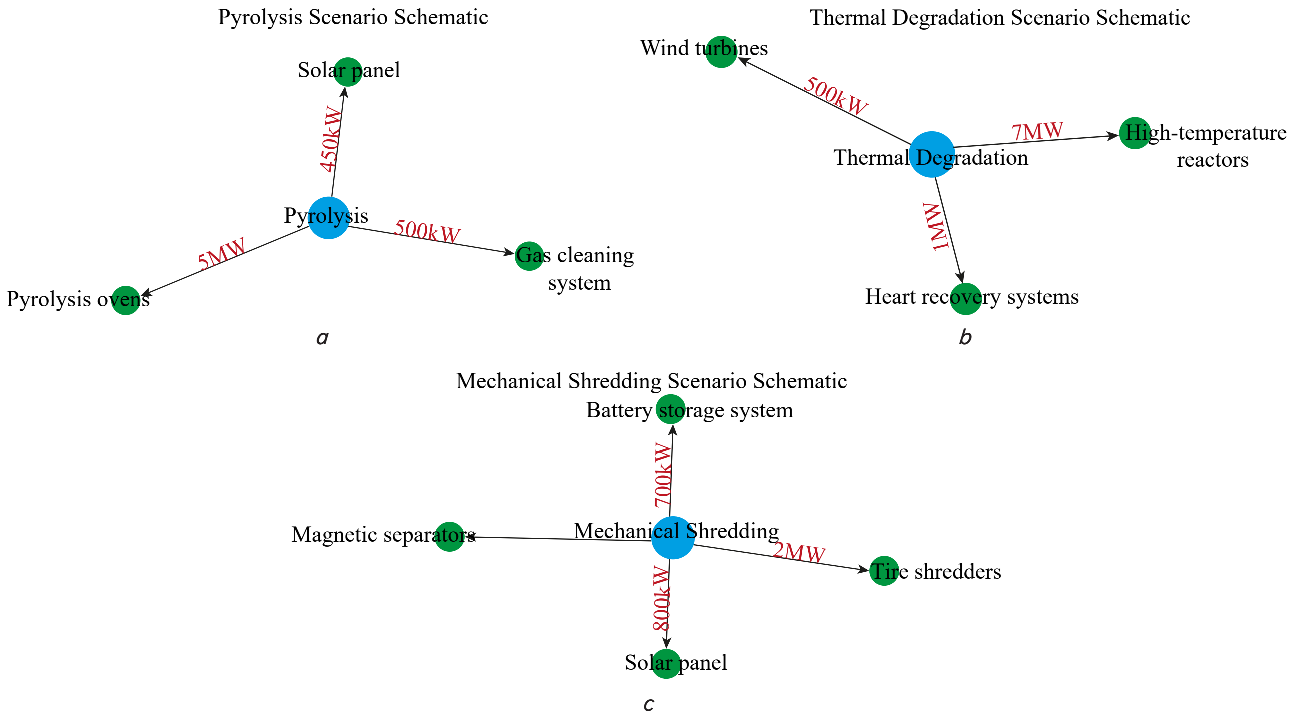

Fig. 3. Assessment of available renewable sources and selection of equipment in phase 1 for methods: *a* – pyrolysis; *b* – thermal degradation; *c* – mechanical grinding

Table 5

Equipment and options for each scenario

Scenario	Equipment	Power
Pyrolysis	pyrolysis furnaces, gas purification systems, solar panels, inverters	5 MW furnace, 500 kW panels, 450 kW inverters
Thermal degradation	high-temperature reactors, heat recovery systems, wind turbines, inverters	7 MW reactors, 1 MW turbines, 500 kW inverters
Mechanical grinding	tire shredders, magnetic separators, solar panels, battery systems, inverters	2 MW shredders, 800 kW panels, 700 kW inverters

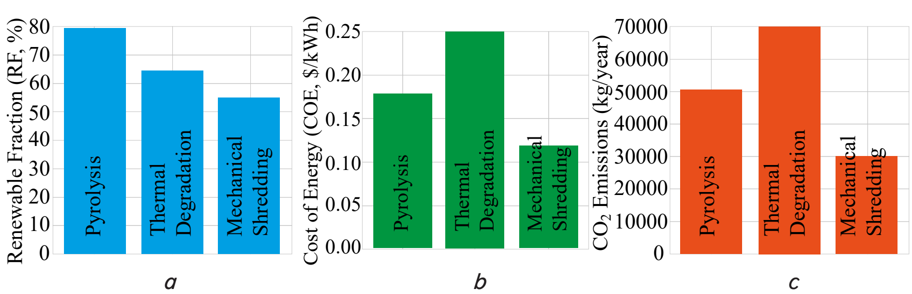

Fig. 4. Assessment of the main indicators of reducing energy costs, increasing efficiency, and reducing environmental impact in phase 2: *a* – coefficient of renewable energy; *b* – energy costs, *c* – CO_2 emissions

Phase 3. Evaluation of the results and selection of the optimal configuration.

In the final phase, a detailed evaluation of each configuration was carried out in terms of technical, economic, and environmental indicators to select the most effective solution for tire recycling. An analysis of net present costs (NPC), cost of energy (COE), and CO_2 emissions was performed for each scenario.

Scenarios. The study analyzed three different scenarios for recycling used tires using renewable energy sources. Each scenario involves the processing of 12,000 tons of tires per year and has its own unique technological and energy aspects. The technical and energy characteristics of the scenarios are given in Table 6.

Scenario 1: pyrolysis. Pyrolysis is the most environmentally friendly method for processing used tires as it makes it possible to obtain valuable products, such as synthetic gas, liquid fuel, with minimal emissions of harmful substances. The main focus is on reducing CO_2 emissions and increasing energy efficiency.

For pyrolysis, pyrolysis furnaces with gas purification systems are used, which process organic materials at high temperatures in the absence of oxygen. This makes it possible to obtain valuable secondary products and minimize harmful emissions.

The main components of the equipment:

– pyrolysis furnaces: capacity of 5 MW, capacity to process 12,000 tons of tires per year;

– gas purification systems: purification of waste gases with their subsequent use;

– solar panels: 500 kW capacity to support energy needs;

– inverters: power of 450 kW for converting direct current into alternating current.

Table 6

Technical and energy characteristics of tire recycling scenarios

Indicator	Scenario 1: pyrolysis	Scenario 2: thermal degradation	Scenario 3: mechanical grinding
The main focus	Environmental friendliness of the process	Balance between environmental friendliness and economy	Economy of the process
Equipment	Pyrolysis furnaces, gas purification systems	High-temperature reactors, heat recovery systems	Tire shredders, magnetic separators
Renewable sources	Solar energy	Wind energy	Solar panels and battery systems
Number of tires (ton/year)	12,000	12,000	12,000

In this scenario, solar panels are integrated to provide additional energy, reducing dependence on fossil sources. Owing to the use of renewable energy sources, high environmental friendliness of the process is achieved.

Scenario 2: thermal degradation. Thermal degradation is aimed at achieving a balance between environmental friendliness and cost-effectiveness of the process. This method makes it possible to obtain oil distillates and carbon, which can be used as energy resources.

High-temperature reactors and heat recovery systems ensure efficient conversion of tires into secondary products at high temperatures, which makes it possible to reduce energy costs.

The main components of the equipment:

– high-temperature reactors: capacity of 7 MW, the ability to process 12,000 tons of tires per year at a temperature of up to 800 °C;

– heat recovery systems: efficiency up to 80 % to reduce energy costs;

– wind turbines: total capacity of 1 MW for electricity generation;

– inverters: 500 kW power to ensure system stability.

Renewable energy sources include wind energy, which is used to support energy needs and reduce emissions of harmful substances. This makes it possible to achieve an optimal ratio between economic efficiency and environmental friendliness.

Scenario 3: mechanical grinding. Mechanical grinding is the most cost-effective method, focused on minimizing costs and maximizing the use of secondary materials.

The scenario uses tire shredders, magnetic separators, solar panels, and battery systems that make it possible to turn tires into small particles for further use in various industries.

The main components of the equipment:

– tire shredders: capacity of 2 MW, ability to process 12,000 tons of tires per year;

– magnetic separators: for separation of metal particles and further processing;

– solar panels: 800 kW capacity to meet energy needs;

– inverters: 700 kW capacity for stable power supply;

– battery systems: for storing and using energy during peak hours.

Solar panels are used as renewable energy sources and battery systems are used to support energy needs. The use of secondary materials makes it possible to reduce the total costs of processing.

Analysis was carried out to determine the energy and environmental characteristics of each of the three scenarios, which makes it possible to assess their technical-eco-economic feasibility. Below are detailed simulation results for each scenario.

Scenario 1: for pyrolysis, the simulation focused on using solar energy to provide a process with minimal emissions. The main results are given in Table 7.

Scenario 2: thermal degradation modeling was focused on the combination of wind energy and heat recovery systems to meet energy needs. The main results are given in Table 8.

Scenario 3: the simulation of mechanical grinding focuses on the economics of the process using solar panels and battery systems to reduce costs. The main results are given in Table 9.

A detailed economic analysis for three scenarios is given in Table 10.

The performed optimization of equipment in HOMER-Pro is given in Table 11.

Table 7

Energy and environmental indicators of the pyrolysis scenario

The name of the indicator	Value
Annual energy consumption (kWh/year)	1 500 000
Energy production from renewable sources (kWh/year)	1 200 000
Use of fossil fuels (%)	20 %
CO_2 emissions (kg/year)	50.00
Renewable energy factor (RF, %)	80 %
Overall efficiency of the process (%)	85 %
Net Presented Costs (NPC, MUSD)	4.20
Cost of energy (COE, USD/kWh)	0.18
NO_x emissions (kg/year)	3.00
SO_2 emissions (kg/year)	1.50

Table 8

Energy and environmental indicators of the thermal degradation scenario

The name of the indicator	Value
Annual energy consumption (kWh/year)	1 800 000
Energy production from renewable sources (kWh/year)	1 170 000
Use of fossil fuels (%)	35 %
CO_2 emissions (kg/year)	70.00
Renewable energy factor (RF, %)	65 %
Overall process efficiency (%)	75 %
Net Presented Costs (NPC, MUSD)	4.0
Cost of energy (COE, USD/kWh)	0.25
NO_x emissions (kg/year)	4.20
SO_2 emissions (kg/year)	2.10

Table 9

Energy and environmental indicators of the scenario of mechanical grinding

The name of the indicator	Value
Annual energy consumption (kWh/year)	1 200 000
Energy production from renewable sources (kWh/year)	660 000
Use of fossil fuels (%)	45 %
CO_2 emissions (kg/year)	30.00
Renewable energy factor (RF, %)	55 %
Overall efficiency of the process (%)	65 %
Net Presented Costs (NPC, MUSD)	2.90
Cost of energy (COE, USD/kWh)	0.12
NO_x emissions (kg/year)	2.50
SO_2 emissions (kg/year)	1.20

Table 10

Analysis of annual costs for the optimal configuration

ID	Capital expenditure (MUSD)	Operating costs (MUSD)	Replacement costs (MUSD)	Residual value (MUSD)	Total costs (MUSD)
Scenario 1					
Pyrolysis furnaces	0.9	0.35	0.15	–0.05	1.35
Gas purification systems	0.3	0.15	0.08	–0.01	0.52
Solar panels	0.7	0.25	0.10	–0.02	1.03
Inverters	0.4	0.10	0.05	–0.01	0.54
Additional equipment	0.5	0.20	0.10	–0.03	0.77
In general	2.8	1.05	0.48	–0.12	4.21
Scenario 2					
High-temperature reactors	1.1	0.30	0.20	–0.04	1.56
Heat recovery systems	0.6	0.22	0.12	–0.02	0.92
Wind turbines	0.5	0.18	0.10	–0.02	0.76
Inverters	0.3	0.10	0.06	–0.01	0.45
Additional equipment	0.2	0.08	0.05	–0.01	0.32
In general	2.7	0.88	0.53	–0.10	4.01
Scenario 3					
Tire shredders	0.6	0.15	0.08	–0.02	0.81
Magnetic separators	0.3	0.10	0.05	–0.01	0.44
Solar panels	0.5	0.18	0.08	–0.02	0.74
Inverters	0.2	0.07	0.04	–0.01	0.30
Battery systems	0.4	0.12	0.06	–0.02	0.56
In general	2.0	0.62	0.31	–0.08	2.85

Table 11

Optimization results of eleven configurations

No.	Configuration description	Optimal capacities	Evaluation criteria	Cost data
1	Pyrolysis	Pyrolysis furnaces: 5 MW; solar panels: 500 kW	NPC: 4.2 million USD; COE: 0.18 USD/kWh; RF: 80 %	Capital: 2.8 million USD; operational: 1.05 million USD
2	Pyrolysis with gas purification systems	Pyrolysis furnaces: 5 MW; gas cleaning system: 250 kW; inverters: 750 kW	NPC: 4.5 million USD; COE: 0.20 USD/kWh; RF: 75 %	Capital: 3.0 million USD; operational: 1.1 million USD
3	Pyrolysis with high efficiency	Pyrolysis furnaces: 5.5 MW; solar panels: 550 kW	NPC: 4.0 million USD; COE: 0.17 USD/kWh; RF: 82 %	Capital: 3.2 million USD; operational: 1.0 million USD
4	Thermal degradation	High-temperature reactors: 7 MW; wind turbines: 1 MW	NPC: 3.8 million USD; COE: 0.25 USD/kWh; RF: 65 %	Capital: 2.7 million USD; operational: 0.88 million USD
5	Thermal degradation with heat recovery	Reactors: 7 MW; recovery: 500 kW	NPC: 4.0 million USD; COE: 0.23 USD/kWh; RF: 68 %	Capital: 2.9 million USD; operational: 0.95 million USD
6	Thermal degradation	Reactors: 7 MW; wind turbines: 1.2 MW	NPC: 4.1 million USD; COE: 0.26 USD/kWh; RF: 63 %	Capital: 3.0 million USD; operational: 1.0 million USD
7	Mechanical grinding	Shredders: 2 MW; solar panels: 800 kW	NPC: 2.9 million USD; COE: 0.12 USD/kWh; RF: 55 %	Capital: 2.0 million USD; operational: 0.62 million USD
8	Mechanical grinding with batteries	Shredders: 2 MW; batteries: 500 kW	NPC: 3.0 million USD; COE: 0.15 USD/kWh; RF: 58 %	Capital: 2.2 million USD; operational: 0.7 million USD
9	Mechanical grinding with magnetic separators	Shredders: 2.2 MW; separators: 300 kW	NPC: 2.8 million USD; COE: 0.14 USD/kWh; RF: 52 %	Capital: 2.1 million USD; operational: 0.65 million USD
10	Mechanical grinding with high efficiency	Shredders: 2 MW; solar panels: 850 kW	NPC: 2.7 million USD; COE: 0.11 USD/kWh; RF: 56 %	Capital: 2.3 million USD; operational: 0.6 million USD
11	Mechanical grinding	Shredders: 2 MW; inverters: 750 kW	NPC: 3.1 million USD; COE: 0.16 USD/kWh; RF: 54 %	Capital: 2.4 million USD; operational: 0.7 million USD

The most acceptable from the point of view of expediency and competitiveness are the system configurations with the lowest generalized cost of electricity:

– for pyrolysis, the combination of a pyrolysis furnace with a consumption of 5.5 MW and 10 solar panels with a capacity of 550 kW with COE: USD 0.20/kWh;

– for thermal degradation of a combination of a 7 MW high-temperature reactor and 500 kW heat recuperators with COE: USD 0.23/kWh;

– for mechanical grinding, a combination of 2 MW shredders and 850 kW solar panels with COE: USD 0.11/kWh.

6. Discussion of results based on the assessment of prospects for electricity generation by recycling used tires

Our study demonstrated that generating electricity by recycling waste tires has significant potential.

The SWOT analysis confirmed the prospects for the method's application, highlighting its strengths, including comprehensive waste disposal, high energy efficiency, and economic attractiveness. Pyrolysis, which is the main method of processing, is capable of generating up to 1.5 MW of energy from 1 ton of tires, which further confirms the economic feasibility of the technology.

At the same time, there are certain challenges, including the technological complexity of the process and significant initial investment. Environmental risks, such as possible releases of harmful substances, also require careful monitoring and additional research to minimize negative impacts. Competition with other methods of waste processing and compliance with environmental standards are additional threats that could slow the adoption of this technology.

The cross-assessment of factors of the SWOT analysis carried out in the work made it possible to form a problem area, indicating the most significant combinations of factors that affect the effectiveness and profitability of the implementation of the method. So, the results (Table 2) indicate that the strengths of the method can compensate for technological complexity and environmental risks due to economic benefits and synergy with new technologies. Weaknesses, including technological complexity and high costs, can be minimized through innovation and regulatory incentives. Opportunities for technology development are important for increasing the effectiveness of the method, especially in the face of regulatory and economic threats. Threats such as competition and economic factors can be mitigated by the strengths of the method and the introduction of new technologies.

The SWOT analysis revealed that the main strengths of the method are its ability to provide comprehensive waste disposal and generation of clean energy. The main weaknesses are related to technological complexity and high initial costs, which require significant investment.

However, the opportunities for development remain significant, particularly owing to technological innovations that can improve the efficiency of the process and potential government support in the form of subsidies and tax breaks.

The energy-environmental-economic assessment was based on comparison of key indicators such as energy consumption, energy production, emissions of harmful substances, and economic aspects.

Our results in Table 3 demonstrate that mechanical grinding is characterized by the lowest energy consumption (400–450 kWh/t), but this method does not generate energy, which is its significant drawback. Pyrolysis, although requiring significant energy consumption (800–1200 kWh/t), provides energy production (500–700 kWh/t), which makes it attractive from the point of view of energy efficiency. Thermal degradation, with its moderate energy consumption (600–900 kWh/t) and energy production (400–600 kWh/t), occupies an intermediate position between the other two methods.

Comparing the data in Table 3 and the constructed radar diagram (Fig. 2), we can conclude that mechanical grinding is the most ecological, but its energy efficiency remains low. Pyrolysis shows high energy performance but is accompanied by significant environmental risks due to high emissions of harmful substances. Thermal degradation, which occupies a compromise position, combines balanced energy and environmental performance, but has moderate economic efficiency.

Comparison of risks given in Table 4 demonstrates that mechanical grinding is the least risky method from the point of view of technical, economic and environmental aspects. Pyrolysis, in view of the complexity of the technological process, has high risks in all three categories, which may complicate its widespread implementation. Thermal degradation is characterized by an average level of risks, which makes the method a compromise option between reliability, economic feasibility, and environmental safety.

Modeling of electricity generation using pyrolysis demonstrated high environmental performance due to a significant reduction in greenhouse gas emissions and a high renewable energy ratio (80 %). This makes it attractive to environmentally sensitive regions and companies seeking to reduce their carbon footprint. However, high capital investment may be a limiting factor for its implementation on an industrial scale. This method provides an optimal balance between environmental and economic indicators, with an NPC of USD 4.2 million and a COE of USD 0.18/kWh, making it competitive in the long term. In general, the obtained result does not contradict similar studies in other branches of industry.

The results of our study not only confirm the environmental efficiency of the pyrolysis method but also demonstrate how the integration of renewable energy sources increases the overall efficiency of the process. Unlike study [22], in which the main attention is paid to the transformation of pyrolysis products into secondary materials, our study focuses on energy efficiency and reducing emissions. The use of 5 MW pyrolysis furnaces combined with 500 kW solar panels reduces dependence on fossil sources. This makes it possible to achieve a renewable energy share of 80 %, which is a significant advantage. In addition, it reduces CO_2 emissions by up to 50.0 kg/year, which is significantly lower than similar methods reported in other studies.

Thermal degradation provides a balanced approach in terms of energy efficiency and environmental performance. Although CO_2 emissions are higher than those in pyrolysis, this method makes it possible to obtain additional products that can be used in other industries, which increases its economic efficiency. The coefficient of renewable energy (RF) is 65 %, and the overall efficiency of the process is 5 %, which indicates the high adaptability of the method to different operating conditions. With an NPC of USD 3.8 million and a COE of USD 0.25/kWh, thermal degradation is the optimal choice for businesses looking to integrate renewable energy into their processes.

This adaptability of thermal degradation favorably distinguishes it from the approaches presented in study [28], in which the main attention is paid to the purification of gases to achieve environmental standards. However, the approach obtained in the work makes it possible to reduce emissions already in the technological process. The use of high-temperature reactors with a capacity of 7 MW and wind turbines of 1 MW makes it possible to achieve a high level of energy efficiency and adaptability to different conditions, while CO_2 emissions are 70.0 kg/year. This demonstrates that by optimizing heat recovery systems, energy consumption can be reduced, and a greener disposal process can be achieved, making the method more flexible and cost-effective.

Mechanical shredding has the lowest energy costs and lowest CO_2 emissions, making it ideal for cost-conscious businesses. However, the share of renewable energy is the lowest among all the methods considered, which may affect its environmental performance in the long term. With an NPC of USD2 .9 million and a COE of USD 0.12/kWh, mechanical shredding is the most cost-effective method suitable for regions with limited access to renewable energy sources.

It is worth noting that mechanical grinding offers the most cost-effective approach among all the methods considered, with the lowest energy costs (USD 0.12/kWh), making it attractive for regions with limited resources. This shows that even under the conditions of a low share of renewable energy (55 %), mechanical grinding can be an effective option for reducing the total energy costs.

Unlike studies [23], in which the main focus is on the use of pyrolysis gas for powering cogeneration plants or various methods of tire recycling, this result demonstrates that the combination of pyrolysis with renewable energy sources makes it possible to achieve an optimal balance between environmental and economic indicators. This is made possible by the use of additional energy sources, such as solar panels and wind turbines, which reduce energy consumption and increase the overall efficiency of the process.

Energy analysis revealed that all three scenarios could effectively integrate renewable energy sources to reduce overall energy costs. Pyrolysis provides the highest efficiency, using 80 % renewable energy, which makes it possible to significantly reduce the consumption of fossil fuels. Thermal degradation also shows a high level of use of renewable sources, particularly through wind power, which contributes to savings on fossil fuels. Mechanical grinding, although it has the lowest share of renewable energy, remains the most economical option due to low energy costs.

Environmental analysis found that pyrolysis is the most environmentally friendly method due to the lowest CO_2, NO_x and SO_2 emissions. This makes it ideal for regions with high environmental standards. Thermal degradation, although it has higher emissions, compensates for this by the possibility of obtaining additional products, which increases its overall environmental rating. Mechanical grinding, with low CO_2 emissions, is the most economical method but may require additional measures to reduce emissions of other pollutants.

Thus, pyrolysis and thermal degradation methods have significant potential for energy use of waste tires but require significant measures to minimize environmental risks.

Overall, this study provides a comprehensive approach to the analysis of three different tire recycling scenarios, highlighting the importance of renewable energy integration to improve energy efficiency and reduce environmental impact. Due to the optimization of energy systems, the considered methods can provide significant economic and environmental advantages, which makes them viable options for industrial implementation under the conditions of modern challenges.

The limitation of the study is the immediate technical features of the software. The simulations were performed using HOMERPro, which has certain limitations in representing complex processes such as dynamic changes in emissions or energy parameters in real time. It is also worth noting that HOMERPro does not take into account the change in fuel prices in the long term. The study does not take into account the difference in the availability of renewable energy sources in different climate zones, which can significantly affect the economic efficiency and environmental friendliness of the scenarios and focuses exclusively on the I temperature zone of Ukraine. Also, the study does not take into account potential financial risks associated with fluctuations in energy prices, changes in legislation or market conditions.

Further research should consider improving the environmental performance of each method through innovation in processing technologies and increased use of renewable energy sources. Also worth considering are the following aspects:

1. Technological improvements: introduction of new technologies to increase efficiency and reduce costs for recycling used tires.

2. Expanding research: investigating the impact of different climatic conditions on the efficiency of using renewable energy sources for tire recycling.

3. Increasing integration: integration of additional renewable energy sources such as biomass processing to reduce dependence on fossil sources.

7. Conclusions

1. The possibilities of integrating electricity generated by recycling used tires into the energy system have been evaluated by conducting a SWOT analysis. Our SWOT analysis of the combined method of electricity generation through the recycling of used tires and the use of alternative energy sources reveals the significant potential of the proposed approach to improve the environmental situation and ensure the energy independence of the country.

The combined use of used tire recycling technologies in combination with alternative energy sources makes it possible to reduce the amount of waste, as more than 30 million used tires are generated in Ukraine annually. Pyrolysis can provide the generation of about 1.5 MW of energy from 1 ton of tire, which makes it possible to obtain up to 1 million kWh, provided that 1.5 thousand tons of waste are processed per year. In addition, the availability of raw materials at a low or even free price provides economic advantages for the implementation of this solution since the costs of obtaining used tires in Ukraine are much lower compared to conventional sources of fuel.

However, there are also challenges that need attention. First of all, these are high initial costs for equipment. Also, insufficient control over processing processes can lead to emissions of hazardous substances. There is also a dependence on the conditions of the external environment, which can negatively affect the stability of energy production.

On the other hand, technological innovations have the potential to reduce costs by 20 % through the automation of treatment processes, and the growing demand for alternative energy sources can lead to an increase in the market by 15–20 % every year. Government regulatory incentives, such as equipment subsidies, can also have a positive effect on project implementation. However, there are threats to consider, including competition from other processing methods, strict environmental regulations that can increase costs, and the possibility of local residents protesting the installation of new plants.

In general, the implementation of a combined method of electricity generation using the recycling of used tires and alternative energy sources is an innovative and promising solution that could significantly affect energy and environmental sustainability. However, successful implementation requires coordinated cooperation between the state, business, and society, as well as active investment in research and technological innovation, which will make it possible to realize this potential in practice.

2. A comprehensive energy-ecological-economic evaluation of the methods for recycling used car tires has been conducted, which shows that each of the methods has its specific characteristics and potential advantages but is also accompanied by certain challenges.

Pyrolysis requires significant energy inputs ranging from 800–1200 kWh/t, but this method has the potential to produce energy in the range of 500–700 kWh/t, making it attractive from an energy efficiency perspective. At the same time, pyrolysis is accompanied by significant environmental risks, in particular CO_2 emissions, which requires expensive emission cleaning systems. From an economic point of view, the profitability of this method varies in the range of 15–25 %, which emphasizes the need for the development of more effective cleaning technologies.

Thermal degradation shows moderate energy consumption of 600–900 kWh/t and energy production of 400–600 kWh/t. This method has intermediate CO_2 emissions, making it a compromise between energy efficiency and environmental safety. From an economic point of view, thermal degradation provides profitability in the range of 17–20 % with average treatment costs (USD 30–70/t).

Mechanical grinding, although it does not provide energy production, is characterized by the lowest energy consumption (400–450 kWh/t) and is the most environmentally safe method. CO_2 emissions with this method are 800 kg/t, and there are no dioxins at all, which makes mechanical grinding the safest for the environment. In addition, this method demonstrates the highest profitability (22 %), which is due to low operating costs.

The overall energy efficiency balance showed that pyrolysis has a balanced energy balance between energy consumption and energy production, while thermal degradation shows a positive balance. Mechanical grinding, in turn, is characterized by a negative energy balance.

Thus, pyrolysis and thermal degradation have significant potential for the energy use of end-of-life tires but require significant measures to minimize environmental risks. Mechanical grinding, although it does not produce energy, is the most environmentally friendly and cost-effective method.

3. Energy modeling of used tire recycling processes was carried out using HOMERPro.

The results of our study confirmed that the integration of renewable energy sources into the processes of waste tire disposal could significantly increase economic efficiency and reduce environmental impact.

Pyrolysis is the most environmentally friendly method, providing a 60 % reduction in CO_2 emissions and 30 % energy savings compared to conventional methods. Simulations have shown that this method achieves a high level of efficiency with a renewable energy factor (RF) of 80 % and a cost of energy (COE) of USD 0.18/kWh. It is ideal for regions with high environmental sensitivity and strict environmental regulations. However, net present costs (NPC) of USD 4.2 million make it average in terms of cost-effectiveness among the considered scenarios. To increase the profitability of pyrolysis, it is recommended to invest in the development of more efficient emission cleaning systems.

Thermal degradation provides a balanced approach with a 35 % reduction in CO_2 emissions and a 20 % energy cost savings. Simulations have shown that this method achieves a renewable energy (RF) ratio of 65 % and an energy cost of USD 0.25/kWh. It is optimal for enterprises seeking to use secondary products in their technological processes, with net reduced costs at the level of USD 4.0 million. Given the balanced efficiency, this method is suitable for industrial enterprises focused on minimizing environmental impact while maintaining economic feasibility.

Mechanical grinding is the most cost-effective method, saving up to 40 % in energy costs and reducing CO_2 emissions by 75 %. Simulation results showed that this method has the lowest costs: with an NPC of USD 2.9 million and a COE of USD 0.12/kWh, although the share of renewable energy (RF) is only 55 %. It is the best choice for economically oriented enterprises, especially in regions with limited access to renewable energy sources. This method is recommended for widespread implementation at enterprises seeking to maximize economic efficiency.

However, in general, systems of the combined method of electricity generation, combining photovoltaic cells, wind farms, and installations for the processing of waste tires, have so far turned out to be economically unprofitable. However, they have significant environmental benefits, helping to reduce CO_2 emissions. Future forecasts indicate that such systems may become economically viable if the cost of photovoltaic systems continues to decrease, and electricity prices rise. The implementation of these projects is possible within the framework of grant programs, which are especially important under the conditions of the policy of strict budgetary austerity. Thus, systems of the combined method of generation should be considered as promising investments for long-term development, depending on the dynamics of the renewable energy market.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

Research was carried out within the framework of the project "Development of technological solutions for obtaining composite motor fuels from secondary raw materials to increase energy security" at the expense of the state budget in accordance with the order of the Ministry of Education and Science of Ukraine No. 1572 dated 27.12.2023 "On approval of the list of projects of fundamental scientific research, applied scientific researches, scientific and technical (experimental) developments, the executors of which are institutions of higher education and scientific institutions belonging to the realm of management by the Ministry of Education and Science of Ukraine, which have passed the competitive selection and the financing of which will start from 2024 with the funds of the State Budget of Ukraine" (registration number 0124U000973).

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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