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Combined energy production systems with Stirling engines: Analysis of global experience and local prospects

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Abstract. The study aimed to identify the potential of combined energy production systems with Stirling engines by analysing international experience and assessing the prospects for their adaptation to local conditions. The study used an analytical approach to examine global experience, technical solutions, and conditions for the local implementation of combined energy systems based on Stirling engines. The study analysed global experience in the use of Stirling engines in combined energy systems in Europe (the Netherlands, Germany, the United Kingdom), Asia (Japan), and North America (using the example of the National Aeronautics and Space Administration), where they have demonstrated high energy efficiency and environmental friendliness. The results confirmed the possibility of effective application of these systems in Ukraine for decentralised energy supply using local resources. It has been determined that Stirling engines can be effective for decentralised energy supply to rural communities, medical institutions, educational institutions, and critical infrastructure facilities, especially in regions with access to biomass or household waste. It was established that the main barriers remain the high cost of equipment (from EUR 10,000 to EUR 13,000) and the lack of a production base. The payback period for such systems is 6 to 9 years, with annual energy savings of EUR 500-900. It was concluded that, with appropriate state support and localisation of production, combined systems based on Stirling engines have the potential for widespread use as part of a strategy for energy decentralisation and the transition to sustainable energy. In addition, the engines have a service life of 40,000 to 60,000 hours, and maintenance costs range from EUR 100 to EUR 200 per year. The study provided well-founded technical and economic conclusions on the possibility of adapting and implementing combined systems with Stirling engines in local energy conditions, which can serve as a basis for decision-making in the field of sustainable energy

Keywords: decentralisation; biomass; heat source; cogeneration; environmental friendliness

Introduction

Growing demands for energy efficiency, reduction of carbon dioxide emissions, and transition to renewable energy sources create new opportunities for the introduction of innovative technologies in the energy sector. One promising technology is combined energy production systems based on Stirling engines, which can efficiently convert thermal energy into electricity using various heat sources, such as solar energy, biomass, or industrial waste. The use of Stirling engines in energy systems, particularly in combined installations, is relevant due to the high potential of these technologies to increase energy efficiency and reduce harmful gas emissions. Y.S. Nikitin & V.M. Pavlenko (2024) investigated the possibilities of using Stirling engines to convert heat from biomass into electrical energy, noting their high efficiency in small-scale systems. The prospects for integrating these technologies into renewable energy allowed for a reduction in carbon dioxide emissions. A. Kubule *et al*. (2024) focused on the application of Stirling engines in microgeneration, especially in rural areas where access to centralised energy networks was limited. This was important for improving energy autonomy and reducing energy consumption costs. S. Zhu *et al*. (2021) compared the efficiency of Stirling engines with traditional heat engines, finding them to be significantly more energy efficient with minimal harmful gas emissions. The use of such engines in various sectors, including utilities

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and industrial installations, is promising. M. Sheykhi & M. Mehregan (2024) investigated the economic aspects of introducing Stirling engines, pointing to high initial costs as the main barrier to their widespread use. According to their findings, the long-term economic benefits due to reduced operating costs and energy losses can be significant. B. Shboul *et al*. (2021) studied the role of Stirling engines in bioenergy systems, especially in combination with other renewable energy sources such as solar and geothermal energy. The technical and economic analysis showed that the system achieved Stirling engine efficiency of 37% and a levelised cost of electricity of USD 0.13 to USD 0.15/kWh year, indicating its significant potential for application in bioenergy and small-scale energy projects.

G.T. Udeh *et al*. (2022) focused on the use of Stirling engines to improve energy efficiency in domestic settings. These systems were important for reducing dependence on traditional energy sources in households. E. Gholamian *et al*. (2024) focused on the environmental benefits of Stirling engines, comparing their CO_2 emissions with other types of generators. The environmental potential of these systems in reducing greenhouse gas emissions when using renewable heat sources was significant. J. Kramens *et al*. (2024) investigated the impact of Stirling engine implementation on energy security in remote regions, particularly in Africa and South America. These technologies could significantly improve access to energy in areas where there are no reliable sources of energy supply. M.D. Al-Nimr *et al*. (2023) focused on integrating Stirling engines with renewable energy sources to ensure a sustainable energy supply in the context of climate change. The opportunities for applying such technologies on the scale of small and medium-sized power systems were great. H. Xu *et al*. (2022) focused on the development of Stirling engine production technology, proposing innovative methods to reduce production costs. This had the potential to reduce the cost of the final product and promote its wider use for commercial and industrial purposes.

Despite these studies, some gaps remain that need further investigation: the impact of integrating Stirling engines into large-scale energy networks and the potential for reducing their production costs to enable mass deployment need to be explored in greater depth. In addition, little research has been done on the potential of Stirling engines in combination with other renewable energy sources, such as solar photovoltaic panels, wind turbines, and geothermal systems, especially in the context of climate change. The environmental performance of these combined systems under different climatic and operating conditions has also been insufficiently studied. The aim of the study was to assess the potential of combined energy systems based on Stirling engines, taking into account current requirements for energy efficiency and environmental friendliness.

Materials and Methods

The study included a comprehensive analysis of combined energy systems based on Stirling engines, aimed at identifying their potential in the context of modern energy transformation challenges. First, the principle of operation of the Stirling engine, which is based on the use of an external heat source, was studied in detail. This made it possible to determine the possibilities of using the engine with various types of heat sources, including solar radiation, heat from biomass combustion, as well as household and industrial waste. Particular attention was paid to the technical characteristics of the engine, such as quiet operation, low vibration, high efficiency in low-power systems, and durability with minimal operating costs.

The study included an analysis of global experience in the use of Stirling engine-based systems in various regions – Europe, Asia, and North America, which are distinguished by the active introduction of innovative energy technologies. In particular, examples of micro-cogeneration plants in the Netherlands (WhisperGen) (Power Engineering International, 2007), Germany (Viessmann) (Viessmann Werke GmbH & Co. KG, 2012), and Sweden (M Microgen Engine Corporation, n.d.) were considered. In the United Kingdom, combined heat and power cogeneration systems (Modern Power Systems, 2007) were tested in social housing, while in Japan, considerable attention was paid to the development of home cogeneration plants with increased energy efficiency as part of the ENE-FARM programme (Japan LP Gas Association, n.d.). Separately, initiatives in the United States were analysed, which included the use of Stirling engines in pilot projects on biomass, in solar thermal concentration systems, as well as NASA (National Aeronautics and Space Administration) space projects, in particular the Kilopower reactor using Stirling technology (Gibson *et al*., 2017) and the advanced Stirling radioisotope generator (Lewandowski, 2013).

To determine the practical potential, the main types of combined systems were classified: combined heat and power, concentrated photovoltaic Stirling, and biomass installations, where the engine performed the function of converting thermal energy into electrical energy. A technical and structural analysis of each type of system was carried out, taking into account their functional purpose, operational requirements, and adaptability to local conditions. Particular attention was paid to the prospects for the implementation of such systems in Ukraine. Data on the availability of local resources – wood, agricultural waste, and solid household waste – as potential energy sources for combined systems was collected and analysed. The potential benefits of using such technologies in various energy sectors were investigated, and key challenges that could affect their implementation and development were considered. The possibilities for adapting these systems to the climatic and infrastructural characteristics of Ukraine were taken into account.

At the final stage of the study, a scenario approach was used to model a hypothetical option for the implementation of Stirling engine technologies in the Ukrainian context. The methodology involved building a logical sequence for the implementation of pilot projects in communities with an existing raw material base of bioresources. The analysis included an assessment of the possibilities for integrating energy systems into educational and medical institutions with a focus on improving the energy sustainability of social infrastructure facilities. In addition, international technical assistance tools, grant funding, and sustainable development mechanisms were analysed for potential support.

Results

Stirling engine: Operating principles and advantages. The Stirling engine, which operates on the principle of an external heat source, is one of the most energy-efficient and versatile types of engines used in alternative energy sources. One of its key advantages is that it can run on any type of thermal energy, from solar radiation to heat obtained from burning biomass, household waste, or other organic materials. Thanks to its ability to convert various heat sources into mechanical energy, the Stirling engine is extremely flexible in its application, opening up new horizons for the use of renewable energy sources (Choque Campero *et al.*, 2024). One of the most significant aspects of this engine is its quietness and low vibration level. This is especially important for applications in places where noise and vibration can be a problem, such as residential or medical facilities. Stirling engines operate without explosive processes, making them much quieter than traditional internal combustion engines. As a result, these engines are suitable for use in environments where noise reduction is important for comfort and safety (Arslan & Kocakulak, 2023).

Another significant advantage of Stirling engines is their high heat-to-electricity conversion efficiency, especially at low power. This allows Stirling engines to be used for power generation in cases where high efficiency must be maintained with limited resources or in small energy systems, such as micro-cogeneration plants or autonomous energy sources. Thanks to this efficiency, Stirling engines can be an ideal solution for energy systems powered by renewable sources such as the sun or biomass (Allouhi *et al.*, 2022). Stirling engines are also durable and have low operating costs, making them economically viable in the long term. Due to the absence of internal combustion and mechanical damage characteristic of internal combustion engines, Stirling engines have a significantly longer service life and require minimal maintenance (Laín *et al.*, 2024). This, in turn, reduces maintenance costs and makes them more attractive for a wide range of applications, from small domestic installations to large industrial solutions (Table 1).

Table 1. *Economic indicators of cogeneration plants with Stirling engines*

Parameter	Value
Average installation cost (household)	EUR 10,000-13,000
Payback period	6-9 years
Energy savings (annual)	EUR 500-900
Engine service life	40,000-60,000 hours
Maintenance costs (annual)	EUR 100-200

Source: *compiled by the author based on data from A.B. Awan et al. (2021)*

Thus, Stirling engines represent an extremely promising technology for ensuring energy independence and sustainability. They can run on a variety of energy sources while providing high efficiency, quiet operation, and low maintenance costs, making them attractive for use in a variety of settings, from residential areas to remote locations.

Global experience in the use of Stirling engines in combined energy systems. Thanks to their versatility and high energy efficiency, Stirling engines are actively used around the world to develop innovative combined energy systems. These systems combine heat and electricity production, making them extremely efficient in conditions where energy autonomy is required or there are restrictions on the use of traditional energy sources. Current global experience in the use of Stirling engines in such systems has demonstrated their high potential efficiency in various regions and areas. In the Netherlands, the market for micro-cogeneration systems is showing steady growth. It is expected to reach USD 115.6 million by 2025, with further growth to USD 270.6 million by 2035, corresponding to an average annual growth rate of 8.9%. WhisperGen company has been actively introducing compact units capable of generating electricity and heat for individual households, helping to reduce dependence on centralised heating and power supply systems (Power Engineering International, 2007).

In Germany, the Viessmann company has become one of the key players in the micro-cogeneration market with Stirling engines. Its units, in particular the 1 kW model, enable households to reduce their annual energy costs by 30-40% through optimised fuel use. The implementation of such systems is part of national energy transition programmes aimed at reducing the use of fossil fuels and CO_2 emissions (Viessmann Werke GmbH & Co. KG, 2012). In Sweden, which is known for its environmental awareness and sustainable development policies, Microgen Engine Corporation (n.d.) is actively promoting Stirling engine cogeneration systems for households. For example, in 2023, an autonomous system based on a biomass Stirling engine was installed at a ski resort near Sapporo, Japan, demonstrating the versatility and efficiency of such technologies even in harsh climatic conditions. In the United Kingdom, combined heat and power systems using Stirling engines are being actively implemented for the simultaneous production of heat and electricity in social housing. For example, the Goldsmith Street project was implemented in Norwich, which includes 105 residential units (45 houses and 60 apartments) and received the Stirling Prize for architecture (Fig. 1). This project provides a high level of energy efficiency and reduces energy costs for residents.

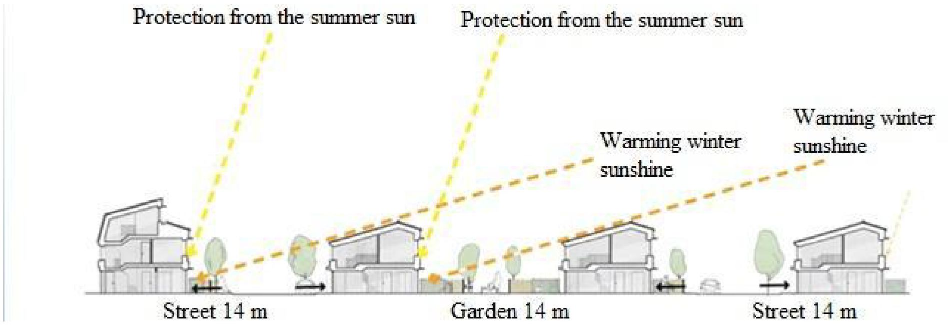

Figure 1. *Goldsmith Street project in Norwich, illustration of natural lighting*
Source: *Modern Power Systems (2007)*

This project demonstrated the effective use of natural lighting thanks to the thoughtful orientation of the buildings and the large window area. This reduces the need for artificial lighting and increases energy efficiency and comfort in the rooms. Japan is actively integrating Stirling engines into energy systems as part of the national ENE-FARM programme, which aims to develop domestic cogeneration systems. As of 2021, approximately 433,200 ENE-FARM systems had been installed in Japan, indicating the widespread adoption of this technology. In 2022, approximately 43,800 new systems running on city gas were sold. These systems allow households to efficiently use local resources to produce heat and electricity, contributing to a reduction in CO_2 emissions and dependence on imported energy sources (Japan LP Gas Association, n.d.).

In the United States, Stirling engines are used in a number of pilot projects aimed at the efficient use of biomass, solar energy, and geothermal sources. In particular, NASA is developing projects such as the Kilopower reactor using Stirling technology (Gibson *et al.*, 2017) and the advanced Stirling radioisotope generator (Lewandowski, 2013), which involve the use of Stirling engines for space power systems. The Kilopower reactor using Stirling technology project successfully passed ground tests in 2018, demonstrating its ability to generate up to 1 kW of electricity, which is an important step in meeting the energy needs of space missions. Global experience in implementing Stirling engines in various regions and energy sectors has demonstrated the significant potential of these systems in achieving high energy efficiency and reducing emissions (Fig. 2).

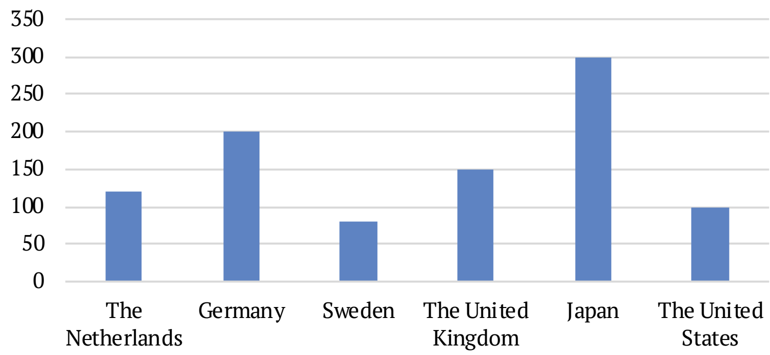

Figure 2. *Global experience in implementing Stirling engine systems: number of projects implemented in leading countries*
Source: *compiled by the author based on data from Power Engineering International (2007), Modern Power Systems (2007), Viessmann Werke GmbH & Co. KG (2012), E.J. Lewandowski (2013), M.A. Gibson et al. (2017), Japan LP Gas Association (n.d.), Microgen Engine Corporation (n.d.)*

Global experience has demonstrated a steady growth in interest in Stirling engine systems, especially in countries with developed energy policies and environmental standards. Japan is the undisputed leader in terms of the number of projects implemented, mainly focused on domestic cogeneration systems. In Europe, Germany, the United Kingdom, and the Netherlands are actively implementing these technologies in the residential sector, using both biomass and natural gas. Sweden stands out for its focus on decentralised heat supply using biofuels, while the United States focuses on industrial and medical facilities. This diverse approach demonstrates the flexibility of Stirling technology and its ability to adapt to different economic and climatic conditions.

Typical combined systems based on Stirling engines. There is growing interest in combined energy systems that combine electricity and heat production. Such technologies are important for ensuring energy efficiency, reducing carbon dioxide emissions, and rational use of local energy resources. One of the most promising solutions is the use of Stirling engines in combined energy systems. There are different types of such systems, each with its own characteristics and applications (Table 2). The combined heat and power system is one of the most common combined energy technologies, which allows simultaneous generation of electricity and heat. It is based on the principle of cogeneration, which ensures high fuel efficiency compared to traditional separate methods of electricity and heat production. Within this technology, Stirling engines run on heat sources of various origins, such as biomass, geothermal energy, solar heat, or even waste. This results in significant energy savings and reduced CO_2 emissions, making the system extremely important for sustainable development. Such systems can be used in industry, municipal services, and residential complexes (Razmi *et al.*, 2021). Another important technology is the concentrated photovoltaic Stirling system, which combines the concentration of sunlight using special concentrators and the conversion of this energy into electricity through a Stirling engine. In this case, the concentration of solar radiation collected using lenses or mirrors is focused on the heating head of the engine, which allows very high temperatures to be achieved and increases the efficiency of converting thermal energy into electricity. Concentrated photovoltaic Stirling systems are capable of producing large amounts of energy, especially in areas with high solar activity. This makes the technology very promising for solar power plants in sunny regions where traditional photovoltaic panels may be less efficient due to limitations in solar insolation (Kandil *et al.*, 2022).

Table 2. *Comparison of the efficiency of systems with Stirling engines*

Fuel type	Electricity generation efficiency (%)	Overall efficiency (including heat) (%)	CO_2 emissions (kg/MWh)
Biomass	15-20	75-85	<100
Natural gas	20-25	80-90	~200
Solar energy	18-22	–	0
Diesel	30-35	50-60	>300

Source: *compiled by the author based on data from A.R. Razmi et al. (2021), A.A. Kandil et al. (2022)*

Bioenergy plants using Stirling engines operate on heat generated from the combustion of biomass or waste. They can use organic materials such as wood, agricultural waste, household waste, and other biological materials to produce energy. Bioenergy plants with Stirling engines are an important part of the strategy for developing renewable energy sources. They not only reduce dependence on fossil fuels, but also help to effectively utilise waste that could otherwise become a source of environmental pollution. These systems are particularly relevant for rural areas where there is access to large amounts of biomass and other renewable resources. Bioenergy plants not only meet local energy needs but also address waste management issues, reducing the negative impact on the environment (Choque Campero & Araoz, 2024).

Combined energy systems based on Stirling engines provide high efficiency and flexibility in the use of various energy sources. They can be adapted to specific conditions and needs, making them extremely promising for a wide range of applications from industry to domestic needs. The choice between different types of combined systems depends on available resources, economic and environmental requirements. Undoubtedly, these technologies play an important role in the future energy landscape, helping to reduce dependence on traditional energy resources and reducing harmful emissions into the atmosphere.

Local prospects for the introduction of Stirling engines in Ukraine. The introduction of the latest energy technologies in Ukraine has significant potential for creating efficient and environmentally friendly energy solutions. One of the most promising areas is the use of Stirling engines in combined energy systems that run on various types of fuel, such as biomass, waste, and even solar heat. One of the main advantages of using Stirling engines in Ukraine is ensuring energy independence. Thanks to the ability to operate on local resources – such as wood, agricultural waste, or household waste – these technologies can significantly reduce dependence on imported energy sources. For example, imported gas accounted for about 30% of Ukraine's energy consumption in 2024, and the introduction of local cogeneration systems could reduce this dependence by 5-10% in the medium term. This not only reduces the cost of energy (up to 20% savings compared to centralised supply) but also supports the development of the local economy, which is an important factor for regions with limited resources for traditional energy supply (Khodakivskyi *et al.*, 2025). In addition, the use of combined energy systems with Stirling engines allows for the implementation of the principle of decentralised energy supply. This is particularly important for rural areas and critical infrastructure facilities, where traditional energy supply methods are often unavailable or unreliable. It is estimated that about 15% of villages in Ukraine have problems with access to a stable electricity supply, and decentralised systems can fully meet their needs (Davydenko *et al.*, 2022). Such decentralisation ensures a stable and efficient energy supply for small settlements, reducing the risks of energy crises. Another important advantage is the use of solid waste as a source of heat. Ukraine generates over 10 million tonnes of solid household waste every year, of which only 4% is recycled, with the rest ending up in landfills. Switching to technologies that allow this waste to be used for energy production not only helps solve environmental problems but also reduces the burden on landfills and waste processing plants. For example, a single 1 kW cogeneration plant fuelled by solid household waste can utilise up to 2 tonnes of waste per year, while generating electricity for one household. In addition, these systems can replace outdated and inefficient boilers and diesel generators used in remote areas. The energy efficiency of modern Stirling engine-based systems reaches up to 85% in combined heat and power mode. Not only are they highly efficient, but they also help reduce CO_2 emissions by 1.5-2 tonnes per year per household (Khalatov & Fialko, 2025).

Despite all the advantages, the introduction of Stirling engines in Ukraine faces several serious challenges. One of the main ones is the high initial cost of the equipment – the cost of a single micro-cogeneration unit ranges from EUR 5,000 to EUR 12,000, depending on the configuration. Such technologies require significant initial investments, which can be a barrier to implementation in small businesses or rural communities without adequate financial support. Another serious challenge is the limited local production base and experience in installing such units. Currently, there are only three companies in Ukraine that assemble or adapt imported micro-cogeneration systems (Luschini *et al.*, 2024). This leads to dependence on foreign technologies and increases transportation and maintenance costs to 20% of the total project cost. To overcome these barriers, government incentives such as "green tariffs", grant programmes and support for technology parks are needed. For example, with a subsidy of 30-50% of the cost of equipment, the payback period for such systems could be reduced from 8-10 to 4-6 years. This would not only reduce the financial burden on users but also promote local production and create up to 1,000 jobs in the renewable energy sector (Klymenko *et al.*, 2023). In the context of ongoing war and the need for large-scale reconstruction in Ukraine, the introduction of Stirling engines is particularly important. These technologies enable fast and efficient energy supply in destroyed or remote regions where centralised networks are often damaged or inaccessible. The use of local resources, such as biomass or solid waste, contributes not only to the restoration of infrastructure but also to the creation of new jobs, which is critical for stabilising the economy in the post-conflict period. Thus, Stirling engines can become a key element in the country's energy security and sustainable development strategy during its reconstruction.

Despite the existing challenges, the introduction of Stirling engines in Ukraine has great potential for the development of a sustainable energy sector. Technologies that allow the use of local resources and ensure energy independence can become a key element in achieving energy stability and environmental security in these regions. To maximise their effectiveness, it is necessary to develop infrastructure, support investment, and stimulate innovation in the field of renewable energy.

Recommendations for the implementation of Stirling engines. Given the great potential for using Stirling engines in energy systems based on renewable energy sources, it is important to formulate recommendations for their implementation in Ukraine. One of the first steps towards the implementation of combined energy systems with Stirling engines should be the implementation of pilot projects in communities with high biomass potential, such as rural areas or agricultural regions. The use of biomass as an energy source has significant environmental and economic benefits, particularly in terms of reducing greenhouse gas emissions and supporting local resources. Pilot projects will not only test the technologies but also demonstrate their effectiveness in practice, involving local communities and businesses in the implementation of renewable energy solutions. The integration of Stirling engine-based systems into educational and medical institutions can significantly improve the reliability of energy supply in these important sectors. This is particularly important for rural or remote areas where access to centralised energy supplies may be limited or unreliable. The use of combined systems will provide not only electricity but also heat, which is especially important for educational and medical institutions, where a stable energy supply is critical for continuous operation. Attracting state support through EU mechanisms is an important step in the development of Stirling engine-based technologies. Grant programmes, technical assistance, and other forms of EU funding can significantly reduce the financial barriers to the implementation of such systems. The EU actively supports innovative projects in the field of renewable energy, which allows countries, including Ukraine, to gain access to modern technologies and expert knowledge. This will help stimulate the development of green technologies and ensure the competitiveness of energy solutions in the region.

Another recommendation is to stimulate the development of local production of technologies based on Stirling engines. The creation of technology clusters in Ukraine will reduce dependence on imported components, reduce transportation and maintenance costs, and create new jobs. Attracting investors to create such clusters will contribute to the development of the industry, ensuring a high level of technological autonomy and reliability. The development of local production will also increase the level of knowledge and experience among specialists, which is critical for the effective application of the latest technologies. Overall, the introduction of Stirling engines in Ukraine has great potential for the development of a sustainable energy sector. For the successful implementation of these technologies, several strategic steps need to be taken, including pilot projects in communities with high biomass potential, integrating systems into medical and educational institutions, attracting support through EU mechanisms, and developing local production. Only with such a comprehensive approach can long-term success be achieved and the energy situation in the region be significantly improved.

Discussion

The study found that Stirling engines have a number of technical advantages that make them effective for use in modern energy systems. Thanks to its ability to operate on any external heat source, this type of engine is versatile in its application, especially in conditions of limited access to the centralised energy supply. Its quietness, low vibration, and long service life make it attractive for use in the residential sector and noise-sensitive facilities. This topic was also explored by C.R. Ghanem *et al*. (2022), whose results confirmed that the Stirling engine is a thermodynamic device that converts heat into mechanical energy through a cycle of gas compression and expansion. It can operate on any external heat source, making it versatile for use in hybrid energy systems that combine different energy sources such as solar, wind or biomass. This significantly increases efficiency and reduces carbon dioxide emissions, which is important for sustainable energy development.

Research by S.M. Vahidhosseini *et al*. (2024) also showed that one of the main advantages of the Stirling engine is the use of an external heat source, which allows it to operate without noise and vibration, which is a big plus for domestic applications. The engine's quietness makes it ideal for use in residential areas, especially in environments where noise tolerance is low, such as homes, offices, or medical facilities. In addition, the efficient use of heat allows the Stirling engine to provide stable and reliable energy without the need for complex or expensive fuel resources. It should be noted that although the Stirling engine has many advantages in the context of hybrid energy systems, its efficiency largely depends on the stability and quality of the heat source. High heat losses or insufficient source power can reduce the overall efficiency and performance of the system. In addition, to ensure optimal operation of the Stirling engine, it is necessary to use high-quality materials and engineering solutions, which can lead to additional costs at the initial stage of introducing such technologies into domestic or industrial energy systems.

International practice has confirmed the effectiveness of using micro-cogeneration systems based on Stirling engines in various regions. In European countries, these technologies have become widespread thanks to government support and favourable renewable energy policies. The results of implementation have demonstrated the possibility of improving energy efficiency and reducing greenhouse gas emissions in the residential sector. G. Battista *et al.* (2023) concluded that the implementation of micro-cogeneration systems in the residential sector in Europe is gaining popularity due to their ability to effectively reduce energy costs and carbon dioxide emissions. Such systems allow households to generate their own energy using a variety of sources, including solar energy, wind energy, and even Stirling engines. This contributes to the decentralisation of energy and reduces dependence on external energy suppliers, which is an important aspect for many European countries focused on sustainable development.

A study by T.A. Minale *et al*. (2024) found that government support is critical to the popularisation of Stirling technologies and micro-cogeneration systems in general. Subsidy programmes, tax breaks, and other incentives can significantly reduce the initial costs of installing such systems and increase interest among households and businesses. In addition, government initiatives can promote the development of infrastructure to support these technologies, which in turn helps attract investment and accelerate the transition to more environmentally friendly and independent energy systems. These results confirmed the above study, as they demonstrated the significant potential of micro-cogeneration systems to reduce energy costs and increase the energy independence of households. The findings indicated that even in the early stages of implementation, these technologies can deliver significant energy savings, which could lead to substantial benefits for both users and national economies in the future. In addition, the data confirmed the effectiveness of state support in promoting such innovations, creating conditions for wider dissemination and adaptation of these technologies at the population level.

The experience of countries with a high level of technological development has demonstrated the feasibility of integrating such systems into national energy modernisation programmes. In some countries, Stirling engines have been actively used as part of an autonomous energy supply in households, with an emphasis on the use of local resources. In some regions, these systems were part of programmes aimed at increasing the energy independence of the population. It is worth noting the work of L. Zhang *et al*. (2023), who also found that the use of Stirling systems as part of national energy policy could be an important element in reducing dependence on traditional energy sources and reducing greenhouse gas emissions. Many European countries are already seeing the gradual integration of such technologies into national energy security strategies, as they allow for greater decentralisation of energy networks. In particular, in countries with high levels of investment in renewable energy sources, Stirling systems can effectively complement other technologies, creating a more flexible and sustainable energy infrastructure.

In turn, Y. He *et al*. (2021) concluded that domestic cogeneration plants are a promising strategy for energy independence, especially in conditions of traditional energy resource shortages. They enabled households to generate their own electricity and heat, reducing their dependence on centralised energy suppliers. With rising energy prices and the need to transition to more sustainable and environmentally friendly solutions, such installations can become an important part of national strategies for energy security and energy system sustainability. These data are consistent with the results presented in the previous section, as they confirm that the integration of Stirling systems into national energy strategies can significantly improve energy stability and reduce greenhouse gas emissions. As the analysis showed, micro-cogeneration plants, particularly those based on Stirling technology, can significantly reduce the load on centralised power grids, which is especially important in times of crisis or energy shortages. Given the trends in Europe and other regions, such technologies are becoming key to achieving energy independence and strengthening national energy security in the long term.

Special attention was paid to promising technological solutions that combine Stirling engines with various heat sources – biomass, household waste, and solar energy. These systems have proven to be particularly effective for small settlements and remote facilities. They are capable of providing a stable energy supply with minimal environmental impact and without the need for significant infrastructure. S. Kallio & M. Siroux (2021) also conducted a study, the results of which confirmed that promoting decentralised energy supply through bioenergy Stirling installations has significant potential for the development of local energy systems, reducing dependence on centralised networks. Such plants can use various types of biomass, providing renewable energy sources for small consumers and reducing carbon emissions. The introduction of such technologies reduces the energy vulnerability of remote and rural areas, where traditional connection to power grids can be expensive or even impossible.

C. Geng *et al*. (2025) also found that integrating Stirling installations with solar and geothermal energy sources provides a stable and reliable power supply for remote consumers where access to traditional energy networks is limited. Solar panels can power the plant on sunny days, while geothermal sources provide stable heat throughout the year, increasing the overall efficiency of the system. Such a hybrid system optimises the use of renewable energy sources, increasing energy independence and sustainability in unstable or remote regions. Comparing these data with those obtained in the study, it can be concluded that bioenergy Stirling installations have significant potential for the development of decentralised energy supply, especially in rural and remote regions. In particular, their ability to use local biomass resources to produce electricity and heat significantly reduces energy supply costs and carbon dioxide emissions. This creates conditions for sustainable development and energy independence, which is an important step in implementing strategies aimed at preserving the environment and optimising energy costs at the local level.

In the context of local conditions, high potential for the use of Stirling engines in decentralised energy supply systems has been identified. The use of local waste and agricultural resources for heat generation opens up new opportunities for regional development. This was consistent with the findings of O. Sadovyi *et al*. (2025), who demonstrated that biogas and biomethane-based cogeneration technologies can ensure stable electricity and heat supply while significantly reducing greenhouse gas emissions and dependence on fossil fuels in Ukraine. At the same time, problems remain related to the high cost of equipment, limited technical base, and insufficient awareness among potential users. Y. Nikitin *et al.* (2024) concluded that the adaptation of Stirling engines into Ukraine's energy infrastructure is feasible given the availability of renewable energy sources, including biomass, solar heat, and geothermal resources. The introduction of these technologies will reduce dependence on imported energy sources and lower CO_2 emissions, which is important for Ukraine's commitments to reduce its environmental footprint. However, the widespread introduction of such systems requires significant investment in infrastructure, as well as support in the form of government programmes and subsidies to stimulate development in this area. R. Torres de Oliveira *et al*. (2022) found that local market constraints, in particular high investment barriers and a lack of technical expertise, are significant obstacles to the implementation of Stirling technologies in Ukraine. High initial costs for equipment and installation, as well as the need to train personnel and develop specialised engineering, may hinder the implementation of such systems. In addition, the lack of broad technical expertise in the country regarding the operation and maintenance of these installations may limit their effective use, requiring additional efforts to train and create conditions for the development of relevant competencies.

When analysing the results of the study, it is clear that, despite the great potential of Stirling engines for Ukraine's energy infrastructure, there are significant challenges to their implementation. This is due to the high initial investment and the need to create a technical base for servicing such systems, which requires both financial and human resources. However, if proper state support is provided in the form of subsidies or tax incentives, as well as investment in training specialists, these technologies can become an important element in the development of the national energy sector, especially in the context of global changes in the energy sector. In order to expand the application of these technologies, it is advisable to focus efforts on developing pilot projects, developing local production, and stimulating investment in this sector. It is also important to provide information support, and training for specialists for the effective installation and maintenance of such systems. A comprehensive approach will make Stirling engine-based technologies more accessible and contribute to the formation of a sustainable energy policy.

Conclusions

The study confirmed that Stirling engines are a promising technology for creating combined energy systems due to their technical characteristics, in particular their ability to operate on various heat sources, high efficiency, quietness, and durability. This versatility allows for the effective use of both traditional and alternative energy sources, including biomass, household waste, and solar heat. Global experience has demonstrated the widespread adaptation of micro-cogeneration systems based on Stirling engines in countries such as the Netherlands, Germany, Japan, and the United States. In Europe and Asia, the main focus has been on application in the residential sector and improving energy efficiency within the framework of government programmes. In the United States, Stirling engines have even found application in high-tech areas, particularly in NASA space missions. Special attention was paid to the possibilities of introducing such systems in Ukraine. It was found that they can significantly contribute to energy independence, reduce environmental impact, and develop decentralised energy networks in rural areas. The average cost of installation for a household is between EUR 10,000 and 13,000, with energy savings of up to EUR 500-900 per year, providing a payback period of 6 to 9 years. The engine has a service life of 40,000-60,000 hours, and annual maintenance costs are EUR 100-200. At the same time, key barriers have been identified: high technology costs, lack of production infrastructure, and insufficient installation experience. Therefore, the successful scaling of such systems in Ukraine is only possible with targeted state support policies, including pilot projects, subsidies, educational initiatives, and incentives for local production. Further research should look into the technical and economic efficiency of integrating Stirling engines into decentralised energy supply systems in Ukraine, taking into account local resource conditions.

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Conflict of Interest

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Комбіновані системи енерговиробництва з двигуном Стірлінга: аналіз світового досвіду та локальні перспективи

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Анотація. Дослідження спрямоване на виявлення потенціалу комбінованих систем енерговиробництва з двигуном Стірлінга шляхом аналізу міжнародного досвіду та оцінки перспектив їх адаптації до локальних умов. У дослідженні застосовано аналітичний підхід до вивчення світового досвіду, технічних рішень і умов локального впровадження комбінованих енергосистем на базі двигуна Стірлінга. У ході дослідження проаналізовано світовий досвід застосування двигунів Стірлінга в комбінованих енергетичних системах у Європі (Нідерланди, Німеччина, Великобританія), Азії (Японія) та Північній Америці (на прикладі Національного управління з аеронавтики і дослідження космічного простору), де вони показали високу енергоефективність і екологічність. Результати підтвердили можливість ефективного застосування цих систем в Україні для децентралізованого енергопостачання з використанням місцевих ресурсів. Визначено, що двигуни Стірлінга можуть бути ефективними для децентралізованого енергозабезпечення сільських громад, медичних установ, освітніх закладів та об'єктів критичної інфраструктури, особливо в регіонах з доступом до біомаси або побутових відходів. Встановлено, що основними бар'єрами залишаються висока вартість обладнання (від 10 000 євро до 13 000 євро) та відсутність виробничої бази. Термін окупності таких систем становить від 6 до 9 років, з річною економією на енергії в межах 500-900 євро. Зроблено висновок, що за умов відповідної державної підтримки та локалізації виробництва комбіновані системи на основі двигуна Стірлінга мають потенціал для широкого застосування як складова стратегії енергетичної децентралізації та переходу до сталої енергетики. Крім того, двигуни мають ресурс роботи від 40 000 до 60 000 годин, а витрати на обслуговування складають від 100 євро до 200 євро на рік. Дослідження надає обґрунтовані техніко-економічні висновки щодо можливості адаптації та впровадження комбінованих систем з двигуном Стірлінга в локальних енергетичних умовах, що може слугувати основою для прийняття рішень у сфері сталої енергетики

Ключові слова: децентралізація; біомаса; теплове джерело; когенерація; екологічність