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Analysing efficiency and economic aspects in organic Rankine cycle systems

Abstract: Research on the technical and economic aspects of organic Rankine cycle (ORC) systems is of great relevance, showing potential for reducing environmental impacts and improving resource efficiency, which becomes critical in the context of the rapid global transformation towards sustainable and energy-efficient solutions. The purpose of this study was to investigate the existing systems in the field of ORC systems, including the technical and economic aspects of their application in small-scale power units. The study employed the statistical method, comparative method, and analysis. The study highlighted the key aspects of the application of ORC technology in small-scale power units. Substantial attention was given to economic analyses to identify factors affecting the competitiveness of technology in the field of small-scale energy projects. An economic study found high unit costs

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to be the main obstacle to the widespread adoption of the ORC in small-scale energy applications. This study also presented a technical review of the techniques for selecting the expander and working fluid. The analysis of these aspects revealed the main parameters affecting the efficiency and cost of the system. Optimization of the ORC to reduce unit cost was highlighted as a priority area for development, facilitating faster payback and widespread adoption of the technology. The role of the expander in the system and reducing the cost of high-speed power generators were also considered prominent factors for improving economic efficiency. The obtained findings may represent a valuable framework, enabling cost reduction in small-scale ORC systems and promoting the development of clean and economically competitive small-scale energy solutions.

KEYWORDS: working fluid selection, expander, power units, competitiveness, specific cost

Introduction

The organic Rankine cycle (ORC) is an innovative energy technology based on the use of organic working media to convert thermal energy into mechanical energy. This cycle, first proposed by French engineer George Claude Leon Rankine, differs from conventional cycles in that it uses organic matter instead of water or steam, allowing for operation at lower temperatures. A distinctive feature of the ORC is its applicability to a variety of industries, including power generation, heating, and even agriculture. The application of this technology in a variety of contexts requires careful analysis regarding the different operating conditions and needs of various sectors. The technical and economic parameters of this technology are also vital aspects to be carefully considered. The study of these aspects is important in the context of society's desire for energy-efficient and environmentally friendly solutions. Determining implementation and operation costs, analyzing resource efficiency, and assessing competitiveness regarding market requirements become crucial elements when considering the ORC's technical and economic aspects. Conducting such research not only contributes to understanding the potential of the technology but also provides the basis for informed decisions on its adoption and expansion in industry.

Dymytrov (2014) touched upon some aspects of the study of the ORC, including the best conditions for the use of the working fluid. This approach helped to discover how thermodynamic conditions change in the context of system operation. The analysis of the results highlighted the significance of further optimization of ORCs and provided valuable data for decision-making in the operation of this type of system. Imamov et al. (2019) also contributed to optimizing small-scale ORC systems by proposing a method to improve the economies of scale. The study found that a single radial inflow turbine can be used in systems with a small power output. This approach, which focuses on optimizing performance at different capacities, offers substantial advantages in system efficiency. The versatility of this approach reflects the potential for scalability, which is vital in the context of small-scale power units.

Tyutebaeva and Baybekova (2015) examined ORC power units in the context of their potential small-scale application for the modernization of the internal combustion engine (ICE). The study found that the system under study was not feasible due to its high cost. This finding highlights the importance of the economic aspect when studying the scalability of ODC systems and their applicability to concrete technology upgrades. Understanding the cost and cost-effectiveness constraints of such systems is essential for developing sustainable and real-world-applicable technology solutions. Sugirov et al. (2023) proposed an innovative spiral element heat exchanger for supercritical ORC systems, thereby successfully improving the heat transfer coefficient. This improvement substantially impacts cycle efficiency, as more efficient heat transfer promotes more efficient utilization of thermal energy in the system and will support the development of sustainable and energy-efficient technologies in the area (Ali et al. 2021; Ali et al. 2022). The research by Tokmurzin et al. (2018), supplemented with experimental data, touched upon the study of a radial turbine for the ORC system using R 245fa as a working fluid. The findings emphasize the potential of radial turbines in ODC systems and support their effectiveness in using certain organics.

Since the studies mentioned above have focused on investigating the detailed technical and operational aspects of ORC systems, the purpose of this study was to provide a complete analysis covering the technical performance and economic aspects of the various systems. To this end, the systems were considered in the context of their applicability and performance for small-scale power generation, as well as the technical features of the expanders and working fluids and economic feasibility issues.

1. Materials and methods

The comparative method, statistical method, and analysis were employed to conduct the study. They were used to evaluate the performance of ORC systems, identifying key factors affecting unit cost and general performance.

The statistical method was used to process economic data, highlight trends, and determine statistically significant relationships between various parameters of the ORC systems. This method allowed for a more in-depth analysis of the factors affecting the unit cost and efficiency of the systems. The statistical analysis findings provided valuable information for making informed decisions in the design and optimization of small-scale power units. The statistical method was also used to evaluate the cost-effectiveness of distinct types of expanders and working fluids in the systems. The evaluation helped identify the relationships between performance and cost parameters, which play a key role in developing system optimization strategies. In addition, a statistical method was used to evaluate the obtained data and determine the statistical significance of differences between different parameters of the ORC systems. It helped to identify patterns and trends as a function of changes in key factors such as power unit capacity and working fluid. The analysis of data by the statistical method has made a valuable contribution to support conclusions and recommendations for the optimization of ORC systems.

The comparative method implemented during the study proved to be an effective tool for comparing a variety of ORC technologies and solutions for small-scale power systems. This method highlighted the key features and benefits of technologies at different scales by allowing different technical approaches to be systematized, compared, and classified. Comparative analyzes of performance, efficiency, and technical characteristics have found the best parameters for small-capacity ORC systems. Based on key metrics such as efficiency, cost, and power, the results provided valuable criteria for selecting the best configurations of expanders and other system components. The comparative method also found trends in the development of ORC technologies as well as factors affecting their effectiveness under different operating conditions. The knowledge gained can serve as a basis for developing recommendations and strategies for optimizing ORC systems in small-scale power generation.

The detailed analysis also played a significant role in identifying the main features and the best parameters of ORC systems for small-scale applications. The analytical approach helped to systematically analyze the effect of different expanders and working fluids on system performance. Through this method, the best operating conditions were highlighted, which contributes to the efficiency and competitiveness of ORC technology in the context of small-scale power generation. These data also provide a valuable basis for further research and engineering developments in ORC to improve performance and cost-effectiveness. Thus, the statistical method, the comparative method, and the analysis enabled a detailed evaluation and comparison of several aspects of ORC systems for small-scale applications, including the choice of expanders and working fluids, as well as economic aspects, showing the main trends and the influence of each component on the system efficiency.

2. Results

At this point, ORC technology is showing maturity in the high-power area, reaching megawatt levels. However, difficulties arise when trying to scale this technology to lower levels, making small-scale installations less commercially attractive. Installation costs for smaller applications are still too high, making providing a reasonable return on investment difficult. The present study focused on the specific cost, considered as the ratio of the cost of each unit of the ORC to the power output, to assess the competitiveness of the power units.

Some other significant market barriers that would prevent small-scale ORC systems from being widely adopted were also identified. The main obstacle is still the high unit cost. The absence of economies of scale worsens this financial obstacle because smaller ORC facilities can have greater particular costs than megawatt-sized installations. Regulatory obstacles may also present difficulties since they may impose limitations or regulations on the use of specific organic working fluids, raising the expense of compliance. There are also technological obstacles in the way of integrating high-speed turbomachines with power generators because these systems may not be as cost-competitive as they may be due to the requirement for expensive and specialized components. To address these barriers, a multi-pronged approach is required. Small-scale ORCs could have lower startup and ongoing costs if research and development efforts to enhance system design, streamline manufacturing procedures, and create more affordable expanders and working fluids are sustained. Financial incentives and advantageous regulatory frameworks are examples of supportive policy initiatives that could increase the economic viability and hasten the adoption of certain clean energy solutions. For small-scale ORC systems to be widely adopted and to realize their full potential for sustainable electricity generation, these market barriers must be addressed through technological advancements and deliberate governmental assistance.

Determining the unit cost of production plays a significant role in assessing the competitiveness of ORC technologies compared to alternative power generation methods. The data presented in Figure 1 include specific costs of installed systems such as wind turbines, solarvoltaic arrays, ICEs, gas turbines, and hydroelectric power plants. This analysis helps to identify the cost level at which ORC technologies become attractive among the various power generation options.

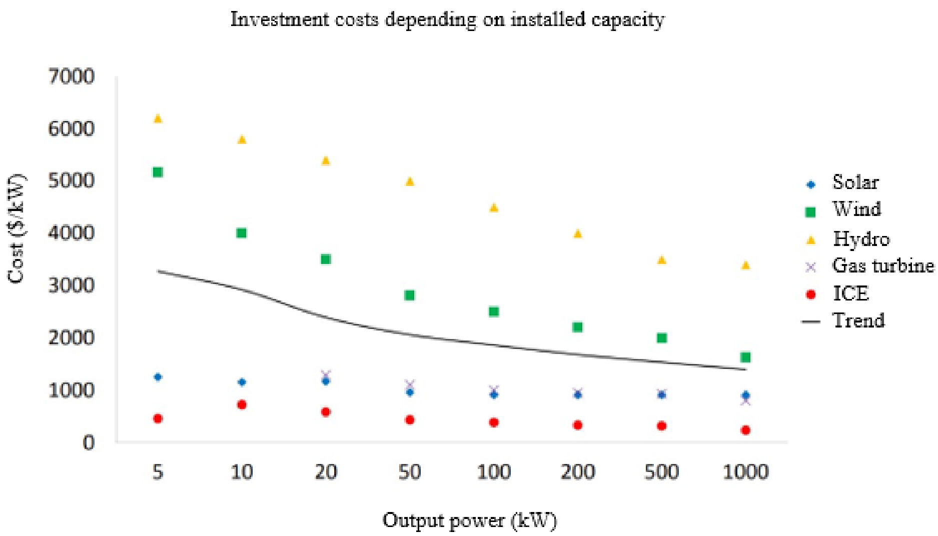

Fig. 1. Comparative graph of alternative energy sources
Source: Razmjoo et al. (2021)

Rys. 1. Wykres porównawczy alternatywnych źródeł energii

Figure 1 presents a trend line showing the average unit cost among all technologies studied. To assess the competitiveness of the ORC technology, this line was chosen as a reference indicator: if the unit cost of the plant falls below this line, then the technology can be considered competitive. According to the data presented in Figure 1, in such a case, the specific cost of

ORC units should not exceed the values of $3,500/kW (5–10 kW) and $2,500/kW (10–100 kW). Among the technologies with a unit cost below the chart average, ICEs, gas turbines, and solar energy stand out. Nevertheless, these technologies have certain disadvantages. Thus, ICEs and gas turbines depend on the use of fuel, which results in carbon dioxide (CO2) emission into the atmosphere (Fialko et al. 1994). This causes additional operating costs for fuel purchases and increases greenhouse gas emissions, which is a substantial factor in assessing their environmental impact (Gielen et al. 2019; Zhumadilova et al. 2023).

One of the key factors in the design of ORC systems is the selection of the working fluid, which impacts the efficiency, reliability, and environmental suitability of the entire system. However, despite active research in this area, no universal fluid is still ideal for all application scenarios for this technology. Different concrete conditions, such as temperature, pressure, cycle requirements, and particular process features, leave room for individual fluid selection depending on the system's particular tasks and application context. The example presented in Figure 2 illustrates the complexity of the selection of the optimum working fluid in ORC systems, providing clear evidence that this choice is closely related to the temperature of the heat source. The decision regarding the working fluid has a profound effect on the thermodynamic parameters of the system, its size, and its total cost, which confirms the significance of this choice in system design.

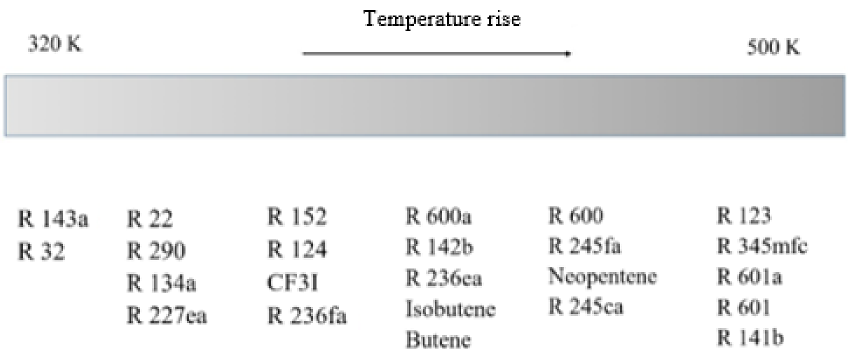

Fig. 2. Dependence of the working fluid selection on the temperature of the heat source
Source: Özcan and Ekici (2021)

Rys. 2. Zależność wyboru płynu roboczego od temperatury źródła ciepła

Investigating the best organic fluid for application in ORC systems is challenging and requires analysis from multiple perspectives. The process starts by differentiating liquids according to various criteria, and the first step may be to classify them based on their chemical composition. In this context, organic compounds are categorized into various groups, including alkanes and esters. Another important classification methodology is the separation of liquids based on the slope of the saturated vapor curve. According to this approach, wet, isoentropic, and dry fluids can be distinguished. Wet fluids have a negative slope of the saturated vapor curve; isoentropic fluids have an infinite slope; and dry fluids have a positive slope. Such a detailed classification allows considering the diversity of chemical and thermodynamic properties of organic liquids, which is an essential aspect in selecting the best option for a particular application in ORC systems (Thurairaja et al. 2019).

According to some studies, dry and isoentropic fluids are the preferred options when selecting the working fluid. This choice is based on several key considerations. Unlike wet fluids, dry and isoentropic variants can stay in the vapor phase throughout the entire expansion process, which prevents blade erosion. This is a significant aspect affecting the longevity and efficiency of the plant (Zhang et al. 2019). Furthermore, dry and isoentropic working fluids minimize the level of de-superheating, which reduces the total heat transfer surface. This has a substantial impact on the cost of the system due to the reduced need for additional heat exchangers. Notably, the use of extremely dry working fluids implies the need for cycle regeneration to improve general system performance. This can increase the size and total cost of the power unit. The selection of the best working fluid for ORC systems is a complex and multilink process. The first step is to limit the choices based on compliance with the requirements prescribed by the regulatory authorities. The thermophysical properties, including auto-ignition temperature, wear temperature, and freezing point, are then analyzed to isolate fluids that match the thermodynamic conditions of the heat source. Special attention is paid to the wear temperature, as it plays a major role in system reliability (Yakymenko et al. 2022). Wear and tear of the organic fluid requires replacement, which involves substantial operating costs. An interesting aspect noted in some studies is that the regeneration of used but not worn working fluid can substantially reduce the operating costs of ORC systems (Herath et al. 2020).

When selecting the fluid for the power unit, the maximum temperature of the working fluid and the heat output of the heat source are set. After a preliminary selection of options, the remaining fluids are examined in detail before making a final decision. A comparative analysis of working fluids in solar systems, considering their thermodynamic and environmental characteristics, emphasized that flammability plays a key role in selecting the best working fluid (Chowdhury and Ehsan 2023). The evaluation of the efficiency of the working fluid in an ORC system is subjected to a thorough thermodynamic analysis, which uses different methods depending on whether it is based on steady or dynamic (unsteady) models. A range of studies includes the application of genetic algorithms to the comparative analysis of organic liquids, where energy efficiency acts as an objective function (Kyshakevych et al. 2023). According to some results, it is noted that organic liquids are superior to water in utilizing energy from low-temperature heat sources, among which R236ea stands out as the best option. Furthermore, individual studies focus on the application of fluid mixtures in ORC systems. However, it is vital to remember that the use of such mixtures complicates the design of the components, as it is necessary to prevent fractionation of the fluid in the heat exchangers during the phase transition. This process involves the separation of chemical compounds into components, which requires special attention in engineering design (Hu et al. 2022).

Notably, the current level of technology in modeling ORC systems is often based on steady-state conditions, which may not be sufficient when considering the dynamic aspects of these systems. Dynamic models provide insight into the behavior of the system under transition conditions. This type of analysis becomes key in cases where the operating cycle of the heat source is subject to changes, such as in the case of vehicles or solar power units (Abdibattayeva et al. 2021). The specifics of the dynamic behavior of ORC systems are closely related to the characteristics of the selected working fluid; among them, an essential factor is the heat transfer properties of the organic fluid, which play a crucial role in determining the dynamics of the entire system. In practice, the heat transfer properties of the working fluid influence the design of heat exchangers, which are the components of the ORC system with the highest time constant. Working fluids with high heat transfer rates allow for more compact heat exchangers. This factor contributes to improving the ability of the ORC to respond quickly to changes in heat source conditions and reduce costs. There are situations where fast-responding systems become critical, especially when the heat source operates in a cyclic mode with no constant thermodynamic conditions, such as a stable temperature and/or mass flow rate. In this context, active research aims to develop the best control strategies aimed at maximizing the performance of the ORC system throughout the heat source cycle. A dynamic model was also proposed to investigate the behavior of small-scale ORC systems used for waste heat recovery (Abdibattayeva et al. 2020; Mikhailova et al. 2024). Small-scale ORC systems refer to power generation systems that utilize the Rankine cycle principle on a small scale with capacities usually below 100 kW, typically for decentralized or distributed power generation applications. This focuses on the analysis of the transient behavior of heat exchangers to develop an effective control system. This approach offers a deeper insight into the system dynamics and optimization of the processes according to the changing conditions of the heat source (Prokopov et al. 1993; Sanaye and Ghaffari 2023).

The study considered an operating map method for an ORC system centered on the selection of the most suitable working fluid, given a radial inflow turbine as an expander. This method allows for determining the best system operation parameters depending on the selected working fluid. It provides a more efficient choice of power media (Cappiello and Tuccillo 2020). Recommendations emerge from the review, highlighting the main parameters that influence the unit costs of small-scale ORC systems:

1. Price. The cost of organic fluids in ORC systems requires a careful search for the balance between economy and high performance. Generally, the fluids used in operating systems are often found in various industries, which helps reduce their cost through extensive use.

2. Density. The low density of the working fluid leads to increased volume flow, which substantially affects the various elements of the system. An increase in volumetric flow rate entails an increase in component size and, hence, cost. However, the high volumetric flow rate favors a lower expander speed, which is beneficial for the durability of turboexpanders. This trade-off requires careful balancing between operating costs and system reliability.

3. Condensation pressure. Preferably, the condensing pressure is as close to atmospheric pressure as possible. In the case of high condensing pressures, the overall system pressure increases, necessitating the use of stronger and, therefore, costlier materials. Reducing the condensing pressure below 0.5 bar increases the cost of sealing to prevent air from entering the system. Furthermore, lower pressures require larger condenser sizes, which can also affect the cost and size

of the system. The best selection of condensing pressure is important to ensure efficient system operation and minimize operating costs.

4. Freezing point. The freezing point of the working fluid must be substantially lower than the minimum ambient temperature at the location where the system is installed. This is to prevent solidification of the working fluid during periods of inactivity for the ORC power unit. A power unit capable of maintaining a sufficiently low freezing point ensures smooth operation of the system in various climatic conditions and prevents damage due to ice formation inside the system.

5. Upper cycle pressure. The upper-cycle pressure must stay well below the critical fluid pressure. This is to avoid liquid formation during expansion and to overcome possible instabilities in the case of evaporation. Reducing the top-cycle pressure enables the use of more economical materials, which benefits the total cost of the system. High pressure, although it assumes a higher fluid density, can reduce the size of the system. However, a compromise must be found by applying techno-economic analysis to balance efficiency, material costs, and overall system economics.

6. Heat transfer coefficient. The heat transfer coefficient plays a decisive role in determining the size and cost of heat exchangers. The choice of an organic compound with high thermal conductivity helps reduce the heat transfer surface. This entails a reduction in the overall size, weight, and cost of the ORC system. Optimization of the heat transfer coefficient is an essential aspect of the design process to create more efficient and economical power units.

7. Fluid decomposition temperature. To ensure system durability, it is necessary to avoid exceeding the decomposition temperature of the working fluid in the evaporator relative to the heat source temperature. This requirement is aimed at maintaining the stability and efficiency of the plant.

8. Molecular weight. The high molecular weight of the working fluid provides an opportunity to reduce the speed of the expander. This factor favors the efficiency of the expander and, as a consequence, usually reduces generator costs. This necessitates the significance of selecting organic compounds with a suitable molecular weight to optimize the performance of the ORC system.

Choosing the right expander is also an essential aspect. The availability of different options comes with both positive and negative sides, making it difficult to isolate the best extender. Notably, this component of the ORC plays a critical role when the capacity of the plants is reduced from the megawatt level to kilowatts, leading to a significant deterioration in their performance. In fact, efficiency falls below the 75% mark in some cases (Capata and Pantano 2020). Expanders in ORC systems can be classified into two main categories: volumetric and turbo expanders. Among volumetric expanders, spiral, screw, and bladed machines are the most common. On the other hand, radial inflow turbines, radial outflow turbines, and axial turbines are the most common types of turbomachines. A distinctive feature of turbomachines is that they are preferred in the high-power region, while they become inefficient in low-power production. This is mainly conditioned by the predominantly high rotational speeds that can cause bearing failure, making turbomachines less suitable for small-scale ORC power units.

Volumetric expanders are usually considered in the context of low power and tend to exhibit their effectiveness up to a certain power level. Above this level, the performance of volume expanders decreases, and their size increases exponentially. This results in increased cost and decreased practicality in the higher power ranges. In the context of small powers, e.g., in the 20–50 kW range, twin-screw expanders seem to be the most promising. This type of volume expander offers an efficiency of 70% at low rotational speeds. Small-scale ORC systems using twin-screw expanders can be installed at a cost of about $1,500/kW, making them an attractive solution in this power range (Chatzopoulou et al. 2019). Figure 3 shows a graph that gives recommendations for selecting the best expander based on specific velocity (N_s) and specific diameter (D_s). The parameters N_s and D_s are calculated as a function of the volumetric flow rate (V_3) and the adiabatic enthalpy drop of the expander (H_{ad}). Different types of expanders exhibit best performance in certain dimensionless parameter ranges N_s and D_s. For instance, piston expanders operate efficiently at low values of specific speed (0.01–0.1), while for radial turbines, the best N_s values are within 30–300.

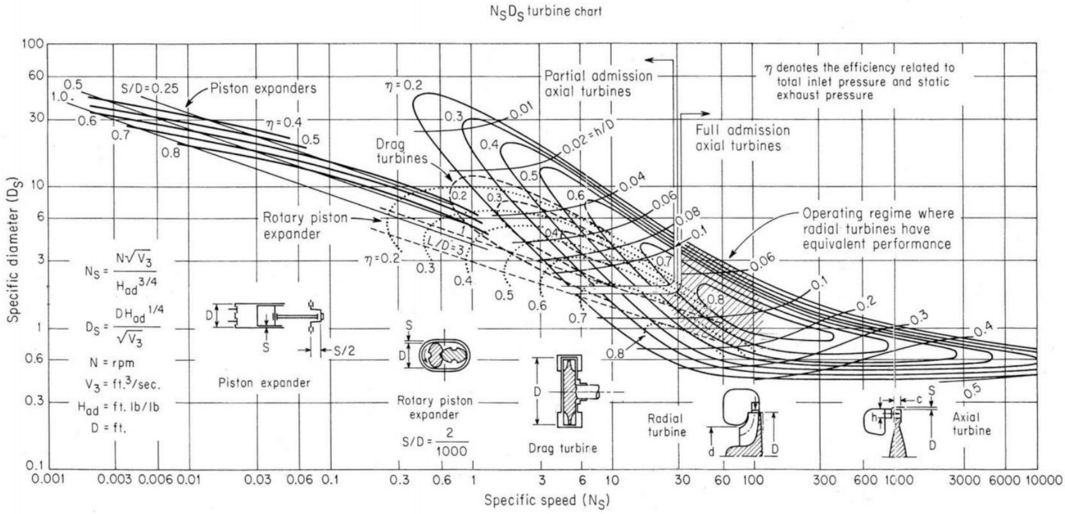

Fig. 3. Expander selection chart
Source: Alshammari et al. (2018)

Rys. 3. Tabela wyboru ekspandera

Notably, this graph is based on the findings of experiments carried out on operating plants using steam or air as the working fluid. Therefore, the values presented in the graph may be different when organic compounds are used as the working fluid. Nevertheless, a general conclusion can be drawn that piston expanders are characterized by large specific diameters and low rotational speeds, while radial turbines show the opposite parameters. The findings presented in Figures 4–7 detail the performance of experimental power units around the world in this range, showing that most of them operate within 1–10 kW. In such a case, according to the previous analysis, the vast majority of such power units are equipped with volumetric expanders. Notably, the top pressure and the coefficient of volume expansion stay at low values in most cases. The findings indicate that the efficiency of volumetric machines under these conditions can range from 50 to 80%.

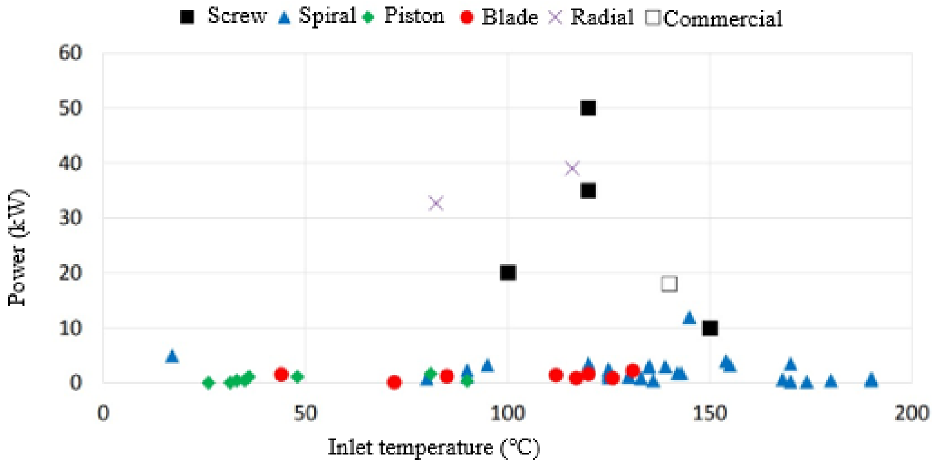

Fig. 4. "Temperature-power" expander experiment
Source: Carraro et al. (2019)

Rys. 4. Eksperyment z ekspanderem „temperatura-moc"

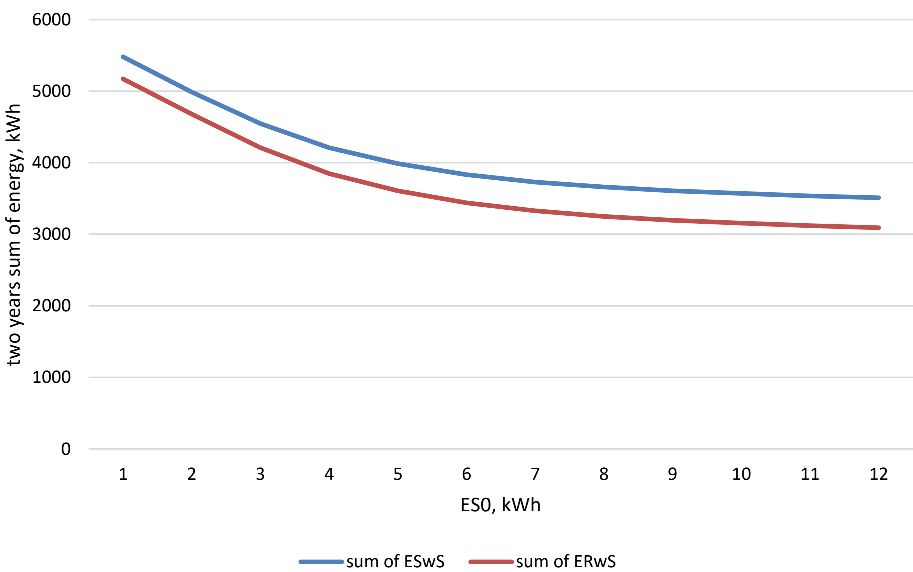

Fig. 5. "Pressure-power" experiment with expanders
Source: Carraro et al. (2019)

Rys. 5. Eksperyment „ciśnienie-moc" z ekspanderami

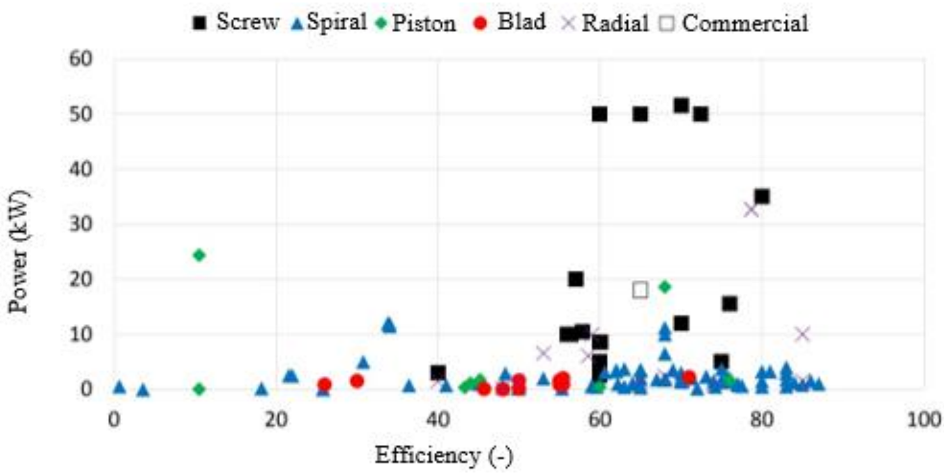

Fig. 6. “Coefficient of performance (COP)-power” expander experiment
Source: Carraro et al. (2019)

Rys. 6. Eksperyment z ekspanderem „Współczynnik wydajności (COP)-moc”

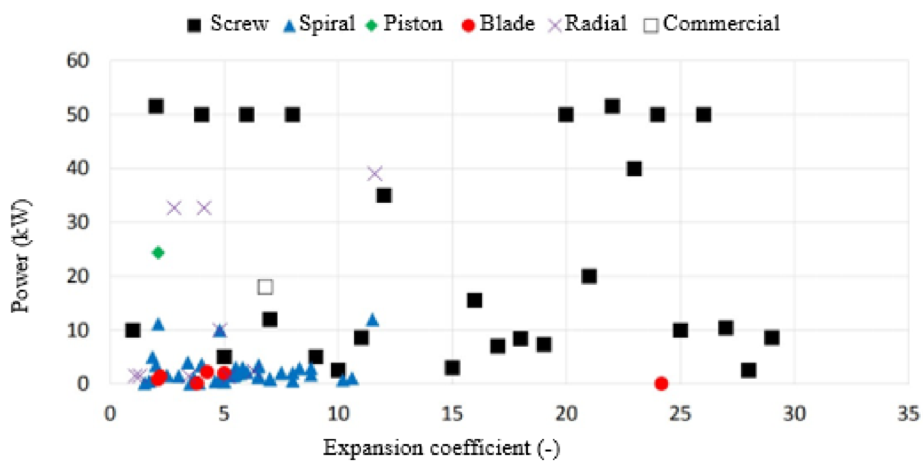

Fig. 7. “Efficiency-power” expander experiment
Source: Carraro et al. (2019)

Rys. 7. Eksperyment z ekspanderem „wydajność-moc”

Figure 8 presents a detailed classification of the experimental power units shown in Figures 4–7, as well as some commercial power units, with respect to the type of expander used. This classification enables a detailed analysis of the variety of technologies used and the preferences for the selection of extenders in different research and commercial projects.

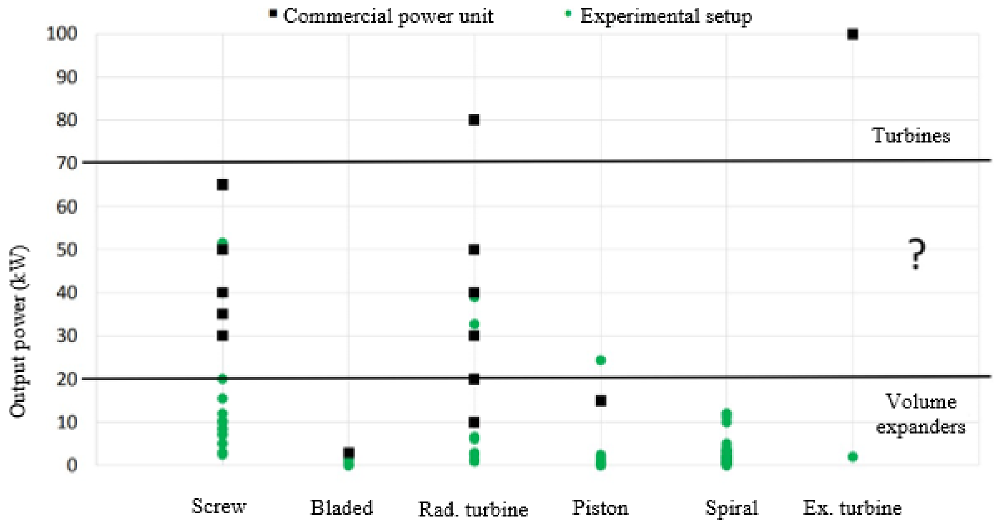

Fig. 8. Detailed classification of expanders
Source: Pantaleo et al. (2019)

Rys. 8. Szczegółowa klasyfikacja ekspanderów

As presented in Figure 8, the choice of expander depends substantially on the output power of the system. The data analysis conducted indicates that volumetric expanders are typically used in the power range of 0 to 20 kW, whereas turbomachines are preferred when the power is at values of 70 kW and above. For systems with capacities above these values, volumetric machines become bulky, and their performance may be reduced due to leakage. In the power range of 20 to 70 kW, the performance of both types appears to be approximately equal. Thus, the choice between the two often depends on the concrete situation. Interestingly, there is a discrepancy between the power output of experimental and commercial systems. In the academic environment, research is predominantly carried out on small power units, with subsequent expansion to higher capacities, while companies involved in ORC technology are mainly developing systems with capacities exceeding 50 kW.

One main aspect that makes volumetric expanders very attractive for integration into small -sized power units is their ability to operate smoothly even under substantial changes in the thermodynamic conditions at the inlet. This allows for high stability of operation under a wide range of conditions. An additional considerable advantage of positive displacement machines is their ability to operate at low speeds, often less than 3,000 rpm, which offers the potential to reduce maintenance costs and increase system durability. The low speeds also eliminate the need for expensive and complex speed control mechanisms, which further contributes to a lighter design and lower total power unit cost (Wu et al. 2019). These factors make volume expanders an ideal solution for low-power applications, providing not only high efficiency over a wide range of operating conditions but also cost-effectiveness, making the use of ORC technology affordable and attractive for a variety of industrial and commercial applications. However, despite their many advantages, volume expanders have disadvantages, predominantly related to the lubrication process and leakages that affect volume and hydrodynamic losses. It is important to consider volumetric losses, which manifest themselves as a reduction in volumetric efficiency due to a reduction in the flow rate required to produce the work. Arising from the expansion gap, these losses form an integral part of the process and are virtually impossible to eliminate (Francesconi et al. 2022).

Furthermore, hydrodynamic losses represent a separate class of problems, subdivided into concentrated and distributed losses, which together have a substantial impact on the efficiency of volume expanders. In addition, as mentioned earlier, turbomachines may face a limitation in producing power below 10 kW due to high rotational speeds. This characteristic poses a challenge when integrating a turbine with a power generator by providing two alternative coupling options. One involves the use of a gearbox, which, however, results in a noticeable mechanical loss. Another option is to use a high-speed electrical generator that is directly connected to the expander. However, despite their effectiveness, the high cost of such systems affects the overall economic viability of ORC power units.

The map of high-speed power generators presented in Figure 9 summarizes the existing systems designed to operate at high rotational speeds. This visualization provides an overview of a variety of high-speed oscillator technologies and models used in different applications.

The examination of this data suggests that the most affordable options in the required power range are associated with the use of permanent magnet machines. This type of generator provides

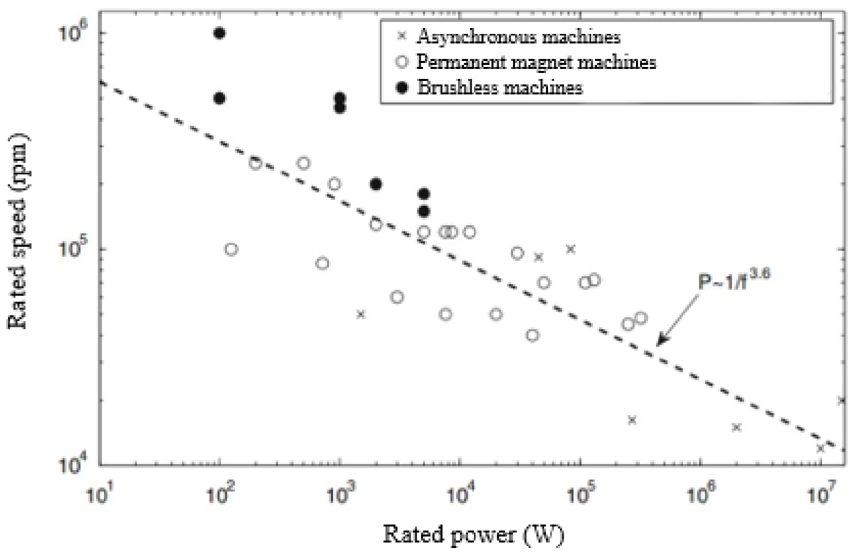

Fig. 9. High-speed power generators
Source: Park et al. (2019)

Rys. 9. Szybkie generatory prądu

the best combination of high efficiency and reliability at high speeds, which is a key factor for successful integration into ORC systems. Notably, matching the turbine to the power generator involves strict balancing, which requires minimum tolerances during the manufacturing process. This is an important circumstance affecting production aspects in the context of high-speed plant development.

The study's major conclusions emphasize how crucial it is to overcome the high unit cost, which is the primary barrier preventing ORC technology from being widely used in small-scale power generation. The particular costs of small ORC systems in the 5–10 kW and 10–100 kW categories need to drop to less than $3,500/kW and $2,500/kW, respectively, in order for them to be economically competitive. Technical decisions regarding expander type and working fluid optimization are crucial since they greatly influence how economical and efficient these small--scale ORC systems may be. Turbomachines become more practical above 70 kW, whereas volumetric expanders such as screw and spiral kinds have demonstrated potential at power levels up to 20 kW. However, the greater efficiency of turbomachines must be carefully evaluated against their higher cost. Improving the overall economic viability of small ORC power units also required lowering the cost of high-speed power generators combined with turbomachines. It will be essential to address these technical and financial issues through optimized system design in order to promote a quicker return and a broader uptake of small-scale ORC solutions that are effective and clean.

3. Discussion

A detailed study of the ORC represents a critical component in the development of efficient systems for converting thermal energy into mechanical work. This cycle is an essential element of modern power generation technologies, especially in the context of the use of organic working media that can improve process efficiency. The significance of investigating ORC stems from the possibility of creating environmentally friendly and efficient systems capable of operating on a variety of thermal energy sources. Research in this area focuses on the development of new materials for organic working media as well as on the optimization of processes related to thermal energy conversion (Zholamanova et al. 2023).

The ORC also plays a significant role in the development of renewable energy sources such as solar and geothermal energy. The use of ORC in these systems enables a more efficient conversion of renewable energy into electricity, which contributes to sustainable development (Kozhageldi et al. 2022). In today's world, where attention to energy efficiency and environmental issues is becoming increasingly important, the study of the ORC represents a relevant and promising area of scientific research. The findings of the present study not only enrich theoretical knowledge but also directly impact the development of clean and efficient technologies in the field of power generation. The significance of techno-economic research on ORC systems should also be considered. These studies play a key role in determining the degree of efficiency and competitiveness of ORC technologies in the energy solutions market (Orynbayev et al. 2023). Technical and economic analyses assess the impact of various parameters, such as equipment cost, operating costs, and energy performance, on the overall economic benefit of the system.

The study of the technical and economic aspects of small-scale ORC systems requires special attention. Small systems have their own unique characteristics, such as limited resources, compactness, and the need for high efficiency. Technical and economic aspects become even more significant in the context of small-scale installations, where even small changes in design or component selection can have a substantial impact on total performance and power costs. Such research can identify the best configurations, materials, and technologies for small-scale systems, helping to improve their efficiency and reduce operating costs. Furthermore, cost-benefit analyses provide a practical assessment of the viability of these systems in the marketplace and can be a deciding factor in their implementation. Thus, a combination of technical and economic research on ORC systems, especially considering their use in small-scale applications, is a necessary step to ensure the sustainable development and successful integration of this promising technology into the energy infrastructure.

According to Lin et al. (2019), spiral expanders are the best choice for system output power up to 25 kW. The distinctive feature of these expanders is their high efficiency, especially in cases where expansion occurs in the presence of a small amount of moisture and at the best volume ratio between the inlet and outlet sections of the plant. Spiral expanders show improved performance in slightly wet expansion conditions, making them an attractive option for low-capacity systems. This type of expander effectively copes with changing thermodynamic conditions, providing stable performance under various loads. It was also noted that the best volume ratio of the inlet and outlet sections of the plant contributes to an additional increase in the efficiency of the spiral expanders. Comparing this study with the current research, it can be emphasized that the latter focuses on the technical and economic aspects of the ORC in contrast to the former. According to the findings, spiral expanders are recommended in systems with relatively low output power. This makes them the best solution for small-scale power plants. Notably, spiral expanders demonstrate stable operation under various loads, which confirms their ability to effectively cope with changes in thermodynamic conditions. In the context of small systems up to 25 kW, spiral expanders can be considered the best solution given their high performance and stability under different operating conditions.

A study by Iodice et al. (2020) aimed at studying piston, screw, and spiral expanders singles out screw expanders as preferable for systems with power of 30 kW and higher. This type of expander has been given special attention because of its ability to effectively cover the requirements of systems with higher power output. Screw expanders also proved their superior performance in medium- to high-capacity applications, and their effectiveness was more noticeable when considerable volumes of media had to be handled. Thus, the findings of both studies confirm the significance of selecting a particular expander type based on the power requirements of the system, emphasizing that screw expanders can be an efficient and cost-effective solution for systems with higher power output. As a result of their study, the researchers point out screw expanders as an efficient and economically feasible solution for systems oriented towards medium and high-power generation, which makes their choice quite promising.

Wei et al. (2020) focused on the economic efficiency of small ORC systems within 30-60 kW and highlighted twin-screw expanders as the most promising in this power range. Based on the study's results, it is claimed that twin-screw expanders can achieve efficiencies as high as 70% at low speeds, making them highly effective in small-scale ORC systems. These results make twin-screw expanders an attractive and economically feasible option for small plants, especially in the context of cost optimization and improved power generation efficiency in the specified power range. When comparing the findings of the researchers with the results of the present study, it is worth noting that the results obtained not only confirm the significance of expander selection but also emphasize the need for and testing of twin-screw expanders in practice. Since economic parameters are key factors in the decision-making process for the use of ORC technologies, the findings of these studies can substantially impact the choice of expanders in concrete power plants. However, despite high efficiency and competitive cost advantages, twin-screw expanders may have certain technical limitations or operational requirements that should be considered when selecting them.

Alshammari et al. (2020) emphasize the lack of experimental research in the field of ORC systems with power greater than 30 kW. It was also noted that turbomachines are a better choice than volume expanders in the 80–100 kW power range. The substantial reduction in turbomachine speed after exceeding 80 kW plays an essential role in preventing bearing wear and facilitating the integration of the expander with the power generator. The marked reduction in size and weight of volume expanders above 80 kW faces challenges such as increased leakage, which reduces general efficiency. These factors emphasize the significance of judicious expander selection based on the required capacity of the ORC system while considering both technical and operational aspects for best performance. The results of the study conducted by the researchers present valuable considerations regarding the selection of expanders in power-dependent ORC systems. However, compared to this study, the researchers did not pay enough attention to systems up to 80 kW, where these devices can demonstrate high efficiency. The lack of experimental data confirms the need for additional research and practical testing to fully understand and optimize expander performance under different operating conditions.

A study by Xu et al. (2020) involved the use of "black box" analysis, where the ORC system was investigated in real time during the process. This method was used to model a double-loop ORC with offshore applications. However, it is noted that this approach, which analyzes the system as a whole, may have a negative impact on the design of individual components. Proceeding from the research conducted, methods were proposed that focus on considering practical constraints in the design of system components. Such methods make it possible to relate the choice of thermodynamic parameters to the real constraints arising in the design process and to factor them in when modeling two-loop ORCs. The findings obtained by the researchers show the significance of balancing thermodynamic requirements and practical applicability, which can lead to optimizing the design process and improving the efficiency of ORC systems for marine applications. Comparing the study with the current research, it can be noted that the present study contributes to a more accurate representation of system performance in marine applications and provides more reliable results for the design of these systems.

Thus, despite the advances obtained in the study of the ORC, further research in this area remains needed. Such research will contribute to the wider commercialization of ORC technology in power plants of various scales, opening new opportunities for sustainable power generation and promoting clean and efficient energy solutions.

Conclusions

The study provided a comprehensive review of the current state of the art of ORC technology in the context of its application in small-scale power units. The focus was on economic analysis to identify concrete factors that could make this technology more competitive in the small power plant field. An economic study has identified the cost at which the technology becomes competitive in the context of small power generation. An important finding of the study is the identification of high unit costs as the main factor hindering the widespread commercialization of ORCs in the small-scale energy sector.

The study also presented a technical review of the techniques used in the selection of the expander as well as the working fluid in the systems. By analyzing these aspects, it is possible to highlight the key parameters affecting the efficiency and cost of the system. It can be concluded that optimization of the ORC system to reduce unit cost is a priority for development. This contributes to a faster return on investment and, hence, a wider spread of this technology in small-scale power generation. The role of the extender in the system also represents one of the key factors in determining general efficiency. One fundamental way to improve the economic efficiency of small-scale plants is to reduce the cost of high-speed power generators. Furthermore, the use of working fluids that can provide sufficient performance without the need for high turbine speeds can be a significant factor in improving the economic efficiency of ORC systems. To advance more deeply in this area, deepening research aimed at optimizing expanders, the choice of working fluids, and other prominent aspects of this technology is worthwhile.

These research areas contribute to the development of environmentally friendly and economically competitive small-scale energy solutions, create prerequisites for successful investment attraction, and ensure sustainable development in the field of power generation.

The Authors have no conflicts of interest to declare.

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Analiza efektywności i aspektów ekonomicznych w organicznych systemach cyklu Rankine′a

Streszczenie

Badania nad technicznymi i ekonomicznymi aspektami organicznych systemów cyklu Rankine'a (ORC) są niezwykle istotne, wykazując potencjał redukcji wpływu na środowisko i poprawy efektywności wykorzystania zasobów, co staje się krytyczne w kontekście szybkiej globalnej transformacji w kierunku zrównoważonych i energooszczędnych rozwiązań. Celem tej analizy było zbadanie istniejących systemów w dziedzinie systemów ORC, w tym technicznych i ekonomicznych aspektów ich zastosowania w małych jednostkach energetycznych. W analizie zastosowano metodę statystyczną, metodę porównawczą i analizę. Badanie podkreśliło kluczowe aspekty zastosowania technologii ORC w małych jednostkach energetycznych. Dużą uwagę poświęcono analizom ekonomicznym w celu zidentyfikowania czynników wpływających na konkurencyjność technologii w dziedzinie małych projektów energetycznych. Badanie ekonomiczne wykazało, że wysokie koszty jednostkowe są główną przeszkodą dla powszechnego przyjęcia ORC w zastosowaniach energetycznych na małą skalę. Przedstawiono również przegląd techniczny technik doboru ekspandera i płynu roboczego. Analiza tych aspektów ujawniła główne parametry wpływające na wydajność i koszt systemu. Optymalizacja ORC w celu obniżenia kosztów jednostkowych została wyróżniona jako priorytetowy obszar rozwoju, ułatwiając szybszy zwrot z inwestycji i powszechne przyjęcie technologii. Rola ekspandera w systemie i obniżenie kosztów szybkich generatorów mocy zostały również uznane za główne czynniki poprawy efektywności ekonomicznej. Uzyskane ustalenia mogą stanowić cenne ramy, umożliwiające obniżenie kosztów w małych systemach ORC i promujące rozwój czystych i ekonomicznie konkurencyjnych rozwiązań energetycznych na małą skalę.

Słowa kluczowe: dobór płynu roboczego, ekspander, zespoły napędowe, konkurencyjność, koszt jednostkowy