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Biomass-fueled stirling engine technology for sustainable electricity generation in remote areas of Indonesia: A review

T Suprianto[1*]

[1] Department of Mechanical Engineering, Politeknik Negeri Banjarmasin, Banjarmasin, Indonesia
[*]Corresponding author e-mail: teguh.suprianto@poliban.ac.id

Abstract

Indonesia, as the world's largest archipelagic nation, grapples with the challenge of providing equitable electricity access, particularly in remote regions. Limited infrastructure and accessibility have resulted in constrained electrical supplies for communities in these areas. This study presents a thorough literature review on the application of Stirling Engine technology fueled by biomass in addressing the power distribution challenges in remote Indonesian regions. The review focuses on the fundamental principles, advantages, and potential challenges of implementing biomass-fueled Stirling Engines in Indonesia. Economic feasibility and environmental impact assessments underscore the technology's potential. The methodology employed in this study involves a comprehensive examination of the literature, encompassing the review of scholarly articles and other pertinent publications. Findings indicate significant promise for biomass-fueled Stirling Engine technology in providing sustainable electricity solutions in Indonesia's remote, biomass-rich regions. However, challenges such as the use of specialized gases and considerations of reliability, equipment costs, maintenance, and efficiency highlight areas for further refinement. This research offers valuable insights for researchers, practitioners, and policymakers seeking sustainable energy solutions for remote electrification in Indonesia.

Keyword

Review, Biomass-fueled stirling, Engine technology, Sustainable electricity generation

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Introduction

Indonesia is an archipelagic nation consisting of approximately 17,000 islands. The widespread distribution of islands in Indonesia gives rise to numerous challenges in the realm of electricity. The issues surrounding electrical energy in Indonesia encompass a spectrum of challenges involving production, distribution, and consumption. Among the primary concerns is the heavy reliance on fossil energy sources. Indonesia remains significantly dependent on fossil energy, particularly coal, as the primary fuel for power generation. The majority of Indonesia's electrical power is derived from various sources, with coal contributing 59.9%, gas accounting for 22.3%, oil making up 6%, and the remaining 11.8% sourced from renewable alternatives [1]. This dependence gives rise to sustainability issues, air pollution, and environmental impacts. Despite efforts to develop renewable energy, achieving specific targets can be challenging due to technological limitations, implementation costs, and integration into the power grid. Additionally, there is the issue of unequal access. Disparities in electricity access persist across various regions, especially in remote areas. Although projects exist to enhance electricity access, geographical and social challenges remain significant obstacles. About 4,700 villages in the outermost, forefront, and lagging regions in Indonesia still do not have access to electricity. Several provinces, including West Kalimantan, North Kalimantan, East Kalimantan, Central Kalimantan, and Maluku, are still below 80% coverage in terms of grid electricity. Additionally, Papua and West Papua are below 50%, especially in difficult-to-reach locations [2].

Biomass energy in Indonesia refers to the utilization of renewable biological resources, such as agricultural waste, organic waste, and other biological materials, to generate energy. The agricultural sector produces biomass waste, such as rice husks and fruit peels. This waste can be utilized as raw material for biomass energy. Several power plants in Indonesia use biomass as fuel to generate electricity. Biomass can also be converted into biofuels, such as bioethanol and biodiesel, for use in the transportation sector. The Indonesian government has policies supporting the development of renewable energy, including biomass energy, to reduce dependence on fossil fuels. Efficient technology development and adequate investment are needed to enhance biomass energy production capacity. The use of biomass can help reduce greenhouse gas emissions and enhance environmental sustainability. Biomass energy can be one of the energy sources to diversify Indonesia's energy portfolio. With increased attention to sustainability and evolving technology, biomass energy has the potential to make a greater contribution to meeting Indonesia's energy needs sustainably. Presently, Indonesia has implemented various technologies for generating biomass electricity. These methods encompass direct combustion for use as coal power plant fuel or co-firing, conversion into refuse-derived fuel, gasification, deployment in sanitary landfills, and utilization in incinerators. Over the period from 2011 to 2019, the installed capacity of biomass power plants has achieved 1857.5 MW, constituting 33.78% of the 2025 target of 5500 MW [3].

Challenges in electricity supply in remote areas of Indonesia involve several issues that can impact the availability and distribution of electricity. Remote areas are often challenging to access, making the development of electrical infrastructure more difficult and expensive. Establishing electrical installations in remote areas may require significant investment. The transportation cost of fuel or electrical equipment to remote areas can increase the production cost of electricity. The primary challenges identified were the distinctive features of rural areas, which include a sparse population, limited income, and low demand for electricity [4]. Some remote areas may have limitations in energy resources, such as restricted access to fossil fuels or renewable energy sources. To meet the electricity needs, some remote areas rely on diesel engine generators (gensets) as the main power source, which can be a temporary solution but often expensive to operate and require routine maintenance. Gensets typically use fossil fuels such as diesel. Currently almost every isolated remote area electricity is powered by diesel generation system [5]. Dependence on these fuels can be problematic, especially if fuel supplies are disrupted or fuel prices experience significant increases. The operational costs of gensets, including fuel purchases and maintenance, tend to be high. This can burden communities in remote areas that generally have economic limitations. The advantages of diesel engine have diminished in significance, not just due to the continual rise in oil fuel prices but also, in numerous instances, because of insufficient fuel supply [5].

With the advancement of technology reaching remote areas, the increasing energy needs may surpass the limited capacity of power plants in remote areas, thus unable to meet the growing energy demands. The quality of electricity is also often a concern in remote areas, where voltage and frequency stability may not meet desired standards in some remote regions. The electrical distribution network in remote areas often experiences high energy losses due to outdated equipment or inadequate infrastructure. Addressing these issues requires sustainable and affordable solutions, including improving electrical infrastructure and utilizing renewable energy technologies. Providing electricity to remote areas in Indonesia requires solutions and alternatives that can meet the energy needs of the community sustainably. Utilizing renewable energy sources such as solar, wind, and water can be a sustainable solution. The development of solar power plants, small wind turbines, and micro-hydro power plants can be environmentally friendly options.

Although solar power plants have many advantages, there are some drawbacks that need to be considered. The installation cost of solar power plants is still relatively high, even though it has decreased with technological advancements. The prices of solar panels and energy storage systems (batteries) can be a constraint, especially for individuals with limited budgets. Additionally, solar power plants heavily rely on sunlight. During bad weather or nighttime, solar energy production can decrease dramatically. Therefore, efficient energy storage methods or additional energy sources are needed to ensure a consistent electricity supply. Another issue is that the energy storage systems (batteries) used to store solar energy are still under development. Complications in land ownership, unattractive tariffs, and a lack of policy support, as well as the absence of local experience, are challenges for this alternative [6].

Wind energy is also a significant potential source of power. Wind energy holds substantial potential as a renewable energy source, although there are some disadvantages or specific challenges related to its implementation in Indonesia. Wind energy heavily depends on the speed and consistency of the wind. In some regions of Indonesia, wind speed may not always be consistent, affecting the productivity of wind energy generators. Some areas in Indonesia experience seasonal changes, such as the rainy and dry seasons. These changes can influence wind patterns and the productivity of wind energy generators. Selecting the right location for wind turbine construction requires accurate mapping of wind speeds. This challenge may necessitate more in-depth studies to ensure that the chosen location is genuinely optimal. Some areas in Indonesia, particularly in remote islands, may face limitations in infrastructure that can support the construction and maintenance of wind turbines. Although the operational costs of wind turbines are relatively low, the initial investment in purchasing and installing turbines can be high. This can be a hindrance, especially for small-scale projects or in less developed regions. Given the substantial wind speed potential in specific regions, a more cost-effective approach to providing electricity to remote and rural areas is through hybrid systems compared to traditional standalone diesel power systems [5].

Micro-hydro energy is also a highly potential source for utilization in remote areas. Nevertheless, there are several drawbacks to consider. The energy efficiency of micro-hydro greatly depends on the availability of sufficient water in rivers or small streams. Dry seasons or changes in rainfall patterns can reduce water availability, diminishing energy production. Although the scale of micro-hydro energy is smaller than that of large hydroelectric power plants, the initial investment for building micro-hydro installations remains significant. This can be a hindrance, especially for small-scale projects or communities. The effectiveness of micro-hydro energy is highly dependent on suitable geographic locations and topography. Not all regions have conditions conducive to micro-hydro development, and improper location selection can reduce efficiency. The operation of micro-hydro requires good maintenance and management. Technical challenges such as water flow control and equipment maintenance may arise, especially with limited manpower. Development of this alternative energy sources is strongly influenced by geographical conditions [7].

From various alternatives, considerations of these weaknesses can serve as a basis to seek solutions or more sustainable and efficient energy supply alternatives in remote areas. One potentially promising technology is the utilization of Stirling Engines. Stirling Engines fueled by biomass or heat energy can be an efficient alternative for electricity generation in remote areas. Stirling Engines have advantages in terms of efficiency and can operate with readily available fuels. This technology may present a more sustainable solution to address the energy availability challenges in remote areas, with the potential to positively impact environmental sustainability and the well-being of local communities. External combustion Stirling engines are regarded as an alternative solution to address the escalating energy and environmental issues. This is attributed to their capability to operate with various heat sources and serve as an efficient energy conversion system [8].

This paper discusses the opportunities and challenges of utilizing Stirling engine technology for micro power generation, particularly in remote areas in Indonesia. The objective of this manuscript is to explore the extent to which Stirling engine technology can be implemented in Indonesia.

Stirling Engine Technology

Cycle and operation

Stirling engines and internal combustion engines differ in their heat-to-mechanical energy conversion methods, and their efficiency levels can be influenced by various factors. The following is a comparison of the efficiency levels between Stirling engines and internal combustion engines (Figure 1). Stirling engines utilize external heat to drive their cycles, allowing for more efficient utilization of heat from external sources, including renewable energy or waste heat. Stirling engines operate in a closed cycle, meaning there is no fuel combustion inside the cylinder, resulting in lower emissions and a cleaner environmental profile. The Stirling engine performs well at lower temperature ranges, enabling the utilization of heat sources that may not be sufficiently hot for internal combustion engines.

The Stirling Engine (SE) utilizes a working fluid such as air, helium, or hydrogen contained in a closed domain. The machine is heated by an external heat source at one end and cooled by an external cold source at the other end. The working gas pressure will increase when heated and decrease when cooled. The repeated heating and cooling process causes reciprocal movement of the piston, which can be converted into rotary movement through a mechanical drive system. The gas in a Stirling engine moves from the hot side to the cold side, experiencing alternating expansion and contraction. This piston movement is converted into useful mechanical work. The Stirling cycle is a reversible cycle, meaning the phenomenon can occur both as a machine producing mechanical power and as a machine converting mechanical energy into heat. The temperature difference applied to this engine produces mechanical power output. In this context, the Stirling engine is referred to as a heat engine. Conversely, applying mechanical energy to the same engine causes the process to produce heat or cold, and in this case, a Stirling engine can be referred to as a heat pump or coolant, depending on the direction of rotation.

Stirling Engine are systematically classified into three primary types, distinguished by the arrangement of compression and expansion chambers, namely: Alpha, Beta, and Gamma configurations (Figure 2). Each configuration represents a distinct design that influences the performance and efficiency of the Stirling engine. In the Alpha configuration, the engine incorporates dual power pistons situated in two separate cylinders [10]. Conversely, the Beta configuration features a single cylinder accommodating both the displacer and power pistons [11]. Meanwhile, the Gamma configuration employs two distinct cylinders, segregating the displacer and power piston functions [12]. The alpha configuration proves to be suitable for recovering waste heat in industrial sectors, particularly where high gas temperatures can be obtained. On the other hand, the beta and gamma configurations are more fitting for biomass and solar energy sources, characterized by lower and medium temperature differences [13].

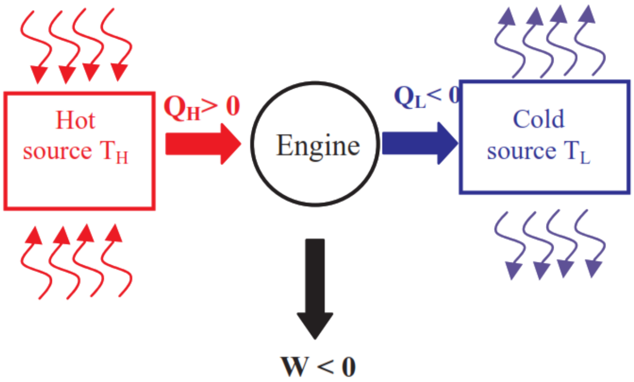

Figure 1. Working principle of Sterling engine [9]

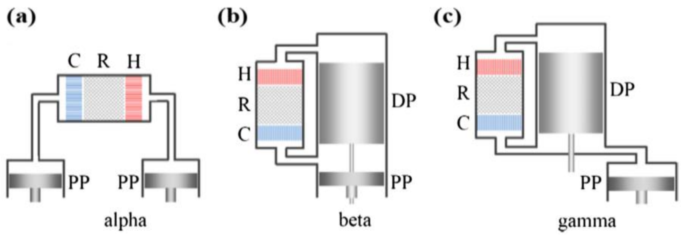

Figure 2. The three main configurations of Stirling engines: such as C: Cooler, R: Regenerator, H: Heater, PP: Power piston and DP: Displacer [14]

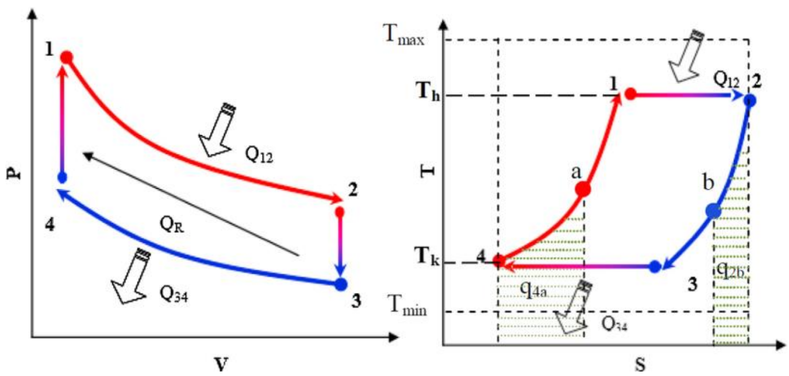

Figure 3. Theoretical cycle in the P-V and T-S diagrams of a Stirling engine [14]

Power and efficiency

Theoretically, the thermal efficiency of Stirling engines is deemed equal to the Carnot efficiency. This efficiency is recognized as the maximum achievable efficiency for heat engines [15]. While Stirling engines generally exhibit lower efficiency compared to internal combustion engines, especially at small to medium scales, simulation results indicate that a Stirling engine fueled by biomass can achieve a power output 87.5% greater than that of solar energy sources, with an efficiency of 46.67%. Stirling engines fueled by biomass demonstrate the potential for higher power output and thermal efficiency, addressing challenges commonly associated with the intermittency of solar energy [16]. In accordance with the ideal cycle, the Stirling engine undergoes four stages: isothermal expansion, isovolumetric cooling, isothermal compression, and isovolumetric heating (Figure 2). The theoretical thermal efficiency of this cycle equals the Carnot efficiency, denoted by the ratio of low and high temperatures (TC and TH). Carnot efficiency represents the maximum thermal efficiency achievable by any heat engine. Equation (1) outlines the practical thermal efficiency (η_{th}) of a Stirling engine, expressed as the multiplication of the Carnot efficiency and the Carnot efficiency coefficient. This coefficient (Cc) illustrates the ratio of the Stirling engine's thermal efficiency (η_{th}) to the Carnot efficiency.

$$\eta_{th} = \left(1 - \frac{Tc}{TH}\right) C_c \qquad (1)$$

Yanmar E-Stir Co., Ltd. has been developing power generation systems that use exhaust heat (waste heat) generated by industries. The engine produces a peak power output of 9.9 kW, operates with heat sources ranging from 500 °C to 800 °C, and provides a three-phase AC200-V output to the electrical grid [17].

Stirling Engine as a Micro Power Generator

Stirling engines are utilized in micro cogeneration systems, typically for domestic purposes. Rural areas in Indonesia, rich in biomass energy, can serve as a source of energy for Stirling engines. An additional advantage of Stirling engines is their versatility in combusting various fuels, including petroleum and biomass-based fuels. Stirling engines exhibit potential as micro-power generators in rural areas, with advantages stemming from their capability to operate on various fuels, including biomass such as wood or agricultural waste. This adaptability makes them suitable for rural regions where biomass resources are abundant. The ability to use various energy sources is one of the main advantages of Stirling engines [8]. Additionally, Stirling engines can operate efficiently using relatively low-temperature heat sources, making them applicable in rural areas with limited access to high-intensity heat sources.

Stirling engines tend to produce minimal noise and vibration during operation, making them environmentally friendly and suitable for quieter rural environments. The Stirling engine features a simple structure with few moving components, facilitating maintenance. This simplicity can be advantageous in rural areas where access to advanced technological maintenance may be challenging. Stirling engines can be utilized to harness residual heat from other processes in rural areas, such as heat from biomass stoves or waste heat from small-scale factories.

In rural areas, natural heat sources such as the sun or biomass may be more readily accessible. Stirling engines can be optimized to harness these heat sources. Because they can operate on local fuels, Stirling engines are not overly reliant on the availability of the general electricity grid. This can be an advantage in rural areas that may not be reached by the national power network. However, there are still several considerations such as initial costs, efficiency, and maintenance that need to be considered before adopting Stirling engines as micro power generators in rural areas.

Advantages and Disadvantages of Stirling Engine

Advantages

Stirling engines stand out in the realm of thermal efficiency when compared to several other types of engines, primarily owing to their operational cycle that can be regarded as an ideal Carnot cycle. The inherent design of Stirling engines allows them to achieve high thermal efficiency levels, making them notable for their performance in converting heat energy into mechanical work. This characteristic is particularly advantageous in harnessing heat from relatively low-intensity sources, such as solar energy or geothermal heat, where conventional engines may struggle to operate efficiently.

The ability of Stirling engines to function effectively at low temperatures enhances their suitability for harnessing heat from diverse sources. This versatility allows them to tap into unconventional heat reservoirs, expanding the scope of applications for renewable energy. Whether it be solar energy, geothermal heat, biomass, or industrial heat, Stirling engines demonstrate the capability to adapt and utilize various heat sources, providing flexibility in the realm of renewable energy applications. Stirling engine stands out for its captivating attributes. It can harness multiple clean energy sources spanning low, medium, and high-grade qualities. Stirling engines, in particular, exhibit commendable part-load performance and are adept at managing elevated heat sink temperatures. Moreover, they generate minimal noise, experience low vibration levels, and boast easier maintenance [18].

Furthermore, the Stirling engine's operation is characterized by low vibration and minimal noise generation [19]. This feature is particularly valuable in environments where noise pollution is a primary concern. The quiet and smooth operation of Stirling engines positions them favorably for applications in residential areas, urban settings, or any location where noise reduction is paramount. A notable advantage of Stirling engines is their capacity to produce electricity with a more stable output compared to some other renewable energy technologies. The continuous nature of their operational cycle contributes to a consistent power generation, minimizing fluctuations in energy production. This stability in power output is crucial for grid integration and reliability, addressing one of the common challenges faced by intermittent renewable energy sources like solar or wind. In addition to their efficiency and versatility, Stirling engines exhibit compatibility with various heat sources, making them an attractive choice for decentralized power generation [20]. Their adaptability to diverse environments and heat inputs positions them as viable candidates for off-grid applications, remote power generation, and distributed energy systems.

Disadvantages

Despite these advantages, Stirling engines are not without challenges. The limitations related to high-temperature efficiency, power-to-weight ratio, size, and response speed necessitate careful consideration and technological advancements. One drawback of the Stirling engine lies in its reactivity to varying mechanical power. The utilization of

Stirling engines for automobile propulsion was initially overlooked until it was explored for hybrid cars. A Stirling engine was integrated into a Ford Torino, but the prototype was not further developed, leading to the abandonment of the project. Notably, the Stirling engine faces limitations in its ability to rapidly change speed [21]. The Stirling engine has a relatively heavy and large design compared to some other engine technologies, making it less suitable for applications requiring high mobility. Stirling engines exhibit slower responses to load changes compared to internal combustion engines, rendering them less suitable for applications that demand instant responses to load fluctuations. Stirling engines did not garner as much attention as internal combustion engines because of their low specific power, lower efficiency, and prolonged start-up period [15].

The production and initial development costs of Stirling engines can be high, especially since the technology is still in the developmental stage and has not reached mass production levels. Some versions of Stirling engines use specific gas such as Helium to achieve optimal performance, thereby increasing production costs [20]. The efficiency of the compressor and expander in the Stirling engine can impact overall performance, and less efficient designs in these components can detrimentally affect the engine's overall efficiency. With limitations in high-speed applications, the Stirling engine is not optimal for applications requiring high rotational speeds.

Challenges of Stirling Engine Utilization

The utilization of Stirling engine technology, despite promising specific potentials and advantages, is not exempt from a number of challenges that need to be addressed. Several key challenges need attention to comprehend its constraints and potentials comprehensively. One of the primary challenges faced by Stirling engines is their efficiency at high temperatures. The engine's performance peaks at elevated temperatures, introducing concerns related to the components' ability to withstand such temperatures. Efficient temperature regulation becomes crucial to prevent potential damage or failure of engine components due to excessive heat.

Another significant challenge is the limited power-to-weight ratio of Stirling engines. While these engines excel at low and medium power levels, their limited power ratio poses a significant constraint. When compared to internal combustion engines or gas turbines, Stirling engines are less suitable for applications requiring high power. Overcoming this challenge demands an enhancement in the power output of these engines to increase their relevance across various applications. The characteristic large size and relative weight of Stirling engines present another hurdle. This can be problematic, especially in applications prioritizing lightweight and compact designs. The success of Stirling engine utilization heavily depends on how effectively its size and weight can be overcome or integrated into its application environment.

Limited response speed to changes in load or power demands is yet another challenge faced by Stirling engines. Applications requiring instantaneous responses to load fluctuations, such as in powered vehicles, may find these engines less suitable. Improving response speed is crucial to enhancing their competitiveness in various applications.

The production cost of Stirling engines tends to be high due to stringent tolerances and components requiring high precision. Complex designs can also add to the difficulty levels in the production and maintenance processes. Therefore, cost management strategies and design simplicity are key factors in enhancing their competitiveness in the market. Heat management, particularly at high temperatures, poses a technical challenge for Stirling engines. Careful design is required to overcome this challenge, including effective thermal insulation and improvements in heat exchange efficiency among engine components. Advances in heat management technology could be the key to enhancing the performance of these engines under high-temperature conditions.

Despite its significant potential, public understanding of Stirling engine technology remains limited. The widespread adoption of this technology faces constraints such as the lack of supporting infrastructure and device availability. Education and socialization efforts about this technology need to be heightened to increase awareness and acceptance within society.

Conclusion

In summary, the discussions and reviews conducted indicate several key conclusions. Firstly, Stirling engines demonstrate substantial potential as power generators, particularly in remote areas. However, there is a recognized necessity for the development of Stirling engine applications that are user-friendly and easier to maintain. Furthermore, it is concluded that future research and additional development efforts are critical to creating a practical engine. This entails the selection of an appropriate configuration, the adoption of an effective working fluid, the minimization of losses, and the development of an efficient control system. The significance of ongoing development and research in the field of Stirling engines is strongly emphasized, highlighting the need for continuous advancements to realize their full potential.

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