Stirling Engine Integrated with Solar for Grid Advancements and Challenges, Possibilities for Residential Use

Abhijit Samanta[1], Dr. Santosh D Dalvi[2]

[1]Assistant Professor, Dept of Mechanical Engineering, Lokmanya Tilak College of Engineering and Technology Mumbai, India.
[2]Associate Professor, Dept of Mechanical Engineering, Lokmanya Tilak College of Engineering and Technology Mumbai, India.
Email: abhijitsamanta1000@gmail.com

Stirling Engine Integrated with Solar for Smart grid technology seeks to revolutionize the conventional use of solar panels power grid by transforming advanced power system with low maintenance and low cost. By harnessing the solar Energy with the help of Stirling engine surpassing the capabilities of traditional solar panels. This paper presents the basic requirements, features, components of Stirling Engine and challenges faced in harnessing solar energy and its implementation for residential purpose. The implementation of Solar Energy offers a multitude of benefits like reducing the transmission and distribution losses, effective load management, continuous power supply and reliability in case of power cut off from grid, low power purchase costs compared to solar panel and low maintenance cost. This paper also highlights the challenges faced in Solar energy, infrastructure upgrades, and regulatory frameworks for tracking the solar energy. However, Stirling Engine offers possibilities like hybrid operation with fuel as well, as renewable Solar energy integration, and grid security. By addressing these challenges, Stirling Engine optimization with insulation can improve the efficiency and power output and operations like improve solar tracking with the sensors , and promote energy efficiency, transforming India's power sector with the help of the hybrid system for the residential use.

Keywords: Smart Grid, Generation, Distribution, Consumption, Communication, Digital Technology, Renewable Sources.

1. Introduction

In India, solar panels are used for grid management is used to operate the Indian Power grid [1]. Robert Stirling, a Scottish clergyman, devised the inaugural “operational closed-cycle air turbine” in 1816. In 1884, Fleming Jenkin suggested renaming all of these engines as Stirling engines. Stirling's initial creation was a heat exchanger, which he named a "economiser" because it enhanced fuel efficiency in various uses. While in operation, this economizer [3] is referred to as a "regenerator". Subsequent efforts by “Robert Stirling and his brother James”, who was an engineer, led to the development of several enhanced iterations of the initial engine, which were subsequently patented, incorporating features such as pressurization. Advanced versions of preliminary engine designs have been investigated in numerous studies to augment performance and efficiency. The enhanced particle swarm optimisation (IPSO) algorithm has been introduced to optimise the ascent phase trajectory for vehicles equipped with multi-combined cycle engines (Zhou et al., 2017). This method has superior performance relative to previous PSO variations and generates less oscillatory outcomes compared to commercial software. An enhanced thermodynamic model has been created to examine the cold start characteristics of diesel engines at low temperatures (E et al., 2019). This model evaluates aspects including gas leakage, heat loss, and clearing volume, offering insights for improving cold start capacity. The study revealed that a reduced clearance volume and elevated initial intake air temperature can enhance the exergy of diesel engines. A 48 V, 4 kW brushless fast starting (BFS) system has been developed for automotive start/stop applications in the domain of starter systems (Hao et al., 2020). This method exhibits enhanced engine autostart and key start capabilities relative to traditional 12 V brushed starters, especially at elevated speeds. The amalgamation of the inverter and motor within the identical casing as the original brush-type starter facilitates a seamless replacement, exemplifying a novel methodology in engine starting systems. Alpha engine

Alpha-type Stirling engines are a prevalent arrangement for waste heat recovery and power production applications. These engines comprise two distinct cylinders for expansion and compression, linked by a regenerator (Almajri et al., 2017; Kaldehi et al., 2017). The alpha architecture provides numerous benefits, including as enhanced power density and efficiency.

In summary, alpha Stirling engines have significant potential for diverse applications, such as micro-CCHP systems and waste heat recovery in heavy-duty trucks. Their performance can be markedly enhanced by optimising geometric and operational factors, achieving overall efficiencies between 79% and 88% across various climates (Kaldehi et al., 2017). The selection of configuration and drive mechanism is essential for attaining optimal power-to-weight ratios and economic feasibility (Egas & Clucas, 2018).

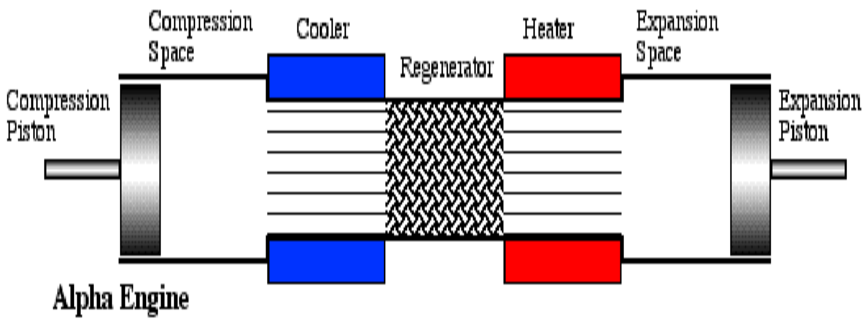


Figure 1 Alpha engine

Source: Walker, G., Stirling Engine, Oxford Clarendon Press

Beta engine

A Beta Stirling engine is a heat engine that functions according to the Stirling cycle, utilising a constant quantity of working fluid (often a gas such as air, helium, or hydrogen) to convert thermal energy into mechanical work. They are a popular configuration for power generation, particularly in remote or off-grid applications. These engines operate on a closed thermodynamic cycle, converting heat energy into mechanical work (Shendage et al., 2010; Shendage et al., 2017). The beta configuration typically consists of a single cylinder with a power piston and a displacer piston, often utilizing a rhombic drive mechanism (Aksoy et al., 2017; Shendage et al., 2010). The beta-type Stirling engines show promise for various applications, including solar power generation and rural electrification (Shendage et al., 2010; Sripakagorn & Srikam, 2011). While they face challenges in terms of design complexity, ongoing research and optimization efforts are improving their performance and viability. For instance, a prototype engine operating at moderate temperatures (350-500°C) achieved a maximum power of 95.4 W at 360 rpm with a thermal efficiency of 9.35% (Sripakagorn & Srikam, 2011). As technology advances, beta-type Stirling engines may become increasingly competitive in niche energy market.

Applications:

Beta Stirling engines are frequently employed in low-power applications, including demonstration models.Renewable energy technologies, such as solar-powered engines. Compact cogeneration systems for thermal and electrical energy generation.

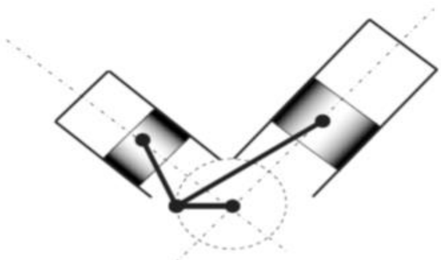


Figure 2 Beta Stirling engine

Source: Walker, G. W., “Stirling Engine,” Clarendon Press, Oxford, 1980

Gamma engine:

Gamma Stirling engines are defined by two different chambers: the hot cylinder and the cold cylinder.

Characteristics:

The gamma arrangement generally has a power piston in one cylinder (hot) linked to a displacer piston in the opposing cylinder (cold). The two pistons typically operate at varying temperatures, facilitating effective heat transfer.The engine functions on the Stirling cycle, comprising a series of isothermal and isochoric cycles. The displacer transfers the working gas between the hot and cold chambers, whereas the power piston transforms thermal energy into mechanical work.Efficiency: Gamma-type engines can attain elevated efficiencies owing to their capacity to sustain a temperature gradient between the hot and cold extremities.

Applications:

Power Generation: These engines are appropriate for applications necessitating dependable and efficient heat-to-power conversion. Renewable Energy: Gamma-type Stirling engines can harness solar heat, biomass, or other renewable resources for operational sustainability.

Benefits:

Minimal Emissions with negligible environmental impact, particularly when fuelled by renewable energy sources. The design facilitates effortless scaling or modification for various heat sources.

Obstacles:

Size and Complexity of Gamma-type engines may exhibit more manufacturing and integration complexity relative to alternative Stirling engine designs. The initial expenses for development and production may be substantial, impacting their commercial feasibility. Gamma Stirling engines represent a distinctive and efficient choice within the Stirling engine category, providing specific advantages for particular applications, particularly in renewable energy. They are a favoured arrangement for low-temperature differential and solar-powered applications. These engines have undergone comprehensive analysis and optimisation for diverse applications. A gamma-type Stirling engine with a swept volume of 276 cc attained a maximum power output of 128.3 W utilising helium at a heat source temperature of 1000 °C and a charge pressure of 4 bar (Çinar & Karabulut, 2004). A further study examined a 220 cc swept volume engine engineered for biomass energy, yielding a maximum brake power of 96.7 W at a heat source temperature of 550°C and a charge pressure of 10 bar (Damirchi et al., 2016). The performance of gamma-type Stirling engines can be substantially influenced by multiple factors. Regenerator imperfection and clearance leakage were found as the two primary sources of dissipation in these engines (Li et al., 2016). The selection of working gas, kind of regenerator matrix, and dead volume can influence engine performance (Alfarawi et al., 2016). The compression ratio of gamma-type engines is essential for determining their appropriateness for particular applications, contingent upon the temperature differential (Egas & Clucas, 2018).

Gamma-type Stirling engines exhibit potential for low-temperature differential and renewable energy applications. Optimisation initiatives have concentrated on enhancing power production and efficiency by many methods, such as thermodynamic modelling (Alfarawi et al., 2016), dynamic response analysis (Hooshang et al., 2015), and mechanical efficiency assessments (Senft, 2002). Despite ongoing obstacles, including the mitigation of inherent mechanical losses, the promise of gamma-type Stirling engines in sustainable energy generation persists in propelling research and development within this domain.

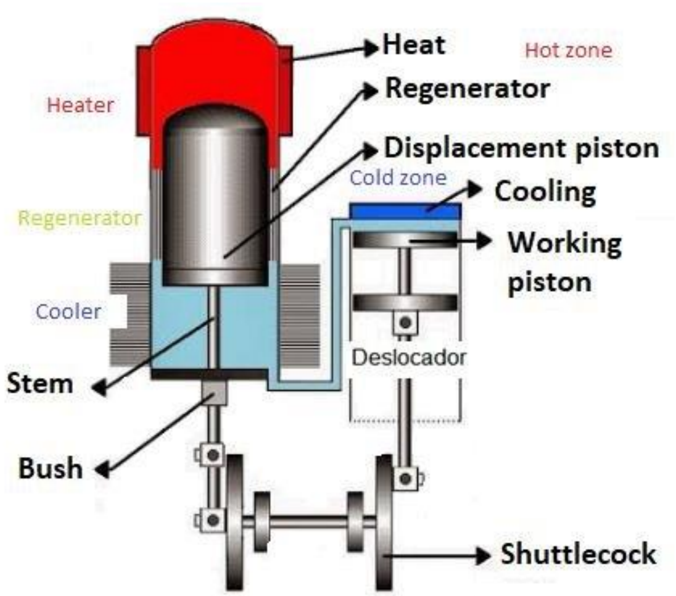


Figure 2 Gamma Stirling engine

Research advances

Research in the fields of heat recovery and waste use is advancing rapidly due to the increased focus on energy generation and environmental sustainability. Environmental sustainability has emerged as a paramount concern in recent years, with numerous sectors and disciplines acknowledging its significance. The concept has transitioned from an ambiguous idea to more exact requirements, frequently articulated in quantitative terms (Moldan et al., 2011). It emphasises the preservation or enhancement of the integrity of Earth's life-supporting systems, tackling the biogeophysical dimensions of the environment (Moldan et al., 2011). The incorporation of environmental sustainability across several sectors has resulted in intriguing advancements and paradoxes. In the hospitality business, there has been a significant rise in initiatives aimed at reducing ecological impacts, despite the sector's previous neglect of environmental concerns (Khatter, 2023). In dentistry, the recognition of environmental sustainability's significance in higher education is swiftly increasing, resulting in the creation of innovative curricula and pedagogical methods (Duane et al., 2021).

- Stirling Engine Project Advancements in India

The increase in demand for renewable energy production is a result of expanding populations and industrial expansion. Energy production and environmental sustainability are intricately linked, with substantial consequences for climate change mitigation and sustainable development. The literature presents several critical insights. Renewable energy sources are essential for enhancing environmental sustainability. Consumption of wind-based renewable energy has demonstrated a reduction in ecological footprints in 8 of the 10 leading wind energy-consuming nations within the European Union (Chang et al., 2022). In Thailand, palm biodiesel production exhibits reduced environmental effect potentials relative to traditional diesel, with possible greenhouse gas reductions ranging from 46% to 73% (Silalertruksa &

Gheewala, 2012).

The relationship between energy production and environmental sustainability is intricate and differs throughout countries. In Canada, environmentally-related technologies mitigate environmental degradation, whereas financial development, energy intensity, and natural resource depletion exacerbate it (Khan et al., 2021). In APEC nations, energy imports and natural resource revenues influence environmental degradation, whereas the profitability of natural gas and renewable electricity production serve as moderating factors (Pan et al., 2023).

The shift to sustainable energy generation necessitates a comprehensive strategy. This encompasses the eco-modernization of energy infrastructure (Karaeva et al., 2023), investment in green innovation and energy production (Bhutta et al., 2022), and the enactment of laws that emphasise sustainable resource management and carbon pricing (Pan et al., 2023). The influence of governance and financial development on fostering environmental sustainability is substantial (Bhutta et al., 2022).

Although advancements have been achieved in enhancing energy sustainability globally, obstacles persist, especially for low-income nations attempting to fulfil Sustainable Development Goals (Sarkodie, 2022). The energy sector must reconcile rising energy consumption with minimising its environmental anthropogenic impact. This necessitates a holistic strategy that incorporates technical advancement, policy execution, and sustainable resource management to attain enduring environmental sustainability.

Research in heat recovery and waste management has become increasingly crucial due to worldwide energy and climate challenges. Waste heat recovery has emerged as a vital field of research, concentrating on the evaluation of waste heat potential and the performance of recovery technologies (Oh et al., 2024). The recovery and utilisation of waste heat across diverse industries is acknowledged as an effective strategy for enhancing economic advantages, conserving energy, and mitigating emissions (Su et al., 2021). Although many studies have examined waste heat potential and recovery technologies, few have investigated the significant correlation between waste heat potential and recovery technology in connection to energy demands (Oh et al., 2024). This research gap underscores the necessity for a more holistic strategy to effectively capture energy from waste heat sources. Furthermore, low-temperature industrial waste heat has been recognised as a significant heat source for industrial processes and utility services, presenting opportunities to diminish fossil energy use and mitigate the risk of global warming (Huang et al., 2016). The domain of waste heat recovery offers substantial prospects for energy conservation and environmental preservation. Recent breakthroughs encompass the creation of innovative technology, sustainable techniques, and the investigation of diverse applications across industries (Nyakuma et al., 2023). Nonetheless, obstacles persist in domains such low-temperature/low-grade waste heat recovery, utilisation, storage, life cycle analysis, and environmental impact assessment (Nyakuma et al., 2023). Subsequent study has to concentrate on rectifying these deficiencies and enhancing heat recovery technologies to optimise energy conservation and minimise ecological repercussions. Research on heat recovery and waste utilisation is advancing, emphasising enhanced efficiency and sustainability across multiple industries. The following are essential areas of emphasis and conclusions.

Stirling Engine components.

Components	Specifications
D_H = Diameter of Hot Cylinder	2.4 cm
L_H = Length of Displacer (hot cylinder)	3.2 cm
$V_{H=}$ Volume of Hot Cylinder	15.71 cm^3
$V_{c\,=}$ Volume of Cold Cylinder	15.71 cm^3
L_c = Length of Displacer (Cold cylinder)	3.2 cm
D_r = Diameter of Regenerator	4.8 cm
Lg= Length of Regenerator	3.2 cm
L_p = Length of Power Piston	1.6 cm
D_p = Diameter of Power Piston	2.4 cm

From Naiver Stokes equation for Conservation of Energy

$$\rho\left(\frac{\partial e}{\partial t} + (u \cdot \nabla)e\right) \equiv -p\ (\nabla u) + \ \phi + \nabla(k\nabla T)$$

Calculation for power by Stirling Engine Beale number is given by:

B=Ppm

P = engine Power (watts)

P_m =mean cycle pressure =P =0.61 MPa

f =cycle frequency or engine speed in hertz= 300 rpm=5 hz

Vs = displacement of power piston

$$P = B\ P_m\, f\ V_s = 0.15 \times 0.61 \times 10^6 \times 5 \times 15.71 \times 10^{-6}$$

$$\mathrm{P} = 7.187\ \mathrm{Watts}$$

- Calculation of power with the Solar Energy

Solar Panel Efficiency: Most solar panels have an efficiency of around 15–20%.

Average Solar Irradiance: The amount of sunlight received per square meter, typically measured in kWh/m²/day. For most locations, it's about 4–6 hours of effective sunlight per day.

Panel Cost: The cost of solar panels varies by location and quality. In 2025, typical costs are about $0.30–$0.50 per watt for standard panels.

$$required\ panel\ capacity(W) = \frac{load\ power(W)}{Sunlight\ hours\ \left({}^{h}/_{day}\right)} = \frac{10}{4} = 2.5\ Watts$$

For inefficiencies (about 20%), increase this by a factor of 1.2:

Adjusted Capacity=2.5×1.2=3 W

A 3-watt solar panel would cost approximately $1.50–$2.00 USD depending on the quality and location $2.00 USD is approximately 171.54 INR.

1-Kilo watt solar panel would cost approximately 72000 INR whereas 1-Kilo watt Stirling Engine would cost approximately 22000 INR and the major benefit of this Stirling Engine is that when the solar energy is also unavailable during that time also electric current can be made available since it is an external combustion Engine and it can run with the help of fuel.

- Benefits for Integration of Solar energy with Stirling Engine to supply power to Grid

The first step in estimating the heat is determining how much energy is being collected by the magnifying lens. This can be done by calculating the total power

$$P_{Total} = I \times A$$

For sunlight, the average intensity I near the Earth's surface is about 1000 W/m².

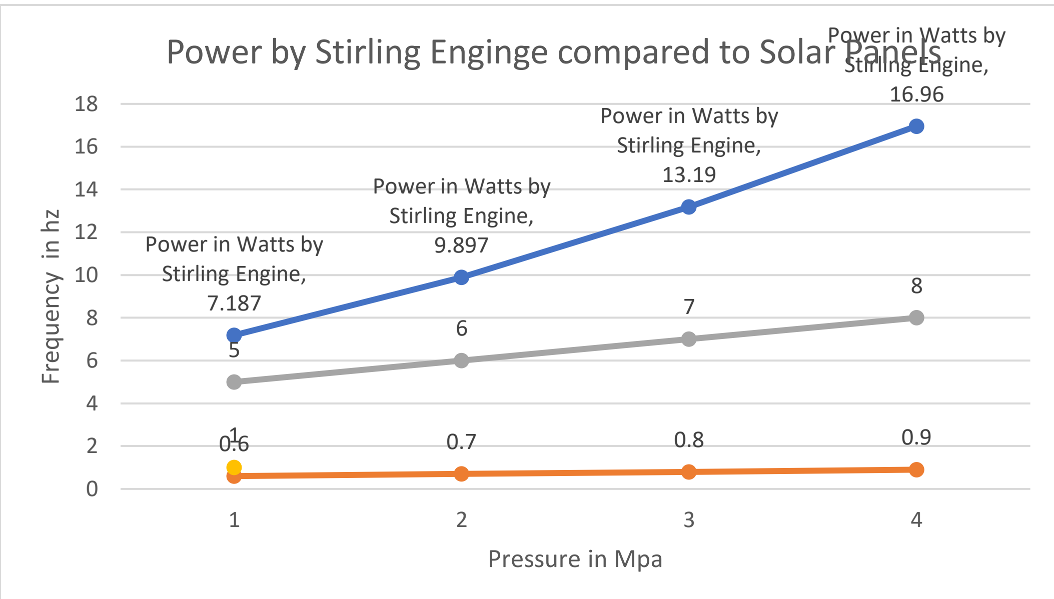
diameter of the lens, you can calculate the area of the lens A:

$$A = \pi \times \left(\frac{d}{2}\right)^2$$

$$A = \pi \times \left(\frac{5}{2}\right)^2 = 19.63\ cm^2 = 0.001963m^2$$

$$P_{Total} = I \times A = 1000\text{W}/m^2 \times 0.00785m^2 = 7.85\text{W}$$

A typical handheld magnifying glass 3 inches in diameter can achieve temperatures of about 400–500°C at the focal point ,so with the help of a magnifying glass micro Stirling engine is generating power up to 16.96 watts o which cost is much cheaper than the Solar Panels.



2. CONCLUSION

In this paper, the current scenario of Power is discussed along with comparison between Solar panel and Stirling Engine. This paper highlights the. The Pilot project was carried out and it was observed that the effectiveness Stirling Engine is much better than Solar panels with respect to efficiency and cost.it can be used in presence of sunlight and in absence of sunlight as well.

From the overall discussion in the paper it is concluded that implementation of Stirling Engine technology has many benefits including reduction of transmission and distribution losses; management of peak loads; enhanced service quality and decrease dependability; decrease in power purchase cost.

References

1. G. Walker and S. Engine, Oxford Clarendon Press. Calgary.
2. G. W. Walker, Stirling Engine. Oxford: Clarendon Press, 1980, p. 198.
3. M. H. Ahmadi, “Thermodynamic analysis and multi-objective optimization of solar dish Stirling engine by the centrality of entransy,” Electr. Power Energy Syst., vol. 78, pp. 88–95, 2016.
4. C. M. Hargreaves, “Improvements for diminishing the consumption of fuel and in particular an engine capable of being applied to the moving of machinery,” Appendix B, English Patent 4081, 1991.
5. B. Kongtragool, S. Wongwises, “Thermodynamic analysis of a Stirling engine including dead volumes of hot space, cold space and regenerator,” Renew. Energy, vol. 31, no. 3, pp. 345–359, 2006. doi: 10.1016/j.renene.2005.03.012.
6. D. G. Thombare and S. K. Verma, “Technological development in the Stirling cycle engines,” Renew. Sustain. Energy Rev., vol. 12, no. 1, pp. 1–38, 2008. doi: 10.1016/j.rser.2006.07.001.
7. D. G. Thombare and S. K. Verma, “Technological development in the Stirling cycle engines,” Renew. Sustain. Energy Rev., vol. 12, no. 1, pp. 1–38, 2008. doi: 10.1016/j.rser.2006.07.001.
8. D. G. Thombare and S. K. Verma, “Technological development in the Stirling cycle engines,” Renew. Sustain. Energy Rev., vol. 12, no. 1, pp. 1–38, 2008. doi: 10.1016/j.rser.2006.07.001.
9. S. Sets, “World record for solar-to-grid conversion efficiency,” Sol. Energy Syst., 2008
10. A. D. Der Minassians and S. R. Sanders, “Stirling engines for distributed low-cost solar thermal electric power generation,” J. Sol. Energy Eng., vol. 133, no. 1, 2011. doi: 10.1115/1.4003144.
11. P. Puech, V. Tishkova, “Thermodynamic analysis of a Stirling engine including regenerator dead volume,” Renew. Energy, vol. 36, no. 2, pp. 872–878, 2011. doi: 10.1016/j.renene.2010.07.013.
12. P. Puech, V. Tishkova, “Thermodynamic analysis of a Stirling engine including regenerator dead volume,” Renew. Energy, vol. 36, no. 2, pp. 872–878, 2011. doi: 10.1016/j.renene.2010.07.013.
13. J. Wood, N. Lanel, and W. Beale, “Preliminary design of a 7 kWe free piston Stirling engine with Rotary generator output,” in Proc. 10th ISEC, Osnabrück, Germany, 2001.
14. K. S. Moon and F. J. Miller, Stirling Solar Engine Design. San Diego State University, 2009.