Solar Micro-Cogeneration using Small Energy Scales and High-Efficiency

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Abstract- This experimental study focuses on a compact solar cogeneration system, which can generate around 1 kW of electricity and up to 3 kW of heat. The system's primary objective is to facilitate decentralized and widespread production of both heat and power, achieving remarkable conversion efficiencies despite its small size. At the heart of this solar system lies a small-scale industrial Stirling engine, serving as a micro cogenerate. Originally designed for combined heat and power applications in gas boilers, this Stirling engine exhibits an impressive electrical efficiency of up to 35%. However, for its adaptation into this solar system, the Stirling engine's heat acceptor has been completely redesigned to cater to solar applications. Furthermore, a solar dish concentrator, precisely controlled by a two-axis tracking system, has been integrated into the system's configuration. Over the span of a year, the system generates an average of approximately 188 kWh/m^2 of electricity and around 860 kWh/m^2 of thermal energy. Consequently, the annual electrical efficiency reaches approximately 9%, with potential for further improvement. Simultaneously, the system achieves an annual thermal efficiency of about 46%. Notably, the collecting surface area of the solar dish measures approximately 9.6 m^2, which accounts for roughly 50% of the surface area required for an equivalent non-cogenerated system.

Keywords: Stirling Engine, Green Energy, Solar Dish, Cogeneration

1. Introduction

The European Commission's ambitious targets for renewable energy coverage and the emphasis on self-production and local distribution of renewable energy sources, as outlined in Directive (EU) 2018/2001 of the European Parliament and the Council, are crucial but challenging objectives to attain [1]. These targets recognize the significance of technological advancements in green energy, which are increasingly vital in all sectors of production and consumption [2]. There is a specific focus on innovative renewable energy techniques that can be applied, particularly in agro-industrial processes, to enhance energy efficiency and conserve natural resources. This localized demand has sparked the development of new small-scale energy production solutions [3]. Among these solutions is the micro-cogeneration system, which belongs to a research strand aimed at developing solar-powered plants that concentrate solar radiation to simultaneously generate electricity and thermal energy, maximizing overall solar generation yield within a given surface area [4]. The European Commission's renewable energy targets for 2020 serve as a driving force for member states to transition towards a more sustainable and clean energy future. The goal of achieving a 17% renewable energy coverage of energy end-use reflects the Commission's commitment to reducing greenhouse gas emissions, promoting energy security, and fostering economic growth in the renewable energy sector. However, the realization of these targets is no easy feat [5]. It requires concerted efforts from governments, businesses, and research institutions to implement effective strategies and technologies that facilitate the widespread adoption of renewable energy sources. In this context, technological solutions play a pivotal role in driving the transition toward green energy. Advancements in renewable energy technologies, such as solar, wind, and biomass, have made significant strides in recent years [6]. These technologies offer promising alternatives to traditional fossil fuel-based energy sources, providing clean and sustainable options for electricity generation, heating, and cooling. Embracing these solutions not only contributes to the achievement of renewable energy targets but also addresses the urgent need to mitigate climate change and reduce reliance on finite fossil fuel reserves [7]. The adoption of innovative renewable energy techniques within the region's agro-industrial processes presents an opportunity to enhance energy efficiency and reduce the ecological footprint [8]. By integrating renewable energy systems into agricultural operations, such as solar panels on farms or biomass conversion from organic waste.. The development of small-scale energy production solutions is a response to both local demands and wider market trends. These solutions aim to decentralize energy generation, allowing for self-production and localized distribution [9]. By empowering local communities to generate their own energy from renewable sources, they become less dependent on centralized power grids and reduce transmission losses. Additionally, small-scale energy production solutions contribute to job creation, local economic development, and the resilience of energy systems. One such solution that aligns with renewable energy goals is the micro-cogeneration system. This system utilizes concentrated solar radiation to generate both electricity and thermal energy simultaneously, maximizing the overall efficiency of solar energy conversion. By combining photovoltaic technology with solar thermal collectors, the micro-cogeneration system optimizes the utilization of solar resources [10]. This approach reduces the land footprint required for energy generation, making it a viable option for areas with limited available space. The micro-cogeneration system offers several advantages. Firstly, it enhances the overall efficiency of solar energy utilization by capturing and utilizing both electricity and thermal energy [11]. This dual output increases the system's energy yield, making it more economically viable and environmentally sustainable. Secondly, the system's modular design allows for flexible installation, making it suitable for various applications, including agro-industrial processes. This adaptability enables the system to meet the specific energy needs of different sectors, further promoting energy efficiency and resource conservation [12]. The European Commission's renewable energy targets and focus on self-production and local distribution are crucial but challenging. Technological advancements play a vital role in achieving these goals. Innovative renewable energy techniques cater to local needs and contribute to energy efficiency. The micro-cogeneration system presented here aligns with the research for solar-powered plants, maximizing solar generation's efficiency.

2. Objectives

Beyond Earth's atmosphere, the Sun emits an average of approximately 1367 W/m^2 of radiation in a plane perpendicular to its rays. This value is referred to as the solar constant. However, not all of this energy reaches the Earth's surface due to various atmospheric phenomena, including reflection, refraction, absorption, and scattering. The solar radiation that actually reaches the ground is composed of three main components. The first component is direct radiation, which represents the portion of solar radiation that bypasses Earth's atmosphere and reaches the surface without significant deviation from the Sun-Earth direction. Direct radiation strikes surfaces at a specific angle of incidence and has a relatively high energy density. For instance, at noon on a clear day in Italy, direct radiation typically measures around 1000 W/m^2. The second component is diffuse or indirect radiation, which results from the scattering of the Sun's rays by the air. Diffuse radiation is the light that we perceive on days when the sun is not directly visible, such as when it is cloudy. Diffuse radiation has a lower energy density compared to direct radiation and constitutes approximately 10% of direct radiation under clear skies. Concentrating solar systems exclusively capture direct solar radiation. These systems, known as Concentrating Solar Power (CSP) technologies, utilize mirrors and/or lenses to focus the incoming solar radiation onto a smaller surface area, thereby increasing the energy density. The primary objective of this approach is to create favorable conditions for operating a cyclothermodynamic unit with maximum efficiency, enabling efficient generation of mechanical, electrical, and heating power [13]. This method of energy production offers economic advantages by reducing the overall cost of energy generation. Cogeneration, which combines the production of electricity and heat, allows for a lower consumption of primary energy compared to separate electricity and heat generation methods. When applied to solar energy, cogeneration also enables a reduction in the overall surface area required for capturing solar energy, surpassing the conventional approach of combining photovoltaic and thermal panels. This improvement significantly enhances the overall conversion efficiency while minimizing land usage [14]. Additionally, cogeneration plants facilitate the recovery of waste heat produced during electricity generation, which would otherwise be released into the environment in non-co-generative conventional plants. This paper presents a solar micro-cogeneration system designed to simultaneously produce electrical and thermal energy with a power output of a few kilowatts. The system employs a two-axis CSP technology and integrates a Stirling-free piston engine to enable micro-cogeneration. The integration of these components allows for the efficient utilization of solar energy while achieving optimal power generation.

3. Methodology

3.1 Cogeneration

Cogeneration, also known as combined heat and power (CHP), offers numerous advantages that make it an attractive energy generation solution. These advantages can be summarized as follows:

3.2 Economic advantages

One of the primary benefits of cogeneration is the efficient use of primary energy sources. By simultaneously producing both electricity and heat, cogeneration systems achieve higher overall energy efficiency compared to separate generation methods. This means that less energy is consumed to produce the same amount of useful energy, resulting in cost savings for end-users.

3.3 Environmental advantages

Despite the use of fossil fuels in cogeneration systems, they still offer environmental benefits. The fuel consumption in cogeneration is lower than in non-co-generative solutions, leading to reduced emissions of carbon dioxide (CO_2). By maximizing energy efficiency, cogeneration contributes to the overall reduction of greenhouse gas emissions and helps mitigate the impacts of climate change. Energy Supply Flexibility: Cogeneration systems provide greater flexibility in energy supply. By generating electricity and heat simultaneously, they offer a reliable and decentralized energy source. This reduces the risks of blackouts and enhances the resilience of the energy grid. In situations where there may be interruptions in the main power supply, cogeneration plants can continue to provide electricity and heat to meet critical energy needs. Financial Advantages: Cogeneration systems in Italy benefit from specific legislative provisions that offer financial incentives. Administrative simplifications are provided for cogeneration projects, making the implementation process smoother. Additionally, cogeneration facilities can benefit from on-site energy exchange rights and the allocation of white certificates, which are mandatory for renewable energy producers. These certificates can be traded, providing an additional source of revenue. Moreover, cogeneration systems may enjoy tax advantages, further enhancing their financial viability. In summary, cogeneration offers a range of advantages, including improved energy efficiency, reduced emissions, enhanced energy supply reliability, and various financial incentives. These factors contribute to its appeal as a sustainable and economically viable solution for energy generation [15].

4. Stirling engine

The Stirling engine is widely recognized as one of the most efficient thermodynamic systems for small-scale micro-cogeneration applications. Unlike internal combustion engines, the Stirling engine falls under the category of external combustion engines. This means that it utilizes fuel to heat a fluid externally, allowing for the conversion of thermal energy into mechanical work. Its name pays homage to its inventor, Robert Stirling, who hails from Gloag in Perthshire, Scotland, and patented the engine on September 27, 1816. The motivation behind its creation stemmed from a need to address the issue of steam boiler explosions. Operating on a closed-cycle regenerative principle, the Stirling engine employs a low-pressure gas as its working fluid. The gas follows a simple cycle involving heating, expansion, cooling, and compression. By traversing two isotherms at different temperatures and incorporating two regenerative isochoric transformations, the engine extracts valuable mechanical work. Remarkably, the Stirling engine boasts the same theoretical efficiency as a Carnot cycle, relying solely on the maximum and minimum temperatures between which the thermodynamic cycle occurs. For the prototype solar micro-cogenerate, the Stirling engine utilized is manufactured by Microgen Engine Corporation Holdings and represents the only industrially available system for small-scale electrical power generation worldwide. Initially designed by Sun Power for large-scale heating, this free-piston engine underwent further development by MEC, a consortium consisting of Viessmann, Subsequently, Microgen took over the responsibility for refining the engine. Noteworthy characteristics of this Stirling engine include the production of alternating current at 220 volts and 50 Hz, with a power output of 1 kW and a heat output of 3 kW.

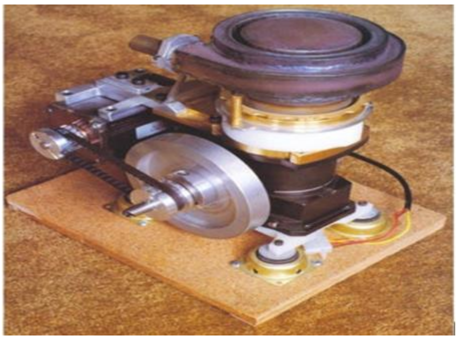

Fig. 1. Stirling Engine

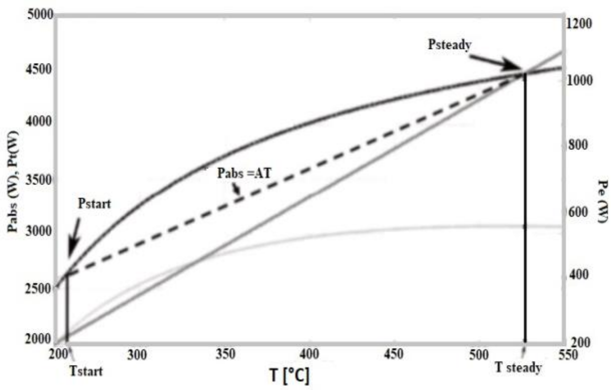

Fig. 2 - Stirling engine operating curves

Fig. 2. illustrates the engine's characteristic operating curves. Microgen's Stirling engine sets itself apart by being valve- and kinematic-free, enabling smooth operation with extended maintenance intervals lasting several years. The

reciprocating motion of the engine piston directly converts into alternating electrical energy, eliminating the need for an inverter. To facilitate its integration with a gas burner in a micro-cogeneration system, Microgen developed a cylindrical-symmetrical, truncated cone-shaped heat absorber positioned on the engine's head. This innovative design efficiently transfers the concentrated heat from the front and side surfaces of the absorber to the fins of the engine's internal heat exchanger. The heat absorber serves a dual purpose: it pre-heats the engine during startup and acts as a stabilizing heat sink. The thermal capacity of the absorber, calculated by solving the differential thermal balancing equations discussed in the subsequent paragraph, ranges between 2800 and 3800 J/Kg°C. Selecting copper as the constituent material results in a mass between 7 and 10 kg.

5. Two-axis tracking solar dish system

The operation of the concentrator is parameterized by means of the energy balancing equation, which is represented by the nonlinear ordinary differential equation:

$$dT/dt=[P_{ric}-P_{abs}(T)-P_{loss}(T)]/C \quad \text{---------} \quad (1)$$

Where,

P_{ric}, thermal power entering the receiver;

P_{abs}, thermal power absorbed by the Stirling engine,- whose mathematical operating curves characteristic of the thermodynamic converter

P_{loss}, radiative, and convective heat loss of the solar concentrating system;

C is the optimised heat capacity of the heat absorber;

T is the interface temperature between the heat absorber and the internal heat exchanger of the Stirling engine, which consists of copper fins surrounding the cylindrical head;

When the operation of a concentrator, such as a solar concentrator, is parameterized using an energy balancing equation represented by a nonlinear ordinary differential equation (ODE), various measurement techniques and instruments can be employed to monitor and control the system.

5.1 Solar radiation measurement: Accurate measurement of incoming solar radiation is crucial for the energy balance equation. Solar pyranometers or radiometers can be used to measure solar irradiance at the concentrator's location.

5.2 Temperature sensors: Temperature is often a critical parameter in the energy balance equation. Thermocouples, resistance temperature detectors (RTDs), or infrared thermometers can be used to measure temperatures at various points within the concentrator system, including the receiver, heat transfer fluids, and surrounding components.

5.3 Pressure sensors: Pressure sensors may be necessary to monitor the pressure of gases or fluids within the system, especially if the equation includes terms related to pressure changes.

5.4 Heat flux sensors: To monitor the transfer of thermal energy within the concentrator, heat flux sensors or calorimeters can be used to measure heat flux at different points, such as at the receiver surface.

5.5 Position and orientation sensors: If the concentrator's orientation or position is critical to the energy balance equation, sensors like encoders or accelerometers can be used to measure its position and orientation accurately.

5.6 Concentration ratio measurement: Some concentrator systems may require measurement of the concentration ratio (the factor by which sunlight is concentrated onto the receiver). This can be done using optical sensors or photodiodes.

5.7 Optical characterization: Spectrometers or photodetectors may be used to characterize the spectral properties of concentrated sunlight, which can be important for certain types of concentrator systems.

5.8 Data logging and control systems: Data loggers and control systems are essential for collecting, processing, and analyzing the data from the various sensors and for controlling the operation of the concentrator based on the energy balance equation.

5.9 Calibration equipment: Regular calibration of sensors and instruments is crucial to ensure the accuracy of measurements and the reliability of the energy balance equation.

It's important to note that the specific measurement techniques and instruments used will vary depending on the unique characteristics of the concentrator system and the details of the nonlinear ODE governing its operation. System design, modeling, and control strategies will also play a significant role in determining the appropriate measurement and control instrumentation.

6. Result and discussion

The solution of the equations governing the solar concentration system provides valuable insights into its operation and performance [16]. By analysing these equations, we can understand how the system's main operating parameters evolve over time. One key aspect that can be accurately modeled is the behavior of the temperature at the interface between the heat absorber and the heat exchanger. This information allows us to determine the electrical and thermal output of the concentrator, which are crucial factors in assessing its efficiency. With the knowledge of the electrical and thermal outputs, we can quantitatively evaluate the system's performance by calculating its electrical and thermal efficiencies [17]. These metrics provide a clear understanding of how effectively the solar concentration system converts sunlight into usable energy, both in terms of electricity and heat. To design the solar concentration system comprehensively, the entire focal assembly has been meticulously considered. The focal assembly, along with its supporting structure, has been conceptualized and visualized in Figure 3, providing a clear representation of the system's architecture. However, the practical implementation of the focal assembly presents some challenges [18]. The metal foils utilized in this setup, for instance, face difficulties due to the double curvature imposed by the rotational departmental profile of the solar dish. This curvature can lead to surface fractures in the foils, even on a small scale. Unfortunately, such fractures can accelerate the aging processes of the foil surface, potentially compromising its longevity and efficiency. Efforts must be made to mitigate these challenges and ensure the structural integrity and durability of the metal foils. Addressing these issues is crucial for maintaining the long-term performance and reliability of the solar concentration system, enabling it to harness solar energy efficiently and sustainably [19].

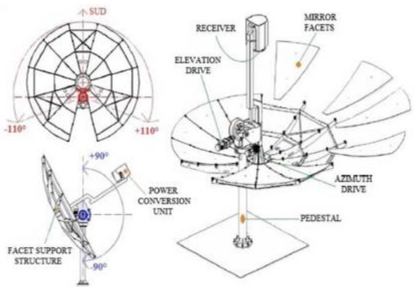

Fig. 3 - Two-axis tracking solar-dish system architecture.

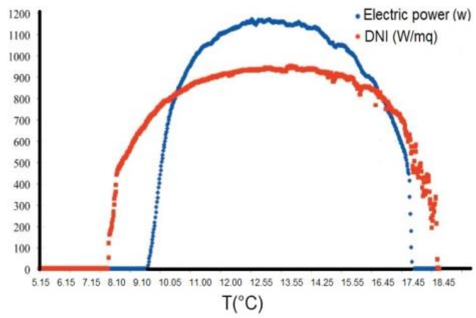

Fig. 4. Experimental measurements of solar radiation (October)

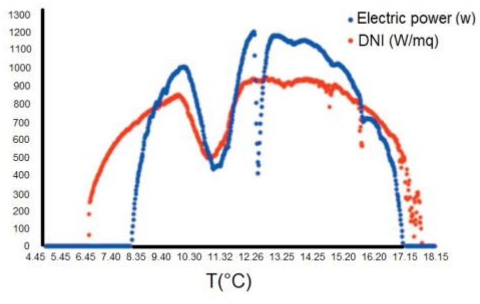

Fig. 5. Experimental measurements of solar radiation (March)

Figure. 4 illustrates experimental measurements conducted on a particular day in October. The red curve represents solar irradiation, specifically, Direct Normal Irradiance (DNI), measured in W/m^2, while the blue curve represents the electrical power generated by the Sunny system in watts (W), reflecting the varying weather conditions. As previously mentioned, the primary optical component of the system is a rotating paraboloid made of reflective aluminum [20]. It possesses a specular reflectance of approximately 88.8% and comprises 11 pre-formed triangular segments, each covering an area of approximately 0.87m^2. Collectively, these segments create a net absorbing surface of around 9.60 m^2. The paraboloid's function is to concentrate solar radiation onto the heating head of the Stirling engine, which is positioned at the focal point of the paraboloid. The Stirling engine is supported by a 2-meter-long arm. To enable precise solar tracking, the paraboloid is equipped with motors that facilitate continuous alignment with the solar disc through two-axis movement [21]. These innovative solutions have been protected by two patents, emphasizing the optimization of the entire Stirling con-center-receiver-head system [9, 10].

Table 1. Monthly average values of electricity and thermal energy produced in a year

Month	Solar radiation up normal floor DNI (kWh/m^2)	Thermal energy Produced (kWh)	Electric energy produced (kWh)
January	126	565	82
February	116	543	81
March	162	700	135
April	180	804	164
May	190	890	145
June	218	930	218
July	226	1020	195
August	220	980	203
September	209	856	216
October	170	771	160
November	135	614	96
December	130	597	85
Average	2082	9270	1780

Extensive studies were conducted to analyze the structural calculations of the load-bearing elements of the concentrator and assess the construction requirements for its installation, with a focus on potential commercial applications [21]. The surface of the mirror is theoretically designed to have a reflectivity of 90%. However, after undergoing spectroscopic measurements following deformation to achieve the required parabolic shape of the concentrator's geometry, its measured reflectivity is approximately 88.8%. Despite the slight reduction, the remains are a highly reflective mirror composed of aluminum foil and a self-supporting plastic resin core [22]. Furthermore, the benefits from a surface treated with nanotechnology, make it self-cleaning and resistant to the accumulation of dirt and dust [23]. Figure. 3. presents a showcasing the implementation of two complete Sunny systems. Ongoing experimentation, comprehensive characterization, and optimization of these systems are still in progress. Figure. 4 depicts the experimental measurements of solar irradiation (DNI) in W/m^2, represented by the red curve, and the corresponding electrical power generated by the Sunny system in watts (W), represented by the blue curve [24]. The graph demonstrates the relationship between weather conditions and power production on a specific day in October. Notably, the Sunny system consistently produced electrical power for approximately 9 hours, with a peak power output exceeding 1150 W at a solar irradiation level of approximately 930 W/m^2. Figure. 4 displays two graphs similar to those in Figure. 5, capturing the experimental observations of a significant event: the partial solar eclipse that occurred on 20th March 2015. The eclipse's occurrence is easily identifiable by the decrease in Direct Normal Irradiance (DNI) between 9:30 a.m. and 11:30 a.m. The graphs in Figure. 5 depict the behavior of the cogeneration system throughout the eclipse period [25]. During the eclipse, there is a noticeable drop in DNI from around 850 W/m2 at approximately 9:26 a.m. to about 500 W/m2 at 10:30 a.m., which marks the maximum eclipse phase [26]. Correspondingly, the system's electrical power production decreases from approximately 1 kW to about 450 W. As the DNI begins to increase in the later stages of the eclipse, the system's production also rises, reaching a peak of about 1.2 kW [27]. However, for safety reasons, the system defocuses the con-centered radiation around 11:30 a.m. and resumes normal production after a 15-minute interval [24]. The trends presented in Figure. 5 are intriguing as they demonstrate the thermal inertia of the heat storage system [28]. The electrical production and DNI curves exhibit an out-of-phase relationship with a typical delay of 13 minutes [29]. Specifically, the DNI reaches its peak at 9:26 a.m. with a value of 846 W/m2, while the electrical output achieves its maximum at 9:39 a.m., with a power of 1000 W, reflecting the characteristic 13-minute lag between the two measurements [30].

7. Conclusions

The cogeneration system presented demonstrates impressive energy production, generating 9270 kWh of thermal energy and 1780 kWh of electrical energy in one year. This is achieved with a solar-capturing surface of 9.60 m2. In comparison, a non-cogenerate system would require nearly 20 m^2, comprising 4.8 m^2 of photovoltaic panels and an additional 14.40 m^2 of thermal panels, to match the energy production of the cogenerate system. Thus, the cogenerate system achieves a 50% reduction in the required capturing area, highlighting its efficiency. The high cost of Stirling micro-cogenerates poses a significant challenge for widespread industrial implementation. Limited production and supply from Microgen, the sole provider, result in higher costs, limiting practical use to niche applications such as emergency management or remote combined heat and power generation. However, as the market expands and new devices emerge, the cost of these components is expected to decrease, opening doors for broader adoption. Ongoing research aims to optimize the system further. Currently, the average annual electrical efficiency of around 9% falls short compared to high-efficiency photovoltaics and other alternatives. Enhancements, including redesigning the optical part for concentrated solar radiation and incorporating a separate optical collector to reduce radiative losses, are being explored. These improvements aim to raise the average annual overall electrical efficiency to at least 12%. Small-scale cogeneration plants, even with low power outputs, offer significant energy yields and contribute to local self-generation chains. The proposed cogeneration system represents an incremental innovation in the energy market, particularly suited for contexts prioritizing local energy self-sustainability in decentralized electricity and heat production.

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