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Connecting Stirling engines with thermal-solar devices for home energy autonomy

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ABSTRACT
Stirling engines are a type of heat engine that works by circular heating and cooling of a gas, usually air or helium, in a closed system for the production of mechanical work. They were firstly invented by the Reverend Robert Sterling in the early 19th century, as an alternative to the inefficient locomotives (/steam engines) of the time. Stirling engines are often considered a promising alternative to internal combustion engines and other traditional heat engines, as they are highly efficient, quiet and can work on any external heat source, including solar energy, biomass and waste heat. They have been used in various applications, from powering electricity generators to heating and cooling systems, and continue to be the subject of continuous research and development. Despite their potential advantages, however, Stirling engines have not yet achieved widespread commercial success and remain a specialized technology in most industries. Taking advantage of the solar potential, concentrated solar systems heat a liquid to produce energy. This paper will study the use of a mirror-like reflector to concentrate solar energy, a Stirling engine, and a lead-acid battery to store the excess energy. The results show satisfactory energy production for a house of 100 sq.m. in Northern Mediterranean (Attica, Greece), with surplus energy that can be fed into the grid.
Keywords: *Stirling engine, external combustion engine, solar energy, thermal-solar system, concentrate solar device, renewable energy source.*

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I. INTRODUCTION

Nowadays, there is a significant global demand for energy, which is mainly met by fossil fuels such as oil and natural gas. However, this reliance on non-renewable energy sources has led to concerns about resource depletion, climate change and ecological degradation. Consequently, research has focused on the development of renewable energy sources to meet global energy needs.Renewable energy systems operate independently and directly to meet energy demand without the use of long transmission lines. The combination of multiple complementary energy production systems based on renewable energy sources as well as non-renewable sources is referred to as a hybrid energy system.

Hybrid systems can take advantage of each technology to produce power ranging from 1 kW to hundreds of kW, making them useful in areas where connecting to the electricity grid or transporting fuel is expensive. They can operate as independent stand-alone instruments or be integrated into power distribution systems, including oil-fired thermal units, after modification. Hybrid systems offer future grid connectivity, high efficiency and reliability, making them effective for supplying energy to specialized consumers or in emergency situations.A typical hybrid system can combine multiple power generation technologies, such as photovoltaics, wind turbines, and generators. Fuel-based hybrid systems tend to operate at the lowest consumption, producing power only when high rates are required or when renewable energy potential is low [1]. The cost of electrifying an area depends on several factors, such as installing high and medium power lines, building substations, building a distribution network, determining the size of load to be covered, and the distance and terrain to be traversed.Hybrid systems are suitable for off-grid rural areas where electricity demand is low and building a distribution network would be uneconomical. In these scenarios, the implementation of hybrid electricity systems is more cost-effective and has a lower impact on the environment. Hybrid power systems are the optimal decentralized solution because they become increasingly reliable over time, offer more environmentally friendly and economical energy, and have minimal transmission losses. Interconnected hybrid power systems can generate power and also provide backup power during power outages and are often used during peak hours when electricity costs are high. Small-scale hybrid systems are implemented in countries with high electricity demand, which can lead to problems of grid instability and even collapse. In addition, it is worth noting that the use of conventional energy sources in residential areas significantly damages the environment [2].

Towards this direction and in this work, the connection of Stirling engines with concentrating solar thermal systems for the production of electricity is examined, with the aim of complete energy coverage and autonomy of homes in urban and non-urban environments.

II. STIRLING ENGINE

Stirling engines are heat engines named after their inventor, the Reverend Robert Stirling, who developed the first practical version in 1816. Stirling engines are a type of external combustion engine, meaning that the heat source is external to the engine and does not come into direct contact with the working fluid [3].

Stirling engines have gained increasing attention in recent years as a promising alternative to traditional internal combustion engines. The Stirling engine operates on the thermodynamic Stirling cycle, which consists of four reversible processes: isothermal compression, constant volume heating, isothermal expansion, and constant volume cooling. The Stirling engine is known for its high thermal efficiency, low noise and low emissions, making it a desirable choice for a variety of applications, including power generation, heating and cooling, and transportation.

The growing demand for sustainable and renewable energy sources has led to a growing interest in Stirling engines as a potential solution for household power generation. Stirling engines are external combustion engines that convert heat energy into mechanical energy, which can then be used to produce electricity. Unlike conventional internal combustion engines, Stirling engines can run on a variety of fuels, including biomass, solar and geothermal energy, making them a versatile and environmentally friendly option for home power generation.

The use of Stirling engines for domestic energy production has been the subject of extensive research in recent years. Numerous studies have investigated the design, operation and performance of Stirling engines in domestic environments, as well as their potential advantages and limitations. The literature on Stirling engines for domestic power generation covers a wide range of topics, including system performance, power efficiency, fuel selection, and thermal management, among others [2].

2.1 The thermodynamic Stirling cycle

The thermodynamic Stirling cycle consists of four reversible changes in a specific order: isothermal expansion, isothermal cooling, isothermal compression, and isothermal heating. The theoretical efficiency of the cycle is the same as that of the Carnot cycle, when the hot and cold reservoirs have high heat capacities at temperatures T1 and T2, respectively, where T1 is greater than T2. The theoretical efficiency of the cycle can be calculated using the formula:

$$eth = 1- (T1/T2) \qquad (1)$$

where eth <1 [4]. However, the actual performance of the machine is always lower than the theoretical performance. On the pressure-volume diagram, a clockwise circle corresponds to a thermal (contracting) engine, while a counter-clockwise circle corresponds to a cryogenic (cryogenic-refrigeration) engine [3].

The thermodynamic processes respectively in a Stirling engine are as follows [5]:

1. *Compression*: In this process, the working fluid, usually air, is compressed by a piston, reducing its volume and increasing its pressure. Compression increases the temperature of the working fluid, but since no heat is added or removed during this process, the temperature increase is adiabatic.
2. *Heating*: In this process, the working fluid is heated by an external heat source, usually a burner or a solar collector. Heat is added to a constant volume and thus the pressure of the working fluid increases, causing the piston to move outward.
3. *Expansion*: In this process, the hot working fluid under pressure is allowed to expand, doing work on the piston and transferring heat energy to a cold sink. The expansion is adiabatic, so the temperature of the working fluid drops as it expands.
4. *Cooling*: In the final process, the working fluid is cooled by an external cold source, usually atmospheric air or water. The cooling is also at constant volume, so the pressure of the working fluid drops, allowing the piston to move inward and complete the cycle.

The efficiency of a Stirling engine is determined by the ratio of work output to heat input. The theoretical maximum efficiency of a Stirling engine is given by the Carnot efficiency, which is equal to 1 minus the ratio of the absolute temperatures of the hot and cold sources [3]. In practice, Stirling engines typically achieve 30-40% efficiency, although some specialized designs can achieve efficiencies as high as 50%.

Stirling engines are unique in that they can operate with a wide range of heat sources, including fossil fuel combustion, biomass and solar radiation. In addition, they have the potential for high efficiency and low emissions, making them a promising technology for a range of applications, including power generation.

2.2 Stirling engine's structural parts

Stirling engines are composed of four basic structural parts [2], described below.

Displacement piston: By placing a slightly smaller diameter piston in the container, the gas is forced through the gap between the piston and the walls of the container as the piston moves up and down. As the bottom and top of the container are heated and cooled, respectively, the elastic material placed continuously around the container expands and contracts due to the temperature difference [6]. As the piston moves to the top of the container, the gas in the container is forced downward, while the bottom of the container is heated to increase the gas pressure. This pressure is transferred through the piston-reservoir gap to the elastic membrane, causing it to expand. Conversely, when the proper force is applied to move the piston down, the gas is pushed to the top of the container. In this case, the upper part of the device is the cold part, and the gas cools, causing a decrease in temperature and pressure, which leads to the contraction of the elastic membrane. As a result, the piston moves up and down freely while the elastic membrane continuously expands and contracts. The main function of the device is to move gas with the movement of the piston, creating a continuous flow between the hot and cold parts of the device.

Crankshaft: The up and down movement of the piston can be achieved by connecting it to a crankshaft. As the crankshaft rotates, the piston moves up and down accordingly. Once the connection between the crankshaft and the piston is made, we heat the bottom of the can while cooling the top. First, we manually move the crankshaft as the alternating heating and cooling applied is not sufficient to complete a full duty cycle. As we move the crankshaft, we observe the elastic membrane expand and contract repeatedly [6].

Project piston: Connecting the piston to a crankshaft allows it to move vertically as the crankshaft rotates, allowing the piston to move up and down. The bottom of the pot is heated, while the top is cooled once the crankshaft-piston connection is made [6].

Flywheel: The previously described components are insufficient for smooth operation because the contraction and expansion of the elastic membrane cannot generate the necessary rotational force to complete a full rotation of the crank. Therefore, a flywheel with high rotational inertia is added to the system. In addition, a weight is placed on the outer surface of the flywheel to provide additional rotational inertia and assistance [6].

2.3 Stirling engine's types

There are three main types of Stirling engines: Alpha, Beta and Gamma [7], [8].

Alpha Stirling (Fig. 1a): This type of engine has two separate cylinders connected to a regenerator. One cylinder contains a working gas and the other cylinder contains a buffer gas. The working gas is compressed and expanded through the heat exchangers, while the buffer gas maintains its pressure constant. The regenerator is responsible for recovering the thermal energy that would otherwise be lost during the cooling process. Alpha Stirling engines are known for their high efficiency and are often used in low power applications.

Beta Stirling (Fig. 1b): This type of engine has only one cylinder with a piston and displacer. The piston is responsible for compressing and expanding the working gas, while the displacer is responsible for moving the gas between the hot and cold heat exchangers. Beta engines are simple and reliable, but their performance is lower than Alpha engines.

Gamma Stirling (Fig. 1c): This type of engine has a single cylinder with a piston and displacer, like the Beta engine. However, the piston and displacer are connected to a common crankshaft, which simplifies the mechanical design of the engine. Gamma engines are usually larger than Beta engines and have a higher power output, but are less efficient than Alpha engines.

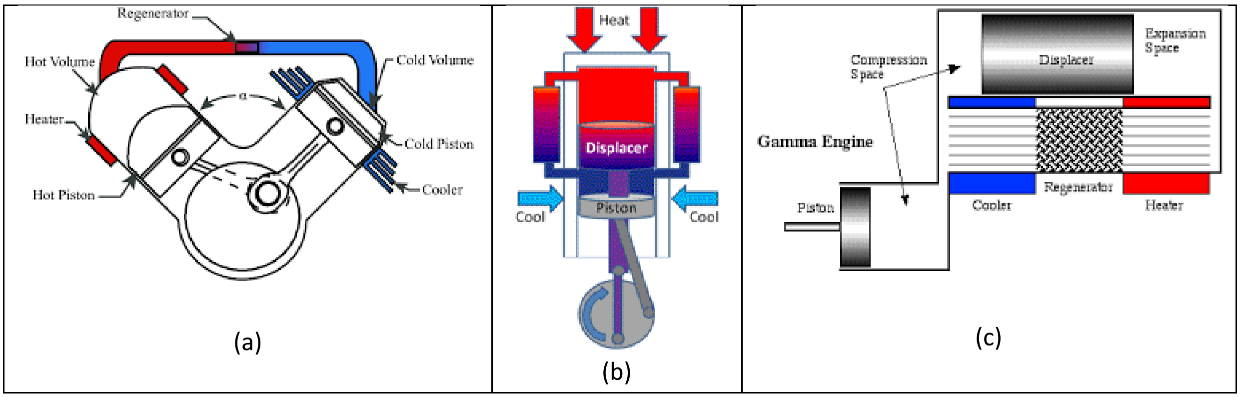

Figure 1: Stirling engines [7], [8]

In summary, Alpha Stirling engines are the most efficient and are suitable for low power applications, while Beta and Gamma engines are simpler and less efficient, but can produce higher power output. The choice of motor type depends on the specific application requirements and design constraints.

2.4 Advantages of Stirling engines

Stirling engines can be directly connected to a variety of heat sources, including solar, geothermal, biochemical, nuclear, and waste heat from industrial and internal combustion engine applications. This allows for reduced emissions associated with the intermittent operation of internal combustion engines [6].

Stirling engines usually have roller bearings and seals on the cold side of the engine, requiring less lubrication and providing longer operating hours than other reciprocating engines [3[.

Stirling engines have simpler mechanisms than many other reciprocating engines, with no need for valves and a relatively simple heat supply system. Some Stirling applications can even be built using materials found in a typical household [3].

Stirling engines use a single-phase working fluid, which makes the risk of explosion relatively unlikely in a properly designed engine, unlike engines that use a two-phase working fluid [2].

The use of low operating pressures allows the use of light cylinders in Stirling engines [2].

Stirling engines can be made to run quietly without the need to supply air, making them suitable for air-independent propulsion (e.g., in underwater applications) [2].

Stirling engines are easy to start, especially after warm-up, and are more efficient in cold weather than internal combustion engines, which start easily in hot weather but not in cold weather [2].

Stirling engines used for pumping water can be set so that the compression chamber is cooled by the pumped water, particularly if the water is relatively cold [3].

Stirling engines are versatile and can be used for both heating and cooling applications, such as combined heat and power (CHP) in winter and cooling in summer [2].

The regenerator in Stirling engines allows the heat dissipated by the engine to be exploited, making it an ideal solution for dual efficiency heat and power applications, unlike the internal combustion engine [6].

2.5 Disadvantages of Stirling engines

Size and cost issues

Heat exchangers are necessary for both input and output heat to the Stirling engine to maintain pressure levels, and the heat exchanger on the expansion side operates at high temperatures, requiring durable materials that can withstand oxidation and deformation. The quality and durability of these materials increases the cost of manufacturing the engine, with about 40% of the cost going to high temperature heat exchangers [6].

Efficient operation in thermodynamic cycles requires large temperature differences and in external combustion engines, such as the Stirling engine, where the heater temperature must be higher than or equal to the expansion temperature, placing high metallurgical demands on the heater. In contrast, internal combustion engines, such as the Otto or Diesel engine, have materials that can handle lower average operating temperatures, since the input heat is not transmitted through the engine [3].

Heat dissipation is a complex issue in Stirling engines, as lower coolant temperatures increase efficiency but also increase the bulk of the heat sinks, making it difficult to adapt the engine to small applications [2].

The overall bulk of Stirling engines and the cost of construction materials prevented automakers from using the engine as a prime mover in automotive applications [2].

Power and torque issues

Stirling engines operating with small temperature differences have relatively large dimensions compared to the power they provide [3]. This is because the heat transfer coefficient of the gases limits the amount of heat that can be transferred by the heat exchangers. Designing these engines to transfer heat in and out of the working substance is difficult and expensive, as the required heat transfer flux increases for smaller temperature differences. However, increasing the temperature difference and pressure can result in higher power output if the heat exchangers can handle the increased heat flow.

Stirling engines take some time to warm up before they start working, which is typical of internal combustion engines. However, Stirling engines may require slightly more warm-up time than other types of engines such as steam engines [6]. They work best when operating at a constant speed, and adjusting their performance requires precise design and additional mechanisms, such as changing the stroke of the piston or adjusting the mass of the working substance.

Working substance/gas issues

To ensure that high pressure can be achieved with a small amount of heat transferred, the working substance used in Stirling engines must have a low heat capacity. Helium is an ideal choice because of its very low heat capacity, but atmospheric air is also an option. However, the use of oxygen in high-pressure air engines may pose a risk of oil explosions [3]. To mitigate this risk, Philips developed Stirling engines that use other gases as working substances. Hydrogen is an ideal gas for use in Stirling engines because of its low viscosity and high thermal conductivity, which allow the engine to run faster. However, hydrogen can diffuse through the solid metal walls of the engine, causing leaks at high temperatures. To avoid this, hermetically sealed chambers are used and materials such as aluminum, stainless steel and ceramics are used to reduce diffusion. Additional mechanisms, such as a backup gas tank or gas fill generator, may be required to maintain high pressure levels in machines with large temperature differences.

Hydrogen is produced through the electrolysis of water, but can embrittle metals and is a flammable gas, creating hazards if it escapes. While helium is an effective working substance that has minimal impact on the engine structure, it is expensive and must be supplied in pressurized containers. It is possible to achieve similar performance to ambient air with the working substance. However, Stirling engines using hydrogen or helium have a much higher efficiency per volume unit.

2.6 Commentary

Much disagreement has been expressed in thermodynamic engineering books about the discrepancy between the theoretical and the actual Stirling cycle, which has caused confusion among scholars. In practice, the main issues are related to the reduction of the actual efficiency, which is affected by physical limits such as heat transfer and friction caused by the viscosity of the enclosed gases. Other engineering issues discussed include the preference for simpler drive systems over more complex ones to approximate the ideal cycle, limitations in available materials and non-ideal gas properties, and mechanical properties of structural materials such as heat transfer, tensile strength, creep, fracture toughness and melting point [3].

Friction and Lubrication: Stirling engines can ignite and explode at high temperatures and pressures, especially if the working substance is atmospheric air or any gas heat engine combined with a liquid lubricant. Such explosions have resulted in injuries and even death. In addition, lubricants can cause “clogging” in heat exchangers, especially in the heat generator [3]. For these reasons, engine designers prefer models that do not require lubrication and are made of materials with low coefficients of friction such as graphite. In some other models, rubber seals are used to ensure piston tightness, which eliminates contact between moving surfaces [6]. These design features contribute to less maintenance and longer life, making Stirling engines more reliable than conventional internal combustion engines.

Comparison with Internal Combustion Engines: To begin with, the Stirling engine has unique advantages over internal combustion engines in that it can efficiently use renewable energy sources, operate with reduced noise levels, and requires minimal maintenance, making it more reliable. Therefore, the Stirling engine is preferred for applications where these advantages play a critical role, especially if the cost per unit of energy produced is more important than the total cost per unit of power. In such cases, the Stirling engine can economically compete with internal combustion engines up to about 100 kW [9]. Although the Stirling engine is heavier, larger and more expensive compared to internal combustion engines in the same power class, it is more efficient and its lower maintenance requirements make the overall energy costs comparable. The thermal efficiency of relatively small Stirling engines ranges from 15% to 30% [6]. Additionally, the Stirling engine is superior in situations where heat and power are produced in small scale applications. It is also preferred for other applications such as water pumping, space missions, and the conversion of energy from surplus sources that are not compatible for use in an internal combustion engine, such as solar energy, biomass, agricultural waste, and municipal waste.

2.7 Applications

Stirling engines have several unique advantages over other heat engines, including the ability to operate with a wide range of heat sources, high efficiency and low emissions. As a result, Stirling engines have many potential applications, such as power generation, heating and cooling, solar energy, transportation, and military applications [2]. Therefore, Stirling engines are an attractive technology for a range of sustainable energy applications.

Power generation: Stirling engines can be used to generate electricity in a variety of settings, including remote or off-grid locations where traditional energy sources may not be available. Stirling engines can be powered by a range of heat sources, including fossil fuels, biomass and solar energy, and can be designed for a variety of output levels. They have the potential for high efficiency and low emissions, making them an attractive technology for power generation [10].

Cogeneration of Electricity and Heat: Stirling engines can be used in combined heat and power (CHP) systems, where they produce both electricity and heat. CHP systems are usually more efficient than separate electricity and heat generation systems because they use waste heat from electricity generation to provide heating or cooling. Stirling engines can be designed for a range of efficiency levels, making them suitable for a variety of CHP applications [10].

Solar power: Stirling engines can be used in solar power systems, where they convert the sun's heat into mechanical work. Solar Stirling engines have the potential for high efficiency and low emissions, making them an attractive technology for sustainable energy production. They can be designed for a variety of output levels, making them suitable for both small- and large-scale applications [2].

III. CONCENTRATING SOLAR SYSTEMS

Concentrated solar power (CSP) is a method of electricity generation that uses the direct beam of sunlight. The mirrors reflect sunlight onto a receiver, which concentrates the heat to produce mid- or high-range heat. This heat is then used to power a conventional thermodynamic cycle such as a steam turbine or heat engine. The end-result of this process is the production of electricity. To ensure continuous operation, the energy generated during the day can be stored in different materials such as molten salts, ceramics, concrete or saline mixtures, which can be used during periods of low solar radiation or at night. The process of generating electricity using solar thermal technology is similar to that of traditional power plants, with the main difference being that the energy source is concentrated solar radiation, which is collected and converted into high-temperature steam or gas to drive a turbine or engine. The four main components required for this process are a central solar collector, a radiation receiver, a heat transfer or storage medium and a heat exchanger [11].

Solar collectors include all devices that harness solar energy by capturing solar radiation and converting it into heat. Concentrating solar panels, on the other hand, require movement and tracking of the sun’s path to gather direct sunlight to a focal point through reflection. Motion can occur around one or two axes of freedom. The concentration of solar radiation results in a significant increase in intensity, leading to higher temperatures at the focal surfaces. As a result, they are used for high temperature applications such as power plant operation. However, the large size and high production cost of concentrated collectors require complex drive mechanisms and maintenance, making them relatively expensive. However, they play a critical role in the operation of concentrated solar systems [2].

The technical unit used to measure energy storage capacity is the GWht, but it is more often expressed in hours, indicating the number of hours a station can operate at its rated capacity, based solely on the storage system. The optimal size of energy storage depends on the characteristics and role of each power plant [12]. It also depends on a station’s “solar multiple”, which is the ratio of the actual size of the solar field to the size needed to achieve the estimated output, given the best possible year-round conditions. This ratio is always greater than one, to ensure sufficient output power in case of variations in solar radiation, hitting the station during the day.

In recent years, an increasing number of concentrating solar power (CSP) plants use thermal energy storage technologies. The rapid decline in photovoltaic (PV) system prices has made energy storage essential for the competitiveness and survival of CSP plants. Energy storage not only enables these systems to be economically competitive in the energy market, but also contributes significantly to the higher penetration of renewable energy sources in the electricity grid, including wind turbines and PVs. With energy storage, CSP plants can supply electricity to the grid entirely or largely during hours when there is no sun or wind. This allows PV or wind systems to have a greater share of grid penetration during sunny or windy hours. Therefore, CSP units become the most flexible renewable energy source for the grid [2].

3.1 Advantages and prospects

Concentrating solar systems have great potential as they allow efficient use of solar energy, with efficiency levels reaching up to 85%. The thermal energy produced can also be used for other purposes, such as industrial applications, district cooling and seawater desalination. Ideally, solar power plants can be designed to meet the load requirements of the electrical system during the day, and with the advancement of energy storage systems in the future, they may be able to meet most of the load. For smaller, distributed generation needs, smaller plants, such as small disc-engine systems with power output ranging from 3-25 kW, can be placed directly at consumption points [1].

Concentrating solar systems have a wide range of implementation possibilities, ranging from small remote energy systems producing a few kW to large power plants producing hundreds of MW and directly connected to the grid. However, due to the high cost of installation, operation and maintenance, it is preferable to use CSPs in large power plants. As concentrated solar technology matures, there will likely be an increase in the use of hybrid thermoelectric systems, which use fossil fuel reserves to ensure electricity production during periods of low solar radiation [2].

For large-scale electricity generation, concentrating solar systems are best suited for areas with abundant sunshine, such as the Mediterranean countries in Europe, the US southwest coast, Central and South America, Africa, the Middle East, China and Australia. In these areas, one square kilometer of surface area can produce 100-200 GWh of electricity per year, which is comparable to the annual output of a conventional 50 MW power plant powered by coal or natural gas [11]. The usage of solar thermal plants can not only be a cost-effective alternative to fossil fuels, but can also help reduce environmental impacts, greenhouse gas emissions and mitigate climate change.

To operate, concentrating solar systems produce none of the harmful environmental impacts that traditional power plants produce. They do not release pollutants, operate silently and can be switched off at any time without problems. In addition, during operation, they do not emit carbon dioxide, the main gas responsible for global climate change. While there may be some carbon dioxide emissions during the construction of the system, they are still much lower than those produced by traditional power plants. It is estimated that harnessing just 1% of the total potential of solar thermal systems worldwide could reduce carbon dioxide emissions enough to stop climate change. Meanwhile, the cost of generating electricity from concentrated solar systems is gradually decreasing. With advances in technology, mass production and improved operation, production costs are expected to drop dramatically. This would eventually make these systems competitive with conventional fossil fuel plants in the next 10-15 years [2].

3.2 Technologies of Concentrating Solar Systems

There are many different types of concentrating solar systems, including combinations with other technologies, renewable or non-renewable, but some widely used and promising technologies are:

- The Linear Concentrating Solar Power (Linear CSP) Systems.
- The Central Receiving Systems (CRS).

These technologies differ in optical design, receiver shape, nature of the transfer fluid, and their ability to store heat before it is converted to electricity.

To maximize solar energy collection, CSP linear arrays consist of several grouped panels arranged in parallel rows, aligned in the north-south direction. These panels are equipped with a single-axis sun tracking system that allows the mirrors to continuously reflect the direct beam of solar radiation to the receivers throughout the day.

CSP linear collectors use large mirrors to reflect and focus the sun's rays onto a linear receiver tube, which contains a liquid heated by solar radiation. The superheated liquid then creates steam, which turns a turbine to generate electricity via an attached generator. Another method of generating steam is directly in the solar field, eliminating the need for expensive heat exchangers. The Parabolic Concave Mirrors and the Linear Fresnel Systems are two types of Linear CSP technology [2].

The Parabolic Concave Mirrors

Parabolic cavity technology uses reflective mirrors to concentrate solar radiation into thermally efficient receiver tubes, positioned along the focal line of each parabolic mirror(Fig. 2). The receiver tubes are designed based on the mirror construction and contain either a heat transfer fluid, such as synthetic oil, or water/steam heated by the sun's rays. If heat transfer fluid is used, it can reach temperatures of around 400 °C and is pumped through a series of heat exchangers to produce superheated steam, which is then used to generate electricity via a steam turbine or combined cycle. The water/steam receiver tubes can be sent directly to the turbine to generate electricity. Parabolic cavity systems can include thermal energy storage, which allows excess heat generated during the day to be stored for use in the evening or on cloudy days to generate additional steam and electricity.

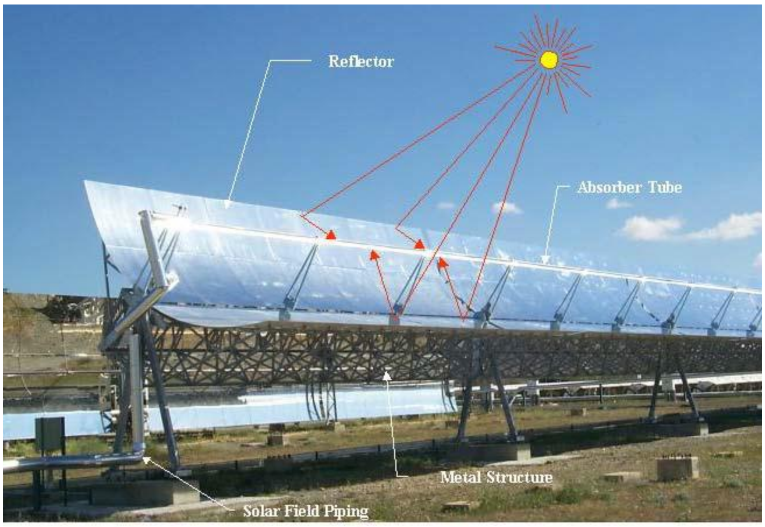

Figure 2: The EUROTROUGHparabolic mirrors array [13]

Since 2006, 50% of the parabolic power plants built in Spain have been equipped with two-tank thermal energy storage systems that use molten salts and can provide up to seven hours of full power generation (assuming the storage system is fully charged). In the United States, three 280 MW power plants were built and connected to the grid in 2013 and early 2014, with two having no storage systems (Genesis and Mojave in California) and the third (Solana Power Plant in Arizona) to have a storage capacity of six hours. Parabolic systems can also be designed as hybrid systems that use fossil fuels to supplement solar output, during periods of low solar radiation, typically using a gas or steam boiler.

Parabolic troughs are an established technology for concentrated solar systems, but there is still room for improvement. Advanced structural designs could improve mirror accuracy and reduce costs, while the next generation of receiver tubes could reduce heat loss and increase system reliability. Better heat transfer media could also boost operating temperatures and system performance. Automating production is a critical step in increasing the widespread adoption of these systems and ultimately reducing costs.

The Linear Fresnel Reflectors

The Linear Fresnel Reflectors are another type of linear collector technology. These systems use flat or slightly curved mirrors mounted on ground trackers and angled to reflect sunlight onto a receiver tube mounted above the mirrors. A small parabolic mirror can be added to the top of the receiver to further concentrate sunlight (Fig. 3). Compared to parabolic troughs, linear Fresnel collectors are simpler to manufacture, making them less expensive. They are able to achieve a higher solar concentration, resulting in lower heat losses. However, Fresnel systems experience more optical losses when the Sun is low on the horizon, leading to reduced power output in the early morning, late afternoon and winter months. However, higher operating temperatures can partially offset these losses.

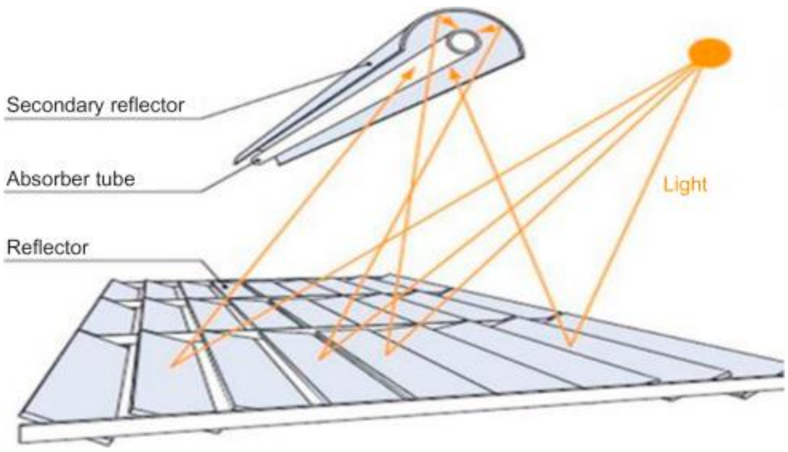

Figure 3: The Linear Fresnel Reflector [14]

Solar Energy Towers

A solar tower, also known as a solar power tower, is a type of concentrating solar power (CSP) system that uses a field of mirrors, called heliostats, to reflect and concentrate sunlight onto a central tower (CRS). Concentrated sunlight heats a liquid that is used to produce steam, which drives a turbine to produce electricity [15].

The (Parabolic) Disk-Machine Systems

The Disk-Motor system is a type of concentrating solar technology (CRS) that produces lower amounts of electricity compared to other systems - typically producing between 3-25 kW. This system works by using a parabolic dish made up of mirrors that reflect and focus sunlight onto a central machine to generate electricity. The two main components of this technology are the solar collector and the power conversion unit.

The solar collector, or disk, collects and focuses the sun's rays and then reflects them to a thermal receiver that absorbs the solar heat. The disk is placed in a structure that continuously monitors the position of the sun throughout the day in order to reflect the maximum amount of solar radiation to the thermal receiver.

To generate electricity, the power conversion unit of the Disk-Motor system consists of two components: the thermal receiver and the machine/generator. The thermal receiver acts as a link between the parabolic dish and the engine/generator, absorbing solar radiation and converting it into heat. The heat is then transferred to the machine/generator and there are two types of heat sinks: one type is a series of tubes containing a coolant such as hydrogen or helium, which is also the working fluid of the machine, and the other type uses heat pipes to transfer thermal energy to the machine. The engine/generator subsystem uses the heat from the thermal receiver to generate electricity. The Stirling engine is commonly used as a heat engine in Disk-Motor systems. It works by using heated fluid to move a piston, which in turn produces mechanical power. Mechanical work, in the form of turning a machine shaft, drives a generator to produce electricity.

Disc(/Dish)-motor systems are highly efficient due to their high optical focus and two-axis solar tracking system. They achieve the highest concentration of solar radiation compared to other concentrated solar systems, resulting in high efficiency. However, despite their superior performance, these systems have become less popular in the energy market. The main reason for this is that the high costs and technological risks associated with these systems have not been successfully minimized to make them competitive with other solar technologies. It is believed that these systems may have a future in decentralized power generation in remote areas.

IV. CASE STUDY

A parabolic mirror Stirling engine is a type of engine that uses a Stirling engine to convert heat energy into mechanical work. The device consists of a parabolic mirror that concentrates the sun's rays onto a heat exchanger, which heats a gas inside a cylinder to drive a piston. As the gas expands, it moves the piston and produces mechanical work. The mechanical work produced by the engine can be used to drive a generator.

An advantage of a parabolic mirror Stirling engine is that it can operate without any fuel input, as long as there is sufficient sunlight. This makes it a promising technology for remote or off-grid power generation. However, motor efficiency is relatively low compared to other types of power generation, and the cost of the parabolic mirror can be a significant barrier to adoption.

Harnessing solar heat to produce electricity through concentration is a critical function of parabolic solar reflector technology. This method is commonly used in smaller applications that have tens of kW power due to the size and weight of available Stirling engines and the effect of wind loads on the transom reflector. The main function of the parabolic solar reflector is to generate electricity within the range of kW to MW. A number of studies have investigated various technologies to achieve optimal arrays for solar reflector systems used in electricity generation. A disk-shaped parabolic reflector with a support structure and a Stirling engine placed at the center of the parabolic mirror to capture solar energy compose the parabolic mirror system [16]. The parabolic-shaped structure that supports the reflectors is made of stamped sheet metal, and the solar concentrator is usually between 3 and 15 meters in diameter, consisting of various sections of fiberglass resin or other reflective materials. Bases and additional construction components are made of steel. High-quality solar mirror reflectors must have various features, such as reasonable weight, resistance to deflection and wind loads, resistance to humidity and temperature changes in different weather conditions and locations, flexible parts, cost-effectiveness, effective reflective materials and long service life.

The solar collector is responsible for collecting all solar thermal radiation and converting it into useful energy. Similar to heat exchangers, solar thermal collectors experience thermal and optical losses, making them more complex devices. The two main categories of solar collectors are focusing (concentrating) and non-focusing (flat collectors) [17]. Concentrating solar power (CSP) technology typically uses a concentrating surface that increases the useful aperture and precisely focuses solar radiation onto a small area known as a thermal receiver. Focused solar panels typically operate at very high temperatures compared to unfocused solar panels and are often coupled with different thermal systems. The efficiency of the solar collector is highly dependent on the geometric ratio of Cr concentration, which is defined as:

$$Cr = \text{Area of aperture}/\text{Area of receiver}. \quad (2)$$

A concentration ratio greater than 1 (Cr>1) indicates a concentration collector, while a value of Cr=1 indicates flat technologies. If the geometric concentration ratio is greater than 5, the solar concentrators use only beam radiation and are known as imaging concentrators. Non-imaging collectors have a value of less than 5 and use partially diffuse radiation, usually in a ratio of 1/Cr.

There are several types of solar thermal collectors, with traditional designs being the most common. Solar power tower technology (SPT) is capable of achieving a high concentration ratio and temperature level of 500-1200 °C, making it a top performer. The parabolic solar dish collector (PSDC) comes in second, with a good concentration ratio and temperature level of 50-600 °C, respectively. Despite its advantages, SPT technology has some significant disadvantages, such as higher greenhouse gas emissions, land use, and water use, making the parabolic solar dish technology a promising alternative.

4.1 The reflective material of the concentrator

The material chosen for the concentrator is a critical aspect of designing a PSDC, as it determines how much solar radiation can be reflected to the receiver. Reflectivity is a key factor in determining whether a concentrator can effectively reflect solar thermal radiation. Traditionally, aluminum or silver reflective plates are used on the front side of plastic or glass parabolic mirrors for solar concentrators [16]. In the past, thin glass reflective mirrors from 1-4 mm thick, with a silver polished surface, were used to reflect the sun's rays.

Some researchers have found that the most effective reflective performance for solar reflectors is achieved with silver mirrors on 1 mm thick glass. In order to reduce costs, designers have used thin layers of polymer coated with silver or aluminum. Other researchers investigated the effect of iron content in the glass on mirror reflectivity. The reflection of silver reflectors in iron-containing glass depends on the thickness and iron content. In a relevant study conducted by [18], experimentally verified a 2.2 m diameter parabolic solar dish concentrator that had a reflection coefficient of about 0.85 and reflected the temperature of 380 °C to the thermal receiver.

4.2 Diameter of a parabolic mirror

Zayed et al. [19] conducted a study to investigate the effect of concentrator diameter on the performance of a solar parabolic trough collector (PTC) system. The study examined various concentrator diameters and their effect on the thermal efficiency and energy production of the system.

The results showed that a larger concentrator diameter can enhance the thermal performance and energy efficiency of the PTC system. This is due to the improved concentration of sunlight on the receiver, as the diameter increases.

However, the study also found that there is a limit to the increase in energy efficiency with concentrator diameter. Beyond a certain point, the marginal increase in energy efficiency does not worth the cost of further increasing the diameter. Therefore, concentrator diameter should be carefully considered when designing a solar PTC system, as it can significantly affect its performance.

4.3 EuroDish

The EuroDish is a concentrating solar power (CSP) parabolic dish with a system that uses a Stirling engine to convert thermal energy into mechanical work [20]. The European system consists of a parabolic mirror, which concentrates sunlight onto a receiver located at the focal point of the mirror. The receiver contains a Stirling engine, which converts thermal energy into mechanical work. The Stirling engine is connected to a generator, which converts mechanical work into electrical energy (Fig. 4).

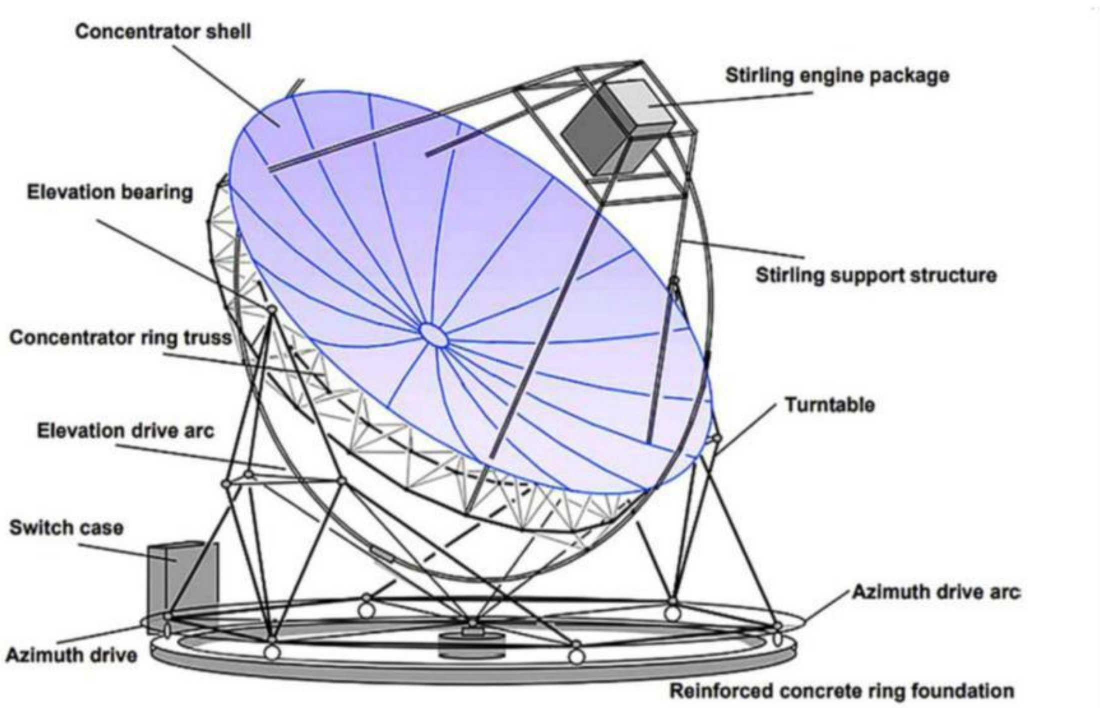

Figure 4: The EuroDish[16],[20]

The EuroDish system has many advantages over other types of solar energy systems. It has high efficiency and can operate at high temperatures, making it suitable for power generation in remote areas or off-grid locations. The system is also modular, meaning that multiple mirrors can be connected to increase the total power output.

The EuroDish system was developed and tested by the European Commission's Joint Research Center (JRC) and has been used in various demonstration projects around the world [16]. The system has proven to be reliable and cost-effective and has the potential to provide clean, renewable energy to communities around the world (Table 1).

Table 1: EuroDish Technical Data[16],[20]

Concentrator	Stirling engine	Tracking and Control
Diameter: 8.5 m Projected area: 56.7 m² Focal Length: 4.5 m Average concentration factor: 2500 Reflectivity: 94 %	Type: single acting, 90° V-engine Swept volume: 160 cm³ Gross power output at 900 W/m² DNI: 9,8 kW Net power output at 900 W/m² DNI: 9,2 kW Grid connection: 400 V, 50 Hz, 3 phase Receiver gas temperature: 650 °C Working gas: helium Gas pressure:20-150 bar Power control: pressure control	Suspension: azimuth Stow position: face down max. allowable wind velocity during operation: 65 km/h Survival wind velocity in stow position: 160 km/h Drive: servo motor Drive velocity: 60 °/min. Control system: PC, micro controller Data transfer: InterBus-S Remote control: telephone / WWW

In order to establish the effectiveness of EuroDish to cover the energy needs of a 100 sq.m. residence, the average annual radiation in areas of the Northern Mediterranean, such as the region of Attica (Greece), was studied, which was measured as 1850 kWh/m^2. Therefore, according to the research carried out in this region [2] it emerged that the average annual consumption of electricity per household amounts to 3,750 kWh and the average annual consumption of thermal energy (for space heating, hot water, cooking, etc.) per household is 10,244 kWh. Therefore, the average gross consumption is 13,994 kWh.

Considering that the efficiency of a Dish-Stirling system, like EuroDish, is about 20%, the total collected (falling) energy (TCE) required is:

$$TCE = 13{,}994 / 0.2 = 69{,}970 \text{ kWh.} \quad (3)$$

Given the above average annual radiation of 1850 kWh/m^2, the required size of the collecting surface S for TCE (3) is:

$$S = TCE / 1850 = 69{,}970 / 1850 = 37{,}822\text{m}^2. \quad (4)$$

Subsequently, the construction of a parabolic mirror for aDish-Stirling system is required, having a diameter D:

D = 2xsqrt(S /π) = 2xsqrt(37,822 / 3.14) = 2xsqrt(12.046)= 2x3.471= 6.942 m. (5)

The above calculations prove the ability of a Dish-Stirling system with the specific dimensions (5) to cover all the annual energy needs (13,994 kWh) of the particular residence (100 sq.m.).

V. CONCLUSION

The case study above was based on the EuroDish model, which was created 20 years ago. Since then several new models with higher yields have appeared. The object of the study is whether, with the Dish-Stirling method, a house of 100 square meters can become energy independent. In this study, economic benefits and costs are not taken into account unless the specific technology is capable of meeting the needs of the household. Ultimately with an average efficiency of 20%, the model will produce enough energy annually to cover its heating and electricity needs (14,000 kWh/year) for one year in the Attica region (Northern Mediterranean, Greece).

In conclusion, the Dish-Stirling system is a promising solar energy technology that uses a parabolic mirror to focus sunlight onto a Stirling engine to generate electricity. This system has the potential to achieve high energy conversion efficiencies and can be used for both large-scale power generation and decentralized applications. However, there are still some technical and economic challenges that need to be addressed to make this technology more viable, such as improving the reliability and durability of the Stirling engine, reducing the cost of materials and manufacturing, and increasing its scalability. Overall, the Dish-Stirling system holds great promise for the future of renewable energy and has the potential to play an important role in the global transition to more sustainable, low-carbon energy systems.

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