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ELECTRICITY PRODUCTION USING DISH/STIRLING CONCENTRATORS: A REVIEW

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Abstract. *This work presents a review of the literature on the study of electricity generation using dish/Stirling Concentrator. Firstly, a brief description of the main components of this solar system is given, which include the Stirling engine and some of its parameters. Following, the CSP (Concentrated Solar Power) is analyzed, and its most common technology is presented. The SPD (Solar Parabolic Dish) power plants are presented, revealing the advantages of the dish/Stirling system among all solar technologies. The dish/Stirling system has proven to be an attractive alternative to produce electricity, especially due to its high efficiency, up to 30%, and its unique design that allows wide flexibility in the choice of fuel. It is also important to note that the dish/Stirling system can be used in isolated locations, where the conventional power grid is not available. This use would mainly benefit the poorer and isolated regions. Although the parabolic trough is the dominant technology of producing electricity using solar concentrator, mainly due to its lower cost, the dish/Stirling system promises to overcome these challenges by reducing capital and maintenance costs and becoming competitive compared with other solar technologies in a few years, especially due to new technological improvements, new developed technologies, and large-scale production.*

Keywords: *Stirling engine, dish/Stirling concentrator, electricity production, solar parabolic dish, concentrated solar power*

1. INTRODUCTION

Energy takes an important role in the quality of life and economic development. Even with the increasingly higher cost of energy production and the environmental degradation, that became more apparent in the last decades, the use of energy continues to increase. This demand growth can be explained mainly by the population growth, economic performance, consumer habits, technological development, industrialization, and urbanization. Therefore, the depletion of non-renewable energy sources is a real future possibility (Shahsavari and Akbari, 2018). In this context, the adoption of renewable energy sources has become crucial in helping to reduce environmental impacts while at the same time delivering huge amounts of energy required for global supply. Recently, the use of renewable energy sources has played a key role in provides energy in many countries. This is due mainly to the development of new technologies that allow the use of natural resources like the sun and the wind as raw materials to generate energy. A sustainable electricity production system can be achieved with the adoption of an energy matrix that adopts the use of various renewable sources generating electricity (Khan and Arsalan, 2016).

Since the early years of the development of new technologies to produce energy using natural resources, solar energy was already giving signals that it would be the most attractive source of renewable energy for electricity production. The sun radiates millions of terawatts to the world every day. So, the use of this abundant, and renewable source of clean energy can decrease fossil fuels dependence as well as reduce the environmental pollutants. Because of that, solar energy stands out as a possible solution to present and future problems of the lack of electricity (Chalvatzis and Ioannidis, 2017).

Even though the solar energy is naturally available in the environment, it is necessary to develop technologies that enable the conversion of this energy into electricity. The main challenge is to become possible the use of the sun rays and convert them into electricity. Several researches were realized to achieve this goal and different processes were developed. One of them is using the indirect conversion of solar radiation into heat using devices that collect and concentrate the rays of the sun to heat a working fluid through the transfer of heat. The other process occurs with the use of the phenomena known as photoelectric that allow the direct utilization of the incident energy in the surface area of photovoltaic cells (Restrepo et al., 2016).

The devices that collect and concentrate the solar radiation are known as Concentrated Solar Power (CSP). These concentrators together with a tracking system, a receiver, a generator and a support structure, form a system that allows the collect and convert of solar energy into electricity. Several types of Solar Concentrator are available in the market, but none of them have the same performance as Solar Parabolic Dish (SPD). These concentrators present the best performances in high-temperature applications compared to other concentrators due to the high concentration of rays that can be achieved with the use of their high reflection parabolic mirrors. In addition, they have high power density and reliability (Yang et al., 2017).

Solar Parabolic Dish has many applications such as desalination and methanol-reforming. But their most common use is in electricity production. In this case, the solar dish collector can be integrated with a thermal machine that operates with the Stirling, the Brayton or the Rankine thermodynamic cycle (Zhu et al., 2019). Generally, the solar systems reach efficiencies near to 20%, but only Solar Parabolic Concentrators associated with Stirling engines are capable to reach efficiencies near to 30%. It is important to note also that the SPD can be used in isolated locations where the conventional power grid is not available to the population. Its use in this case would mainly benefit the poorer and isolated regions.

In a world that seeks for renewable energy sources to meet its growing demand with lower environmental impacts and lower costs, the knowledge of the Dish/Stirling technology emerges as an alternative for the generation of electricity using solar energy as a renewable source in places that allow its installation. The purpose of this review is to fill a gap in knowledge and promote the dissemination of this technology, as few scientific works have been done in this area. To achieve this goal, basic background and description of the Dish/Stirling system and its components, a description of how it works, its advantages, disadvantages and state of art of this technology have been provided.

Several current articles and theses were used for the bibliographic review of the CSP and Stirling engines. A detailed literature review of the research efforts was also performed.

2. LITERATURE REVIEW

The consumption of fossil fuels is related to many environmental problems, such as increased greenhouse gas emissions, deforestation, global warming, and air pollution. Currently, 80% of global primary energy is produced from fossil fuels. This situation causes great concerns because fossil fuels are non-renewable and highly pollutant resources. To reduce these problems and preserve the environment, stringent environmental laws are been created to regulate the energy sector. Awareness of the limitation of global energy resources leads the science to develop new techniques to achieve better use and value of existing resources. By improving energy efficiency and developing technologies that enable the use of abundant, clean and renewable energy sources such as solar radiation, biomass and wind to minimize environmental impact (Alper and Oguz, 2016).

Since the early years of developing technologies that allow the use of natural resources as a raw material to produce electricity, solar energy has always highlighted. This happened because solar energy is a renewable resource that is highly available, green, renewable and cheap. Until today these characteristics are responsible for the recognition of this natural resource as one of the most competitive among all other renewable resources. Devices such as Concentrated Solar Power (CSP) was created to enable the collection of sun rays, turn them into thermal energy and then generate electric energy (Barreto and Canhoto, 2017).

2.1 Stirling Engine

The Stirling engine is a sealed system with a working gas that is cyclically compressed and expanded during its movement through two chambers that is in different temperatures. The thermal cycle that features these machines is a closed regenerative thermodynamic cycle with two isochoric and two isothermal processes known as the Stirling cycle. This cycle is executed in four phases: isothermal compression, isochronous heating, isothermal expansion and isochronous cooling (Saxena and Ahmed, 2017).

Caetano et al. (2017) state that the main components of Stirling engine are the three heat exchangers that are known as the heater, the cooler and the regenerator. The working fluid moves alternately inside the engine and there is no mass transfer for the environment except for the leakage between the engine parts. Stirling engines allow operation with a wide range of working fluids such as air, hydrogen, helium or nitrogen. Two pistons, a piston and a power piston, operate by a crankshaft. Usually the piston guides the power piston 90 degrees. The engine has a high temperature chamber where expansion occurs and another low temperature chamber where compression occurs. The total volume of the working fluid varies with the movement of the power piston. Power piston movement varies the proportion of working fluid in the compression and expansion chamber while maintaining the same gas pressure on opposite sides of the piston. When the plunger is in the highest cylinder position, most of the working fluid is in the compression chamber. Lowering the plunger causes movement of the working fluid from the compression chamber through the regenerator to the expansion chamber. The heating of the working fluid increases the fluid pressure in the expansion space. As a result of the tendency of pressure balancing throughout the working fluid volume, a high pressure emerges on the face of the power piston. Upward movement of the plunger causes much of the working fluid to move from the expansion chamber through the regenerator to the compression chamber. In the compression chamber, this working fluid will decrease the temperature and the power piston face will be at low pressure. The alternating expansion and compression of the working fluid cause variations in the pressure that acts on the power piston surface, resulting in the work transfer to the piston.

Li et al. (2017) cite that the Stirling engine can be commonly found in three different configurations that are classified according to the arrangement of the expansion and the compression chambers: alpha, beta, and gamma. The alpha configuration has two power pistons connected and on different cylinder with the same diameter. The beta configuration utilizes the power piston and the displacement piston accommodated in a single cylinder. The gamma configuration has the power piston and displacer mounted on separate cylinders with different diameters. Based on works presented in the literature, it is possible to state that the beta configuration is the most used for solar applications, being presented in works such as Sripakagorn and Srikam (2011), Thirugnanasambandam et al. (2010) and Aksoy and Karabulut (2013). Figure1 illustrates the three different configurations of Stirling engines.

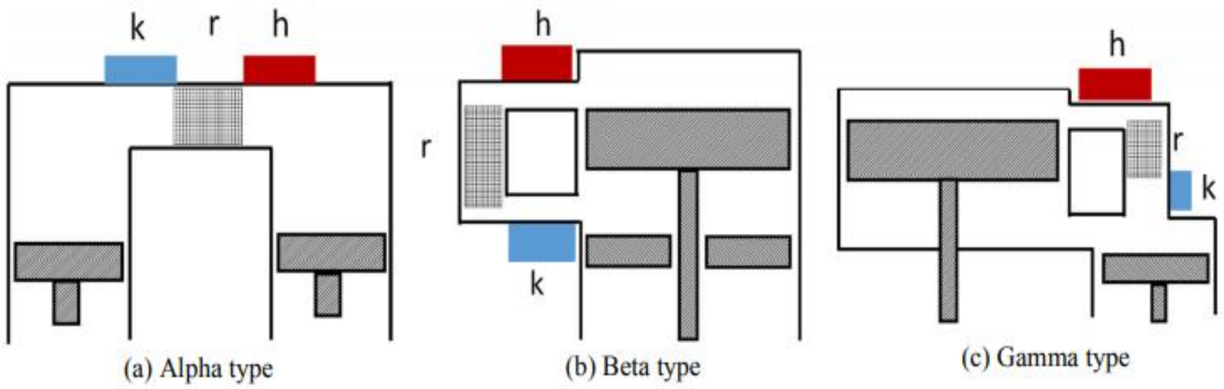

Figure 1. Schematic drawing of three types of Stirling engine (Li et al, 2017).

The features of this engine are responsible for its main advantages: the high efficiency and flexibility in the choice of fuel source. Theoretically, the Stirling engine has the highest energy efficiency compared to other thermal machines. It occurs because the efficiency of its ideal thermodynamic cycle is close to the Carnot cycle (Alfarawi et al., 2016). During the fifties and sixties, Dutch company and Philips company constructed some experimental Stirling engines that were capable to reach a theoretical thermal efficiency of about 45%, surpassing the efficiencies of the gasoline engine, diesel engine and steam engines that present efficiencies between 20% and 35%. Some researches managed to get created small Stirling engines with high thermal efficiency greater to 30%. Stirling engine is an external combustion engine that's why it can operate with any power sources, for example, with any fossil fuel or biofuel, biomass waste, methane, geothermal, coal, and wood pellets (Rinker, 2018).

Erol et al. (2017) state that due to large sizes and acceleration variations, the Stirling engine were little used and ended up being overtaken by the other engines in the nineteenth century. Especially, during the earlier years of the Stirling engines development, the internal combustion engines presented a high-power density and greater responsiveness. Hijazi et al. (2016) describe serious constrains that were presented by the Stirling engine, at that time, due to problems presented by those engines to work properly under high temperatures and pressure. The main challenges at that time involving the leakages on the cylinders seals and the materials of the walls that could not withstand severe operating conditions.

Shendage et al. (2017) demonstrate that in the present days, due to technological advances in the area of materials and manufacturing processes, the viability and reliability of the Stirling engines have greatly increased. And today, those old difficulties were partly overcome. Moazami et al. (2017) cite that the modern Stirling engines are more efficient than the early Stirling engines and can use any high-temperature heat source. Until today, several researches keep on being developed to improve the efficiency and performance of the Stirling engines. The geometric and physical parameters and working fluid are the factors that most influence the performance of the Stirling. Most of the current works are focused on the design of the Stirling engine to achieve high power output levels, high thermal efficiency, and relatively low cost of construction and maintenance.

Damirchi et al. (2015) cite several advantages that characterize this engine such as constant power output, quieter operation, simplicity in design and construction, easy operation, low vibration, long life expectancy and release of fewer pollutants than the internal combustion engine. These engines could have various applications such as power generation, the automotive area, criogeny, space projects, irrigation, refrigeration and the use with a fuel hybrids system to produce work and assurance higher production of electricity in CSP power plants.

During the production of electricity using solar dish concentrator, the Stirling engine will be placed exactly on the focus of this parabolic dish. Then, the concentrated solar rays will directly reach the hot chamber providing the heat necessary to power this engine. The displacer and the power piston are on a common axis linked to a crankshaft and the rotary generator, that is connected to this shaft. When the engine starts to work, its shaft starts to move and runs the generator, producing electricity (Wardhana et al., 2016).

Beltrán et al. (2015) cite that some studies are still necessary to achieve better performance of the Stirling engine such as a better control of the power modulation of this engine, reduce the large volume and weight and increase the compression ratio. Ould et al.(2016) states that the gas sealing keeps on being a problem at this engine and in some applications with Helium and Hydrogen, it is still necessary an extra system to store and supply the working gas to the engine due to the leakages. Some improvements in reduction of cost, increase of reliability, and packaging envelope is still required. Caballero et al. (2017) state that the companies that sell Stirling engines do not provide all information about them because of that, the biggest barrier for research in this area, is the lack of data about their performance and operational parameters. This barrier can be overcome using mathematical models and computational simulations that predict the engine performance and enable to develop the engine projects and fabrication. Figure 2 shows a sectional view of commercial engines operating with solar radiation as a heat source.

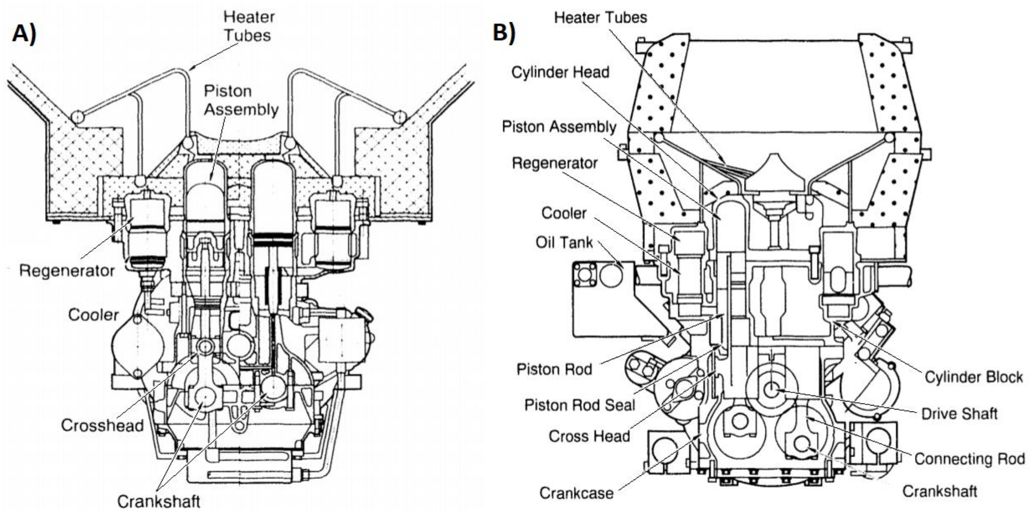

Figure 2. *S*ectional view of commercial Stirling engines. A) United Stirling 4-275, B) United Stirling 4-95 MKII (Stine and Diver, 1994).

2.2 The Concentrators

Solar energy is naturally abundant and available in the environment. But to produce useful work using the sun radiation, it is necessary to develop mechanisms that enable the use of this power. One way to promote the use and conversion of this solar energy in useful work is by the use of solar concentrators. These devices use geometry and thermal phenomena to collect and direct the incident solar radiation in its concentrator dish to the absorber. When a Stirling engine is placed as a receiver with its expansion chamber on the focus of a parabolic collector, it is possible to run this engine and produce useful work (Sandoval et al., 2019).

Ratismith et al. (2017) defined concentrating solar collectors as thermal devices which allow the conversion of incident solar radiation over its surface area into thermal energy. This absorbed energy can be directly transmitted to the hot water or space conditioning equipment or can be stored in a tank to be used in the absence of the sun. There are two types of solar collectors: non-concentrating or stationary and concentrating ones. The non-concentrating collectors are characterized by its collector opening area that is almost equal to the absorber area. Thus, the entire surface area of this collector behaves as an absorbent surface. It is unnecessary a solar tracking system for its correct operation. Because of that, they are cheap and don't demand sophisticated technical skills to install. The basic differences among those configurations are the motion and their operation temperature. They can be classified as Flat plate collectors (FPC); Stationary compound parabolic collector (SCPC); Evacuated tube collectors (ETC).

The concentrator collector consists of a concave reflecting surface that allows the capture of the solar rays and concentrates them in a single point called focus, increasing the radiation flux. Many different designs have been developed to allow this concentration of sunrays (Maatallah et al., 2018). The concentrators may operate as reflectors or refractors. They may have a cylindrical or a parabolic shape and may be continuous or segmented. Their receptors may have a convex, flat, cylindrical or concave shape and can be covered with glass or inverted (Sonawane and Raja, 2017).

According to Singh and Kumar (2018) the goal of the collector system is to enable the capture and transmission of the heat needed to keep the engine running. The thermal receiver of a collector system is divided into two parts: an aperture and an absorber. While the aperture receives the beam of concentrated sunlight supplied by the solar concentrator, the absorber transmits the resulting heat to the working gas which is enclosed within the Stirling engine. Then, the Stirling engine uses this thermal energy to produce mechanical work. CHP (Combining Heat and Power) applications require that the receiver absorbs the solar energy radiation and transforms it into thermal energy through the heat transfer to a working fluid. Heat can be converted into work by integrating a motor directly into the receiver, or this thermal energy can be accumulated in a central system by the use of pipes.

Stefanovic et al. (2018) perform a numerical thermal model in EES to predict the performance of a parabolic dish system. Parameters such as inlet temperature, flow rate, absorption emission, optical efficiency, wind speed, and ambient temperature were combined to determine their optimized values for several designs and 27 different operational conditions. Experimental data obtained from a pilot prototype of solar panels of collectors with an absorbent coil were used to validate the model. The values that maximize exergetic performance are the fluid temperature of 212.3°C and a optimum flow of 314.6 l/h of water, with thermal and exergetic efficiencies equal to 49.83% and 21.42% respectively. This study proved that this solar concentrator is an innovative and attractive device to produce thermal energy using the sun rays at low cost. Figure 3 illustrates the collector system of Stefanovic et al. (2018). Highlight that the absorber acts as a secondary reflector.

Figure 3. Collector system with spiral absorber and 13 coils (Stefanovic et al., 2018).

A fixed metal structure in the ground underpins the hole solar dish/Stirling system. Several materials can be used in the surface of the dish-Stirling concentrators. Some of these concentrators present multiple layers of fiberglass, while others present several segments of resin or any other material that facilitates reflection of the sun rays. The addition of a thin layer of glass in the material of the parabolic dish surface can increase its reflectivity until it reaches almost 94 %. Due to construction difficulties to obtain an ideal parabolic shape, an approximation allows the use of several mirrors in a spherical shape that is shored by a truss (Oommem and Jayaraman, 2001).

Commonly, the bleachers and almost the entire fastening structure are made of steel. Normally, the diameter of a SPD is very large, being able to measure several meters. The power and the size of the Stirling engine are directly related to the diameter and the material of the solar collector (Bravo et al., 2012).

Hafez et al. (2016) demonstrate that the selection of the optimum material of the surface dish, based on the desired power output and costs, can optimize the performance of the parabolic dish. Materials with low reflectivity result in an increase of the diameter of the solar dish. It happens because a bigger amount of solar radiation is necessary to be collected to provide the power output that is required. Zeng et al. (2016) cite that extensive variations of large order of magnitude can be found in the ratios of aperture for different concentrators. In this case, the optical precision requirements and the positioning of the concentrator system will represent a great increase of costs and technical difficulties.

During the day, the dish follows the sun's trajectory. It is necessary because just the direct solar radiation can be captured by the concentrator and a minimum amount of solar energy is required to guarantee the function of this device. Hence, the tracking system is essential to the correct function of this technology. The tracking of the sun can be accomplished in two different ways. The altazimuth method is usually used in the parabolic solar collector because it allows a better return of the system of tracks, in both altitude and azimuth. On the other hand, the second tracking method has an axis and allows only the movement in one direction, either from east to west or from north to south. The disadvantage of this system is the need of continuous adjustments to correct the variations of the sun's orientations (Suneetha and Rajan, 2017).

2.3 Solar Parabolic Dish (SPD)

Dish/Stirling systems are high-temperature solar concentrators, in which the directly incident sun rays, are directed by parabolic reflectors to a receiver located at a focal point. In the case of dish/Stirling system, a dish receiver is used to collect and direct the sun rays in such a way that the concentrated sunbeam is transferred to the fluid inside a Stirling engine. This engine is responsible for producing the work that will be converted into electricity (Pheng et al., 2014).

SPD technologies offer electricity in large-scale, constant production capacity through the integration of thermal energy storage and in hybrid operation. The highest electric conversion efficiencies of all the solar technologies are achieving by the Solar Parabolic Dish (Ahmadi et al., 2016). The Solar Parabolic Dish (SPD) is one of the most potential solar technologies among all renewable energy technology (Giovannelli, 2015). The main characteristic of the SPD systems are the highest solar-to-electric conversion efficiency, near 30%, that is one of the biggest values when comparing with another solar system (Naik et al., 2017).

Solar Parabolic Dish has a small complexity in construction and safe operation. Those characteristics became possible to apply SPD systems in remote and small isolated grids, especially, rural areas (Affandi et al., 2015). SPD can be applied as a grouped system for small-grid or end-of-line utility. It is possible to place them on irregular topography or slant surface. Historically, the dish-Stirling systems have targeted high-value remote power markets. But, due to opportunities, the development of the SPD industry is increasingly interested in operating in larger, grid-connected markets and some small remote power grids at about 10 kW (Baharoon et al., 2018).

Recently, studies and experimental projects with small scale of dish/Stirling have been developed. As for example, the Eurodish system that is under development in Europe and the EUA. Their main objectives are to improve the reliability and thrust of these systems. These dish/Stirling prototypes units have started to operate in Spain, France, Germany, Italy, and India producing an electric power near to 10 kW (Gholamalizadeh and Chung, 2017). Various studies carried out by researchers on SPD design that have produced very promising results. Combined heat and power generation is one of the new ideas that have been developed by dish/Stirling manufacturers. The concentrating solar irradiation can be used for high-temperature applications such as solar cooling, industrial heat, desalination, and methanol reforming (Hepbasli and Alsuhaibani, 2011). Recently, new applications stand out, such as satellite power supply and substitution of steam turbines in nuclear power plants (Korlu et al., 2017).

The global distribution of Direct Normal Irradiance (DNI) is used to help the selection of places with high potential for construction of SPD power plants. The knowledge of the available radiation in places becomes the major information to enable the project and planning of future CSPs and the determination of their stages. Consolidated forecast models allow the determination of solar irradiation in many places based just on experimental measurements. Because of that, the cost of these researches became less expensive (Parrado et al., 2016).

Aiming to maximize the production of electricity and minimize the costs, the correct selection of places to execute the installation of the SPDs power plants is crucial. Appropriated places that can provide the required irradiation and allow the better performance of the SPD units can guarantee the development of viable solar power plants. In this case, the major influence on the electricity production is the solar irradiance. To normally operate and be viable the amount of 5 kWh/m^2/day of Direct Normal Irradiance (DNI) is necessary for SPD systems (Belgasim et al., 2018).

Liu et al. (2016) declare that some decades ago, SPD power plants presented the highest cost in comparing with other types of solar power generation. Because of this, some industries that worked with dish/Stirling power plants canceled some projects. Today, the majority of CSP projects that are undergoing or currently under construction adopted the parabolic trough technology.

But, several studies point to a trend that the capital and operating costs of the dish/Stirling systems will reduce soon. There are even predictions that affirm this technology will be financially competitive such as parabolic trough and the solar power tower in just a few years. Some features of the dish/Stirling enable the improvement of the productivity of electricity such as the possibility to modulate the solar dish, its high efficiency compared to other solar concentrating technologies, and the ability to operate in conjunction with any fuel sources to ensure a more reliable generation under different climatic conditions. Thus, the dish/Stirling system will play a crucial role in the future viability of renewable energy systems where it can be financially attractive. Lower costs can be achieved with technological improvements and large-scale volume production (Hang et al., 2008).

According to Bijarniya et al. (2016) there is an operational and commercial SPD power plant located at Utah in the EUA. This power plant will have capacity to produce till 1.5 MW. It consists of 429 solar dishes, so each of them has a

Stirling engine accoupled. The target of this SPD power plant is to produce 30% of the electricity requirements of the US Army facility. The other SPD power plant is non-operational, and it is at Peoria, in Arizona, EUA. It has 60 solar dishes, and each of them has a Stirling engine. Another example of SPD power plant is the project that is under constructed in Middle East, where various large-scale projects based on this technology were announced (Enjavi-Arsanjani et al., 2015).

3. CONCLUSION

The presented work has provided a brief review of the electricity generation using dish/Stirling concentrators. The studies of several works of this technology allow to conclude that dish/Stirling systems have some characteristics that highlight them among all solar system, for example, its multi-fuel capability, the low release of pollutants, the simple construction, easy and quiet operation, the possibility to work in an isolated grid, the work hybridized with other fuels or the cogeneration, the CHP (Combining Heat and Power) applications.

The energy sector is a very competitive market, and only the financially viable technologies and at the same time, meets the population demands and the requirements of the energy industry, remain in this market. However, due to its implementation cost, the dish/Stirling technology may be unfeasible in some cases. So, some concerns about the improvement of the dish/Stirling operation the reduction of their costs remain.

Therefore, this scenery is changing mainly due to the increasing commercialization of this technology, the new methods, and designs that allow to maximize the overall efficiency and minimize losses and costs of these thermal machines, new improvements, and new technologies. Although the dish/Stirling system is not currently functioning on a commercial scale in the energy market, it is increasingly noted as one of the most promising solar energy technology of electricity generation.

An analysis of the solar power systems allows to state that the dish/Stirling system has the highest efficiency when compared to other solar systems. And, trends point out that the dish/Stirling will be a more profitable technology in just a few years.

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5. RESPONSIBILITY NOTICE

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