Realization of an Energetic Hub Based on a High-Performance Dish Stirling Plant

G. Cipriani, G. Ciulla, V. Di Dio,
V. Di Maria, V. Lo Brano
Department of Energy, Information engineering and Mathematical models, DEIM
University of Palermo
Palermo, Italy
giovanni.cipriani@unipa.it, giuseppina.ciulla@unipa.it, vincenzo.didio@unipa.it, vincenzodimaria7@gmail.com, valerio.lobrano@unipa.it

G. Larson
Ripasso Energy AB
Gothenburg, Sweden
gunnar.larsson@ripassoenergy.com

C. Chiaruzzi, A. Costantino, I. Manduca
Horizon S.r.l.
Palermo, Italy
c.chiaruzzi@horizonitalia.it, a.costantino@horizonitalia.it, i.manduca@horizonitalia.it

***Abstract* — In this work the realization of an energetic hub based on a high-performances dish Stirling system, at the DEIM of the University of Palermo, is presented. The realized system is the first top rated solar thermodynamic plant directly connected to the national electric grid. The connection permits the electricity injection into the grid and allows to access to national renewable energy incentives regime. The system realization was possible thanks to an international cooperation between the University of Palermo and the private company Horizon S.r.l., official partner of Ripasso Energy AB, owner of this technology. Initial data of the plant energy production and the foreseen improvements for the hybridization of the system and its integration with an electrical and geothermal storage system are also presented.**

Keywords—Dish Stirling; Thermal Storage; Electric storage, Hybrid Systems; Renewable Energy, Solar plant.

I. INTRODUCTION

In the last few decades, academic and industrial research have been focused on renewable energy sources and clean energy production. However, optimal utilization of available solar energy is still an open research topic also considering the opportunity of hybrid system that allows the employment of thermal waste [1].

The solar source is now widely exploited thanks to the photovoltaic systems that guarantee the production of significant quantities of electricity. One of the problems related to the construction of new photovoltaic systems is the occupancy of large areas of land , also due to the modules low efficiency.

For this reason, for the exploitation of the solar source, in addition to the traditional photovoltaic systems, the industrial and academic researchers have taken into consideration other technologies [2–4]. The most promising, in terms of efficiency and reduction of land occupancy, are the solar plants based upon sun's rays concentration.

In this paper the realization of an energetic hub based on a high-performance dish Stirling system, now available at the DEIM of the University of Palermo, is presented. The system is connected to the electric grid and it permits the electricity injection into the grid allowing the access to national renewable energy incentives regime.

Section II briefly describes the different typologies of concentrating solar plants.

Section III describes the dish Stirling plant of Palermo, realized thanks to an international cooperation between the University of Palermo and Horizon S.r.l. [5], official partner of Ripasso Energy AB [6].

In section IV issues about development path, construction and commissioning are reported.

In section V initial data of the plant energy production are reported.

Section VI presents the foreseen improvements due to the hybridization of the system and its integration with electrical and geothermal storage systems.

Section VII resumes the conclusions.

II. CONCENTRATING SOLAR POWER TECHNOLOGIES

Generally, Concentrating Solar Power (CSP) technologies use mirrors to concentrate the Direct Normal Irradiation (DNI) of the sun's light energy and convert it into heat in order to create steam to drive a turbine that is mechanically linked with an electric generator [2]. The generic plant consist of two parts:

- the collector, that concentrates solar energy and converts it into useful thermal energy

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- the energy conversion system, that converts the thermal energy in electrical energy [7].

According to the collector typologies it is possible to make a classification of CSP.

A. Linear parabolic collectors

Linear parabolic collectors capture the sun's energy with large mirrors reflecting and focusing the sunlight into a linear receiver tube. The receiver contains a fluid that is heated by the sunlight and then used to perform a traditional thermodynamic cycle connected to a steam turbine system that drives an electric generator [2]. The length of these collectors can be up to 100 m while their width can be up to 6 m. They are usually mounted on parallel rows with the axis of the collectors placed in the north-south direction. The tracking system, quite simple, is of the monoaxial type and acts in the east-west direction.

The linear focus is characterized by hot receptors pipes which convey the working fluid of the thermodynamic cycle. Thermo-mechanical conversion is generally operated by a Rankine thermodynamic cycle.

B. Fresnel collectors

Linear Fresnel reflectors use long, thin segments of mirrors to focus sunlight into a fixed absorber located at a common focal point of the reflectors, known as Fresnel lenses. These mirrors are capable of concentrating the sun's energy which is transferred through the absorber into some thermal fluid. The fluid then goes through a heat exchanger to power a steam generator. The most common installations use water as thermal vector, eliminating losses due to the use of an intermediate fluid. These installations are characterized by a receiver tube placed along the focal axis. Unlike the linear parabolic collector the receiver tube is fixed. The mirrors are installed close to the ground to reduce the effects of the wind and to minimize the use of support structures. Fresnel systems are relatively easy to implement and quite inexpensive compared to with linear parabolic reflectors. The reason is mainly due to the greater simplicity of the concentrator, the receiver is in a fixed position, and the support structures are much simpler. However, these systems have a lower efficiency [2].

C. Dish collectors

These circular parabolic reflector systems are characterized by a solar collector consisting of a parabolic dish concentrating the DNI in the focus of the parabola, where a receiver is placed. Some concentrators approximate the paraboloid using a set of trapezoidal shaped mirrors mounted on a support structure. The collector is always equipped with a two-axis solar tracking system. In this device generally the produced thermal energy can be directly converted into electrical energy through a Stirling engine coupled with an alternator unit, mounted in the focal point. Alternatively, the thermal energy produced by several collectors can be transferred to a heat transfer fluid and used by a centralized conversion system.

Industrial applications of this system allow to obtain operating temperatures higher than 700 °C and daily average efficiency of conversion of solar energy into electricity of about 30%, with peaks of 35% and more. These efficiency values are the highest of all current existing solar technologies. In most cases these plants use a production unit based on a Stirling engine powered by air or hydrogen while recent prototype plants have been realized with the use of air microturbines (Bryton cycle).

III. The Dish Stirling Solar Plant Realized in Palermo

A Concentrating Solar Plant with a peak power of 33 kW_e based on dish-Stirling technology has been installed at the Department of Energy, Information engineering and Mathematical models (DEIM) of the University of Palermo. The plant is directly connected to the electric grid, permitting the electricity injection into the grid with a monetary gain.

The plant (see fig. 1) consists of single-dish with a 12 m diameter parabola (net surface of 101 m^2) of mirrors collecting and concentrating the DNI. There are 104 mirrors characterized by an high optical efficiency (ability to focus in the same point) granted by an assembling procedure during the construction supported with a professional 3D camera and special 3D targets points. The parabola is supported by a reticular galvanized steel structure assembled and welded on site with a tolerance of 1 mm.

Fig. 1. Dish Stirling plant of University of Palermo

The whole structure weights about 8 ton and it is driven by a biaxial sun tracking system that absorb only 300 W: the dish is mounted on two elevations beam, that track the height of sun; the dish and the elevation system are coupled to a turn-table able to follow the solar azimuth moving on a circular concrete foundation. The shape of the foundation is only about 80 m^2 and the height of the plant is about 15 m. In the focus of the parabolic dish is placed the receiver that captures the solar radiation connected with the Stirling engine and the coupled asynchronous electric generator. The receiver is the hottest part of the Stirling engine and acts as heat exchanger. In the receiver takes place the conversion of solar radiation into thermal power supplied to the Stirling thermodynamic cycle using hydrogen.

The crankshaft of the Stirling engine is coupled to an asynchronous generator connected to a frequency converter and to an inverter which fed the produced electricity into the grid through an energy meter. The nominal operating conditions are: 1000 W/m^2 of DNI, 20 °C of air temperature, 720 °C of hydrogen temperature at $2 \cdot 10^7$ Pa (200 bar). The certified net efficiency from sun to the grid in these conditions is 32.4%.

IV. ISSUES ABOUT DEVELOPMENT PATH, CONSTRUCTION AND COMMISSIONING

The solar unit built at University campus of Palermo, still now holds the worldwide record in terms of net conversion efficiency from solar energy to electricity and represents the first commercial release of dish-Stirling plant connected to the national grid.

Italian rules and strategic targets, according to European guidelines, promote power plants with CSP technologies. From 2008 in Italy, there is a Feed In Tariff (FIT) to boost and catalyse this promising new Renewable Energy Systems (RES) based generators, similarly to Photovoltaic (PV) and Wind turbines in the last 10 years. Despite this scheme of FIT, the concentrating solar power technologies did not successfully entered into the Italian market: the Italian Energy Services Manager (Gestore dei Servizi Energetici or GSE) in 2017 received only one request of FIT from the Dish Stirling Demo Plant built inside University Campus of Palermo. One of the main reason is linked to the power peak of the CSP plants: nowadays a parabolic dish plant to be effective in terms of efficiency and cost needs a very large land. As example, for a 50 MW plant a land of minimum 250 hectares is needed to reach a yearly net efficiency about 20%. Instead, a single unit of the dish-Stirling, like that one installed in Palermo, with rated power of 33kWp, covers an area of 80 m^2 and guarantees a yearly net efficiency about 30%. For these reasons, nowadays the energy produced by CSP technologies is not near the grid parity unlike PV and Wind plants. In the next future a growth of CSP technologies is expected, also considering that the diffusion of this plants is one of the target from now to 2030 of the National Energetic Strategy (published at the end of 2017). New tools will be issued by the Italian government that recently announced a new higher FIT and a "guarantee fund" to permit the bankability of CSP technologies.

The bureaucratic and authorization process of new innovative technologies is not simple and for this reason, a set of new national rules and guidelines, applicable for plants with power peak up to 1 MW, have been announced in the last years. More in details, concerning the dish-Stirling in Palermo a quick authorization path called "simplified and asynchronous conference" has been used. This procedure allowed the full authorization of the plant in less than six months.

The authorization, the construction and the commissioning were not simple to reach, coordinate and manage, but the knowledge and experience of Italian and Swedish company, linked with the effectiveness support and precious knowhow of the team of professors from University of Palermo, allowed to focus and solve any technical and an administrative issues. The Demo Plant in Palermo is a "Solar Lab" born from a virtuous formula of co-marketing, a joint venture of University and Company to produce and transfer new knowhow.

V. INITIAL DATA OF THE PLANT ENERGY PRODUCTION

The CSP unit inside the Palermo University campus is equipped with a high precision weather station that includes a certified sun tracker with a pyrheliometer and a pyranometer. The station detects and collects on a timestep: DNI, diffuse irradiation, air temperature, wind speed and wind direction. This set of data, with the electricity production and the auxiliary consumption are the main inputs of the monitoring system. The collected data is stored on a server to permit a post processing statistical analysis. Preliminary analysis on dish-Stirling energy production during a typical spring day have been resumed in figure 4. This chart includes air temperature, DNI and power output.

A comparison between effective power output and calculated power output has been conducted [8], [9].

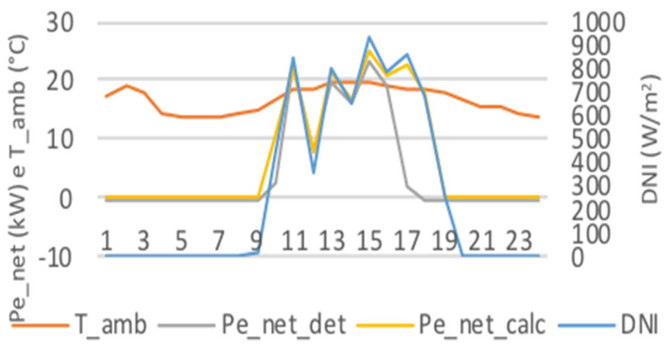

Fig. 2. Performances of Dish Stirling plant of Palermo on 9 April 2018

The analysed day was characterized by a good irradiation and good values of DNI. In these working conditions, the conversion efficiency was approximately 27%, an excellent result taking into accounts that the mirrors are affected by a superficial deposit of dust and dirt conveyed by the wind and rain.

In order to evaluate and forecast the energy performance of the system on hourly basis, a numerical model in Trnsys has been developed. Weather condition has been considered by using Meteonorm software. The model relates the producibility shown in figure 3 with the variability of the weather conditions.

The simulation results in term of monthly energy and electricity production are summarised in Table 1 and illustrated in figures 4 and 5.

In particular, in table 1 the following values are reported:

- **DNI**: Direct Normal Irradiance
- **DNI_{eff}**: Effective Direct Normal Irradiance
- **$E_{sol,inc}$**: Incident solar energy
- **$E_{el,gross}$**: Gross Electricity
- **$E_{el,ads}$**: Electricity absorbed by auxiliary systems
- **$E_{el,net}$**: Net electricity production

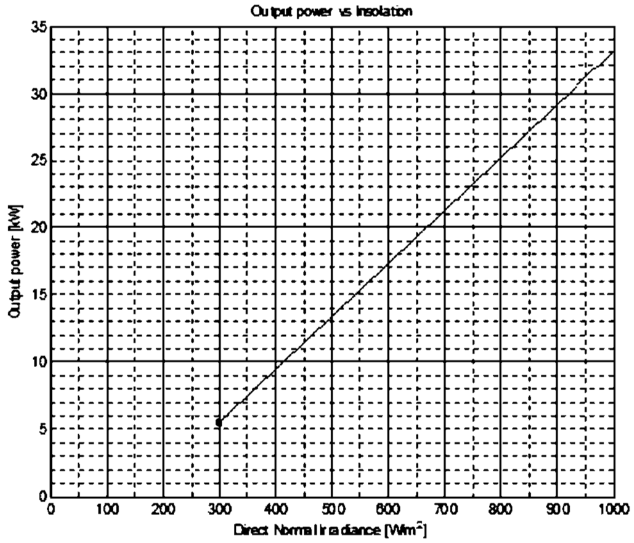

Fig. 3. Net output power at nominal operating conditions (5.5 kW at 300 W/m^2, 31.5 kW at ≥960 W/m2).

TABLE I. MONTHLY PRODUCTION OF A DISH STIRLING UNIT IN PALERMO

Months	**Energy (kWh/m^{2}y)**		**Monthly Energies (kWh)**			
	DNI	**DNI$_{eff}$**	**$E_{sol, inc}$**	**$E_{el, gross}$**	**$E_{el, ads}$**	**$E_{el, net}$**
Jan	89.3	74.8	8,272.4	2,438.3	237.7	2,200.7
Feb	82.3	72.2	7,983.8	2,407.9	207.1	2,200.9
Mar	138.0	127.9	14,129.7	4,274.0	371.6	3,902.3
Apr	151.0	135.2	14,939.4	4,517.8	387.9	4,130.0
May	222.2	212.5	23,486	7,141.3	637.3	6,503.9
Jun	233.0	225.9	24,960	7,459.8	775.5	6,684.3
Jul	270.4	264.0	29,174.5	8,796.5	898.7	7,897.7
Aug	214.7	203.8	22,515	6,690.5	751,3	5,939.2
Sepr	171.1	160.2	17,697.8	5,322.7	532.2	4,790.5
Oct	145.6	134.1	14,818.5	4,476.9	424.6	4,052.3
Nov	118.3	110.5	12,206.7	3,660.5	341.4	3,319.2
Dec	96.5	84.3	9,318.1	2,812.5	245.0	2,567.5
Total	**1,933**	**1,805**	**199,502**	**59,999**	**5,810**	**54,188**

These results show a cumulative DNI, per unit area, of approximately 1933 kWh/m^{2}y in the Palermo area, coherently with scientific literature. The effective energy used by the dish Stirling collector amount to 1805 kWh/m^{2}y, corresponding to 189.5 MWh collected by a single unit.

Solar energy yearly converted into gross electricity amounts to 60 MWh; this value is reduced to 54.19 MWh considering auxiliary consumption (tracking system, dry cooler, etc.). This last value represents the electricity that can be transferred to the electricity grid.

VI. FROM THE DISH-STIRLING SOLAR PLANT TO AN ENERGETIC HUB BASED ON DISH STIRLING TECHNOLOGY

The project partnership strongly believes in this type of plant, a proof of this is the realization at its own expense and expense of a plant operating at full scale of the Dish Stirling concentrator of peak electrical power equal to 33 kW that is placed on the university campus, near the building that houses the DEIM.

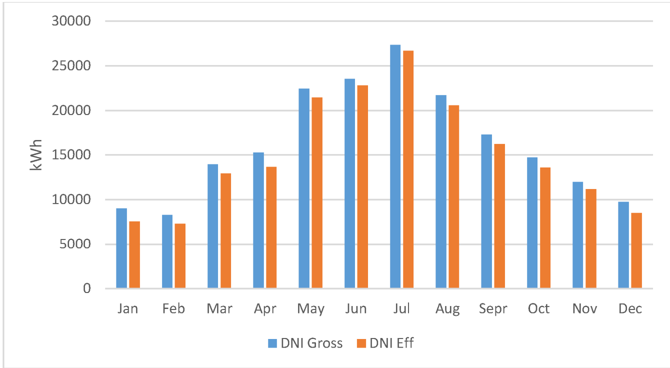

Fig. 4. Monthly values of DNI characteristic of the Palermo area

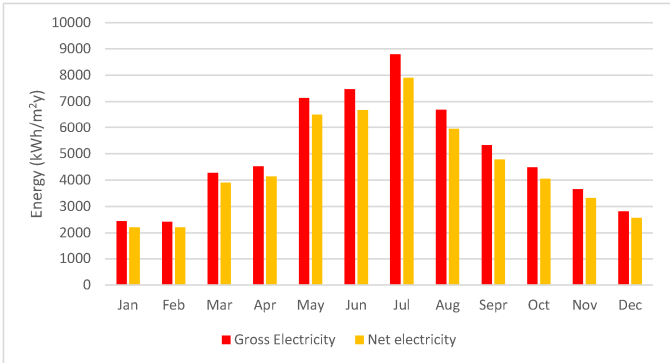

Fig. 5. Monthly values of electricity produced of the Palermo area

Even if the installed dish-Stirling concentrator already constitutes the state of the art in the field of CSP, the localization inside an university campus characterised by a good amount of direct normal irradiation allows to hypothesize and design a further series of innovations that would make the site unique in the world thanks to its integration with an highly advanced poly-generative system. The poly-generative system that will be implemented will have the following innovative features:

- production of thermal energy for heating and cooling systems;
- increasement of the global conversion efficiency by transforming the solar system into a tri-generative system;
- test of storage of the electrical energy in kinetic and electro-chemical devices (lithium polymer batteries).
- integration with borehole thermal energy storage [10], [11];
- use and experimentation of fuels from biomass exploitation;
- deployment of specific management logics for poly-generative system;

- deployment of specific management logics for off grid and grid connected working condition.

With this project, therefore, we intend to start a series of experimental research activities aimed at:

- analysing the existing dish-Stirling system by surveying and analysing the operating parameters and developing forecast models;
- providing the hybridization of the Stirling engine (allowing its operation even in the absence of solar radiation) through a system of production of biofuel from the gasification of pruning cuttings coming from the university campus;
- equipping the dish-Stirling system with innovative electric storage systems;
- equipping the dish-Stirling plant with borehole thermal energy seasonal storage for exploitation of the thermal waste [11];
- providing the dish-Stirling system, integrated by the devices described above, with an advanced monitoring system in which the key factors identifying the operating conditions of the plant will be detected, acquired and historicized by a centralized database;
- developing energy management logics for the various components of the integrated system taking into accounts the variability of weather and of load condition.

The energetic hub will be characterized by a high degree of innovation by combining the exclusive exploitation of renewable energy sources with a series of smart functions based on the use of ICT technologies useful for optimal control of the plant that will represent an example of a sustainable model for meeting the demand for electricity, heat and cooling for civil use.

VII. CONCLUSIONS

This article presents the realization of a thermodynamic solar plant system based upon a dish-Stirling technology located at University of Palermo. The plant has been connected to the grid and it allows the electricity injection into the grid and to access to national renewable energy incentives regime. The plant has been equipped with a high precision weather station and an advanced systems monitoring the most important electrical parameters.

A dynamic model of the plant has been deployed in Trnsys environment. The assessed producibility are summoned in the present work and shows a peak value of the net monthly electricity of about 8,000 kWh for the month of July.

Further improvement of the plant are foreseen, realizing an energetic hub that will be characterized by a high degree of innovation by combining the exclusive exploitation of renewable energy sources with a series of smart functions based on the use of ICT technologies. With these improvements, the presents plant, already a top rated CSP device in the world, will represent a successful example of a sustainable model for meeting the demand for electricity, heat and cooling for civil use.

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