Application potential analysis of auxiliary energy supply solutions for dish-Stirling systems

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Abstract

The main goal of the project this paper is based on is to evaluate the possibility of incorporating new technologies, such as thermal storage and/or hybridization, into a thermosolar power generation system, specifically, into a 10 kWe EuroDish system with a 53.10 m^2 concentrator shell. This action aims to obtain a continuous operation of the dish-Stirling, and therefore, a continuous electricity generation, even during the night or during overcast periods. As a result, the availability and management of the resultant system will be improved.

In order to carry out the calculations to obtain these results, an analysis software was developed. It is able to analyse the irradiance data from any location and evaluate if the installation of any of the suggested auxiliary systems will be feasible for that location.

Regarding the specific case evaluated in this paper, analysed data show that thermal energy storage system could potentially increase the electricity generated by a dish-Stirling in 29.38%, but its installation on an engine that is able to work at variable input power presents no significant contribution. In the case of hybridization, the results are an increase of 49.29% in a constant load engine, and a contribution of 17.64% in the most realistic scenario.

Keywords: Dish-Stirling system; Hybridization; Thermal energy storage; CSP; Productivity improvement

1. Introduction

Every kind of electricity generation system could be defined in terms of a parameter called "equivalent operating hours" which represents the number of hours that a system operates per year to generate a fixed amount of energy, assuming that it works at its nominal operation capacity all the time. This index shows the availability of the generation facility during a year, since it represents the ratio between the working hours of the system and the hours of a year.

The periods where a generation plant is not operative are called periods of unavailability. Every facility, unavoidably, suffers the appearance of these periods due to either scheduled maintenance activities or unexpected breakdowns. However, renewable energy technologies are also subjected to an additional kind of unavailability period sources due to its renewable nature (Monné et al., 2011a) (Monné et al., 2011b) (Palacín et al., 2011).

Talking about concentrating solar power (CSP) plants, there are two main additional causes of unavailability. Obviously, the most relevant of them is owing to the fact that during night periods the system does not receive any solar irradiance whatsoever. And the second one lies in the fact that solar irradiance depends on the Sun movement along the day, and furthermore, it is also affected by environmental and weather conditions and sky cloudiness. Therefore, it is not possible to ensure a constant solar irradiance receipt for the electricity generation system.

In order to improve the availability and management of large CSP plants by means of increasing the number of its nominal operation hours, it is possible to provide the plant with a molten salt thermal energy storage system which stores the excess radiant energy collected during some periods of the day and releases it when needed (Abengoa Solar NT, 2008) (Solar Milennium AG, 2008) (Torresol Energy, 2010).

Nevertheless, it has not been possible to find a solution that could be applied to a specific kind of CSP technologies yet. This is the situation of dish-Stirling systems. This difficulty in finding a solution is due to the fact that this kind of technology is usually installed as small and independent power modules instead of being part of a large generation plant, which does hamper the use of conventional thermal storage or hybridization solutions.

There are a lot of conceptual designs that try to present an alternative to be applied in dish-Stirling systems (Moreno et al., 1999) (Diver et al., 1990) (Mayette et al., 2001) (Manzini et al., 2003) (United Stirling Inc., 1986) (Laing and Reusch, 2001) (Infinia Corporation, 2010), but there is a lack of accessible researches about how the installation of this kind of auxiliary supply technologies could improve the overall performance of dish-Stirling. For this reason, this paper analyses the influence of these technologies on the operation of a hypothetical EuroDish system located at Sevilla (Spain) having taken into account the solar irradiance data of this location collected during the years 2000, 2003, 2005 and 2008. With this aim, an analysis software (Quintana, 2011) has been programmed and developed as a helpful tool to speed up the required calculations. It is needed to clarify the fact that the results obtained thanks to the analysis of the radiation data of Sevilla are perfectly extrapolated to any other location with similar irradiance conditions, and for this reason, they are a representative analysis for the dish-Stirling performance at any other similar location. Moreover, the software developed could analyse any other irradiance data from any other location in order to draw the corresponding results without any significant modification in its source code.

2. Description of the involved technologies

2.1. Dish-Stirling systems

Dish-Stirling systems, also called parabolic dishes, are little electricity generation devices that convert thermal energy from the solar radiation to mechanical energy, and subsequently to electricity. Dish-Stirling systems use a group of mirrors to reflect and focus the solar radiation onto a receiver, with the aim of reaching the needed temperature to convert this thermal energy into work efficiently. The solar radiation is absorbed by the receiver and transferred to an external combustion engine, such as the Stirling engine.

Dish-Stirling systems are characterised by great efficiency, modularity and stand-alone operation. They have shown the greatest energy conversion coefficient among all the solar technologies, 29.4% (Droher and Squier, 1990) (Stine and Diver, 1994), and therefore, they own the potential to become one of the lowest-cost sources of green electricity. Moreover, their modularity allows them to operate individually (remote locations), or to be associated with several dish-Stirling systems to operate in small groups and be connected to the electrical grid (village power).

The main components of a dish-Stirling system (Fig.1) are: concentrator shell, receiver, Stirling engine, tracking system, cooling system, and structural framework.

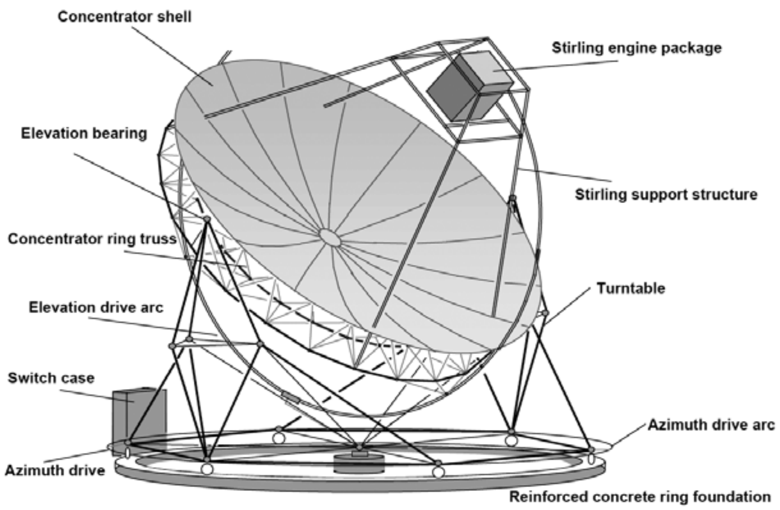

Fig.1 Dish-Stirling thermosolar generation system sketch (Schiel, 2001)

2.2. Auxiliary energy supply technologies

Available technologies as auxiliary heat suppliers are thought to be able to ensure, theoretically, an operation period of 24 hours per day. These technologies could be classified into two different groups: the ones based on solar-conventional fuel hybridization (Moreno et al., 1999) (Diver et al., 1990) (Mayette et al., 2001) (Manzini et al., 2003) (United Stirling Inc., 1986) (Laing and Reusch, 2001) (Infinia Corporation, 2010), and the ones that try to make profit from the excess solar radiation by means of storing it in a storage media, such as phase change materials, that are the kind of storage selected to this analysis (Neila et al., 2008) (PCM Products Ltd., 2009) (Acem, 2007)

2.2.1. Thermal energy storage: description and performance limitations

Technologies based on thermal energy storage (TES) systems, installed as auxiliary energy supply to electricity generation devices, try to solve the problems related to solar resource unavailability, trying to ensure a continuous and constant electricity generation. Therefore, what it is tried to do is, basically, to adjust the unavoidable time lag between electricity generation and electricity demand. Installing a TES system, it is possible to introduce a delay between energy collection and electricity demand, avoiding using all the received radiant energy at the same moment it is received, being able to store it to use it when needed.

Nevertheless, it is needed to bear in mind that thermal energy storage (TES) systems can only operate in the situations where storage materials have been previously charged by the excess solar radiation during the nominal operation periods. Hence, assuming that the storage system has an upper limit of 50 $W \cdot h/m^2$ (Abengoa Solar NT, 2008) (PCM Products Ltd., 2009), and taking into account the fact that all the stored energy will be required by the system before the end of a natural day (this hypothesis will be always fulfilled because during the night periods there is a complete lack of solar supply), it is needed to calculate what percentage of the needed energy to ensure a 24 hours operation period could be supplied by this kind of auxiliary technology. The rest of energy needed must be supplied by a conventional combustion system (hybridization).

2.2.2. Hybridization: description and performance limitations

Hybridization, understood as the use of several energy sources in the same device, has really important advantages, such as: adaptation to the electricity generation (flexibility), transient period stabilization capability, better management of generation plants or devices, better recovery of the investment, and great usefulness during the start-up periods. Even more important role has this kind of technologies when the energy sources involved are both renewable energies.

Regarding its application in dish-Stirling systems, the developed technologies to ensure a hybrid operation of the system are based on conventional fuel-solar hybridization. Natural gas is mainly used, although it is intended to replace this conventional energy source by another renewable source, specifically biomass (biogas preferably).

Due to the use of conventional fuels, it is needed to highlight the fact that, in Spain, there is a limit, regulated by RD661/2007 (RD661/2007, 2007),, for the amount of energy that could be supplied by conventional sources in a solar hybrid device, provided that the operator of the power plant wants to be included in the Spanish feed-in tariff system. This limit was set at 15% of the annual electricity produced, if natural gas is used, and 12% in the case of other fossil fuels. In order to allow the hybridization solution to be more competitive, natural gas was chosen as the conventional fuel used.

This limitation has been implemented in the hybridization performance analysis as a representative case of similar feed-in tariff regulations worldwide (Mohr et al., 1999) (Geyer et al., 1998) that limit the application of fossil fuel in renewable energy plants. Moreover, this limitation is the essential reason why it has been decided that, when possible, the intraday energy demands of the dish-Stirling will be supplied first and foremost by the energy stored in the thermal energy storage system, keeping the contribution of the combustion system to be transferred to the engine at dawn period, where greater amounts of additional energy are required. It is also possible to turn on the combustion system at dusk, but it is preferred to cover the extra energy demand at dawn where TES is fully discharged, and consequently, it is not able to operate.

3. Methodology

3.1. Differences between the analysis conducted

Two different analyses have been conducted assuming different operation conditions of the Stirling engine. Firstly, it has been considered that the Stirling engine is only able to work at a constant load, which means that it will be only operative when the received radiation reaches a fixed value, being in a stand-by mode when the radiation is lower (henceforth, this analysis will be referred as “constant power”). This input power value has been translated to a DNI value of 880 W/m^2, which is the required energy input to produce 10 kW$_e$ as output. The global system efficiency (solar to electricity) has been estimated at 25%, according to bibliography (Reinalter, 2005) (SOLO Kleinmotoren GmbH, 2009) (Schiel, 2007) (Fraser, 2008) and researcher experiences. This analysis will show the best possible performance of the auxiliary energy supply systems, but underestimating the operation features of the Stirling engine. As conclusion, it will be possible to know the maximum potential of these systems. On the other hand, and with the aim of conducting a more accurate and real analysis, knowing the operation curve of the SOLO engine of the EuroDish (Fig.2), it has been possible to substitute the single operation mode condition for the real operation curve of the engine (henceforth, this analysis will be called “variable power”). This mode of operation allows the engine to generate electricity even if the received irradiance is below the nominal point, but with a reduction in efficiency as trade off. Both analyses, as well as the software that conducts them, have been developed following a similar procedure.

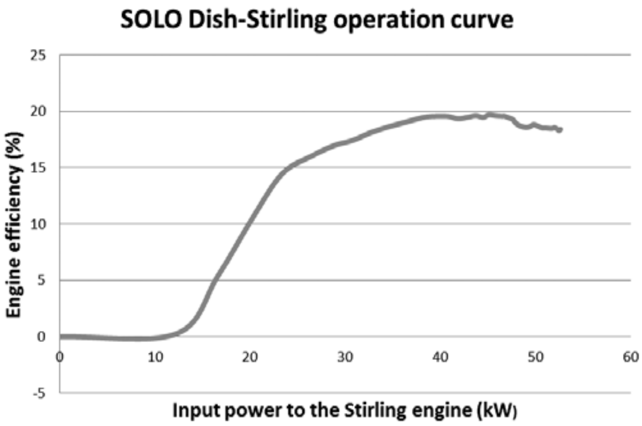

Fig.2 SOLO dish-Stirling operation curve (Reinalter, 2005)

3.2. Analysis procedure

3.2.1. Directly useful radiant energy

The first magnitude that has to be calculated is the amount of radiant energy the system could make profit from (Fig.3), that is, the received energy that allows the system to generate electricity. In the case of “constant power” this variable matches with the energy received at DNI equal or higher to 880 W/m^2, and in the case of “variable power” it is analogous to the received energy that makes the dish-Stirling work with not null efficiency (almost all the received radiant energy).

Notice that depicted graphs (such as Fig.3) are referred to “constant power” case since it is more easily understood, but the concept represented could be perfectly extrapolated to “variable power” case.

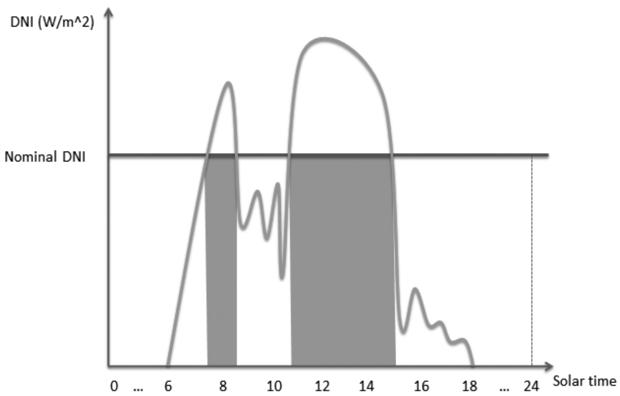

Fig.3 Directly useful radiant energy collected during a generic day (shadowed area)

3.2.2. Excess radiant energy

It is also needed to know the percentage of the received radiant energy that could not be used as direct power supply to the Stirling engine since it would cause its overheating (excess energy, Fig.4), but could be stored in a TES media, and therefore, could be supplied to the engine when needed in a future period. This percentage will show the maximum energy that could be supplied by this kind of auxiliary system, in its best and most desirable performance.

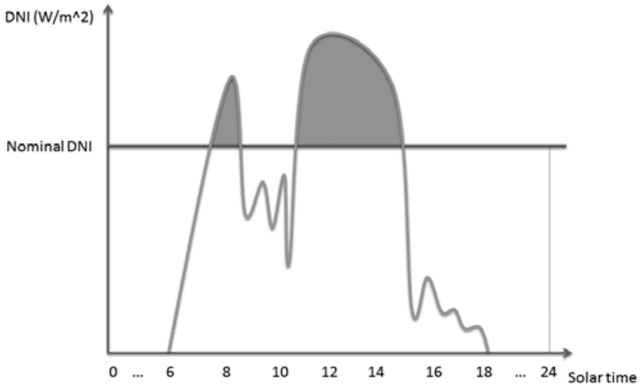

Fig.4 Excess radiant energy collected during a generic day (shadowed area)

3.2.3. Energy needed to be supplied by the auxiliary systems to ensure an all-day operation

Nevertheless, the most important parameter that has to be analysed is the amount of energy that should be supplied by the auxiliary systems to ensure a 24 hour operation of the dish-Stirling system (Fig.5). In other words, the energy needed to be supplied in order to reach the optimum aim of an all-day operation. However, in principle, and bearing in mind the assumed hypothesis, this state could not be reached due to the limitations of the Spanish regulations (RD661/2007, 2007), so, even more important this calculation is as it will show the percentage of the energy required to an all-day operation that could be supplied by the auxiliary systems.

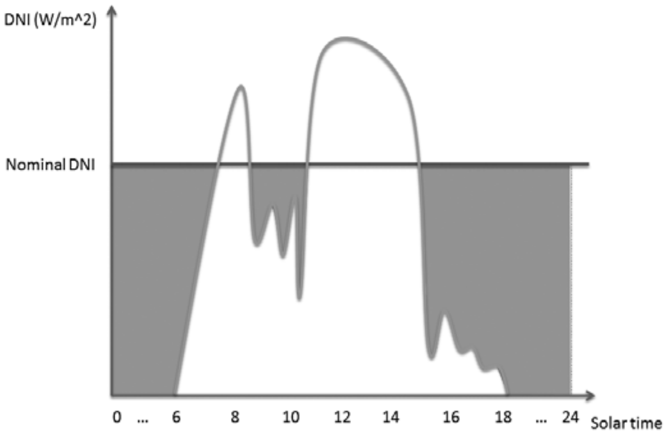

Fig.5 Energy needed to be supplied by the auxiliary systems to ensure an all-day operation in a generic day (shadowed area)

3.2.4. Auxiliary systems contribution

Finally, it is needed to translate the magnitudes obtained from the irradiance data analysis to its influence on the performance of the auxiliary energy supply systems because they will be the needed parameters to check the feasibility of the auxiliary technologies. To carry out the calculations required for this translation, it is needed to take into account the premises put forward in section 2 of this paper, as they contain the information that explains the operation hypothesis assumed and the limitations of the auxiliary energy supply technologies. Thus, starting from the excess radiant energy available to be use by the TES system plus its technical limitations, and the energy required to be provided by the hybrid system plus the local regulations, and taking into account the performance of the dish-Stirling itself, it is possible to calculate the amount of electricity that could be generated thanks to the contribution of auxiliary supply technologies.

To sum up, the analysis carried out try to clarify the contribution of the proposed auxiliary systems to extend the dish-Stirling operation period. This contribution will be finally quantified in terms of extra generated electricity, by means of calculating the additional electricity generated thanks to the extra energy supplied by the auxiliary systems plus the non-profitable radiant energy revaluated by the installation of the auxiliary systems.

4. Results

4.1. “Constant power” analysis

Table 1 shows the results obtained from the analysis that evaluates the electricity generation improvement thanks to the application of auxiliary supply technologies. In order to simplify the presentation of the results, and offer more conclusive information, the presented values are an average of the results obtained from the individual analysis of each year.

As it was explained, in the case of “constant power” the system it is not able to make profit from the irradiance received below the limit of nominal operation. The dish-Stirling is in stand-by mode during these periods. For this reason, the energy stored in the TES media is mainly used to complement the lack of energy during the intraday periods, where the irradiance drops are usually either short in time or small in magnitude and consequently, not much energy is required to lead the system to its nominal operation point again (this fact could be observed in Fig.6). Hence, it is possible to observe an important contribution of the TES system to the annual electricity generation. Specifically, the amount of electricity generated is increased in an extra 29.38%.

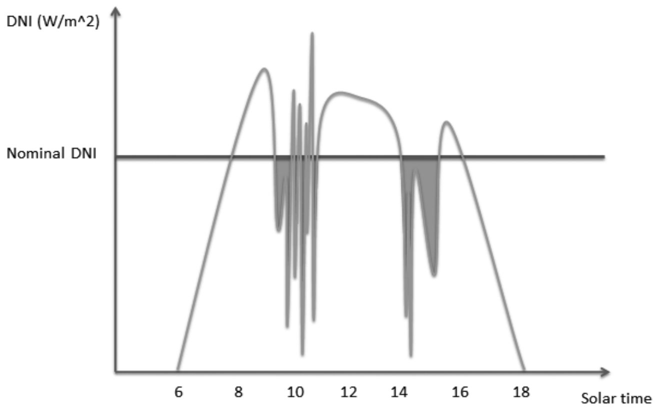

Fig.6 Energy needed to be supplied by the TES system during the intraday periods in a generic day (shadowed area)

The hybridization of the dish-Stirling by means of installing a natural gas burner yields a percentage increase of the electricity generated of 49,29%. This important result is owing to the additional supply energy carried out from another source of energy, and the revaluation of the radiant energy received below nominal DNI level. With the purpose of making the best benefit from the share of natural gas allowed by the regulations (RD661/2007, 2007), whenever possible, the energy from the combustion system will be supplied to complement the radiant energy received. Therefore, in case of relatively long periods (more than five hours) with lack of solar supply, there will not be burner supply either. Thus, the energy supplied by the auxiliary system will provide a higher amount of additional operation hours at nominal power, and therefore, a great amount of additional electricity generated.

Moreover, both auxiliary systems could operate independently, because they do not interfere in each other during their operation, since the combustion systems works at dawn, and the TES system works mainly during the intraday periods, and also at dusk if enough excess energy has been stored. For this reason, the contribution of both auxiliary systems are directly added to the extra electricity generated, increasing it in 74.28 kW·h/m^2·year, which represents 78.67% of the electricity generated by the dish-Stirling without any support.

Table 1
"Constant power" analysis: Electricity generation improvement per year associated to the application of auxiliary supply technologies (average values)

System	Dish-Stirling (only solar)	Dish-Stirling + TES	Dish-Stirling + Hybridization	Dish-Stirling + both auxiliary technologies
Estimated electricity generation (kW·h/m2·year)	**94,44**	**122,18**	**140,98**	**168,72**
Electricity generation improvement in percentage terms	**-**	**29,38%**	**49,29%**	**78,67%**

Fig.7 shows an intuitive pie chart where it is shown the electricity generated by a dish-Stirling system provided with the auxiliary technologies analysed, differentiated by its source. The whole circle represents the energy produced by the dish-Stirling if it was working 24 hours a day, 365 days a year. The darkest area squares with the energy that would be produced during the hours that the system is not operating.

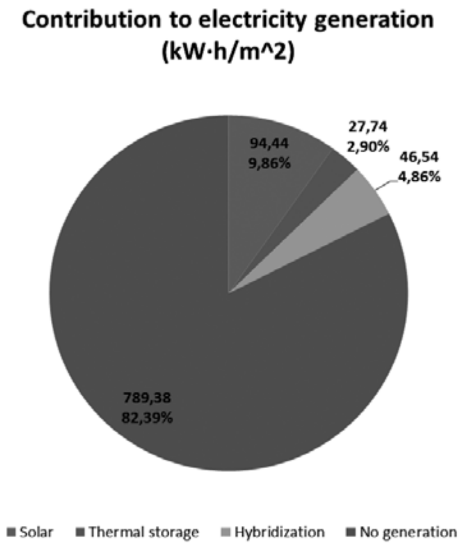

Fig.7 "Constant power" analysis: Contribution of the different auxiliary technologies to the annual electricity generation

It is important to highlight the fact that the application of both auxiliary technologies, thermal storage and hybridization, confers on the system the capability of recovering 7.76% of the hours (equivalents to energy in the "constant energy" case) that the dish-Stirling would not be working without support, transforming them into productive hours.

4.2. "Variable power" analysis

The main difference between the first analysis presented in this paper and the "variable power" analysis lies in the capability of the Stirling engine to make profit from the received radiant energy. Assuming that the engine could operate at different levels of irradiance, by means of increasing or decreasing its efficiency, the engine could present better results in the only-solar case. In other words, as shown in Table 2, the system is able to generate much more electricity than in the "constant power" case since it could use the whole range of irradiance received to make itself operate. For this reason, the same system, without support and working at these conditions, could generate, approximately, the triple amount of electricity (331.40 kW·h/m^2·year).

Therefore, the relevance of this second analysis is to present the performance of the auxiliary technologies in a more realistic scenario, instead of studying the best possible performance of these systems which was the goal of “constant power” analysis.

As shown in Table 2, the installation of a thermal energy storage system in a dish-Stirling that works at the assumed conditions entails no benefit at all in the amount of electricity generated, only an annual increase of 200 W·h/m^2. This fact is due to the capability of the dish-Stirling to generate electricity at different values of irradiance received what makes the contribution of the TES system during the intraday periods to scarcely increase the efficiency of the engine, and as a consequence, there is no substantial advantage on installing this system. The great contribution presented in the “constant power” analysis is due to the fact that really small amounts of extra energy provided by the TES system helped the engine to recover its nominal point and this makes the engine goes from stand-by mode to operation mode easily.

Moreover, the high nominal DNI level of the dish-Stirling also influence the performance of the TES system because almost all the radiant energy received is used by the engine itself to produce electricity, so there are no significant amounts of excess radiant energy that could be stored in the TES media, and therefore, there is no energy to be supplied by this kind of technology. For this reason, TES media is not effective in dish-Stirling systems that works at high nominal DNIs, but could be useful in other systems designed to produce less electrical power (1 kW_e, 5 kW_e…) which operates at lower DNI levels. However, technical storage limit of TES media, set at 50 W·h/m^2, is also a determinant factor that does not allow the system to storage more energy even available. But this is a problem that could not be avoided, unless thermal storage technology was improved.

The results obtained for the hybridization show again the advantage of a “variable power” engine over a “constant power” engine in the only-solar mode, which leads to an apparent worst performance of the hybridization system. However, the best possible features of the whole system are looked for, and in this way, the hybridization system increase the electricity generation capacity in 17.64%, adding 58.48 kW·h/m^2 to the annual figure. Actually, in spite of seeming less important to the whole contribution of electricity generation, due to the great performance of the dish-Stirling itself, in global figures (kW·h/m^2·year), it represents a greater quantity of electricity added than in the case of a “constant power” engine.

Table 2
“Variable power” analysis: Electricity generation improvement per year associated to the application of auxiliary supply technologies (average values)

System	Dish-Stirling (only solar)	Dish-Stirling + TES	Dish-Stirling + Hybridization	Dish-Stirling + both auxiliary technologies
Estimated electricity generation (kW·h/m^2·year)	**331,40**	**331,60**	**389,88**	**390,09**
Electricity generation improvement in percentage terms	**-**	**0,00%**	**17,64%**	**17,64%**

It is obvious that the performance of the hybrid system and the combination of both auxiliary systems present a similar performance since the thermal storage device does not contribute to supply almost any power to the Stirling engine.

In Fig.8 it is shown an intuitive pie chart, analogous to Fig.7, for the case of “variable power” engine. Worthy of comment is the fact that the hybridization of the engine confers on the system the capability to recover 6.10% of the energy that the dish-Stirling had not been able to generate without the support of this auxiliary system.

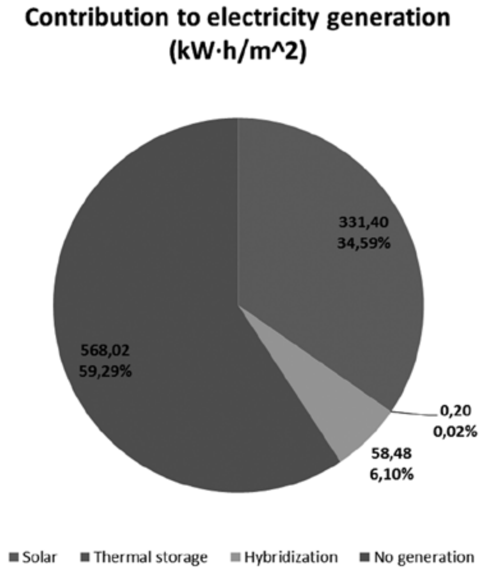

Fig.8 "Variable power" analysis: Contribution of the different auxiliary technologies to the annual electricity generation

5. Conclusions

An analysis software has been developed in order to study the potential of application that a couple of auxiliary energy supply systems, thermal energy storage and hybridization, have to increase the amount of electricity generated by a thermosolar dish-Stirling unit. This software is able to process any solar irradiance data from any possible location provided that they were saved in a specific file format. As a high irradiance location case, Sevilla (Spain) data have been analysed, drawing the following conclusions (these results could be extrapolated to any other similar location):

Stirling engines that are able to work with different levels of input power present a better performance in their application to a dish-Stirling system since they could make profit from the whole range of irradiance received.

Thermal energy storage systems have a great potential of application in "constant power" engine devices due to the fact that their use could add the energy required to lead the system to its nominal operation point, switching, with this action, the engine from its stand-by mode to its production mode. Nevertheless, in a real application with a "variable power" engine the habitual length or magnitude of the irradiance drops does not allow them to influence significantly the electricity generation. Bearing in mind this fact, as well as the scarce level of development of the materials needed for high temperature TES, investing on this kind of solutions is not advisable nowadays.

Hybridization seems to be the best available solution to increase the number of operating hours of a dish-Stirling system. It has shown interesting results both in "constant power" case (maximum potential of the system) and "variable power" case (real situation). As an example, the dish-Stirling described in the point 2 of this paper fulfilling the Spanish regulation (RD661/2007, 2007) contributes to the electricity generation in an estimated additional 6.10% in a real situation.

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