2012 International Conference on Environmental, Biomedical and Biotechnology
IPCBEE vol.41 (2012) © (2012) IACSIT Press, Singapore

Enhancing Electricity Generation in a Dish-Stirling Device by Means of Hybridization and Thermal Energy Storage Systems Installation

J.L. Quintana[+], C. Monné, F. Moreno, M. Muñoz, and S. Alonso

Department of Mechanical Engineering, Aragon Institute of Engineering Research (I3A), University of Zaragoza, C/ Mariano Esquillor s/n, 50018 Zaragoza, Spain

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 needed to obtain these results, an analysis software has been developed. It is able to analyse the irradiance data at any location and evaluate if the installation of any of the auxiliary systems suggested will be feasible in 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 the dish-Stirling in 29.38%. In the case of hybridization, the results are an increase of 49.29% working for a constant load engine.

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

1. Introduction

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 [1, 2, 3]. Talking about concentrating solar power (CSP) plants, there are two main additional causes of unavailability: overcast periods and night periods. 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 [4, 5]. 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.

There are a lot of conceptual designs that try to present an alternative to be applied in dish-Stirling systems [6, 7, 8, 9, 10, 11, 12], 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 from the year 2000 to 2008. Furthermore, an analysis software has been programmed and developed as a helpful tool to speed up the required calculations.

[+] Corresponding author: Tel.+34 976 761000 ext.5258 ;
e-mail: jlquinta@unizar.es

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 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% [13, 14, 15], and therefore, they own the potential to become one of the lowest-cost sources of green electricity.

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 [6, 7, 8, 9, 10, 11, 12], 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 [16, 17, 18].

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. The installation of a TES system introduces 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 $W \cdot h/m^2$ [17], 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, and great usefulness during 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. There is a wide range of fuels that could be used for this purpose: natural gas, propane, butane... even a renewable source, such as biomass (biogas or syngas preferably), could be supplied to the hybrid system. 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 [19], 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. This limitation has been implemented in the hybridization performance analysis as a representative case of similar feed-in tariff regulations worldwide [20, 21] that limit the application of fossil fuel in renewable energy plants.

3. Methodology

The analyses have been conducted assuming 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 [22, 23, 24, 25].

3.1. Analysis Procedure

3.1.1. 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. 1), that is, the received energy that allows the system to generate electricity. This variable matches with the energy received at DNI equal or higher to 880 W/m^2.

3.1.2. 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. 1), 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.

3.1.3. 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. In other words, the energy needed to be supplied in order to reach the aim of an all-day operation (Fig. 1). However, in principle, and bearing in mind the assumed hypothesis, this state could not be reached due to the limitations of the Spanish regulations [19], 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.

3.1.4. 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.

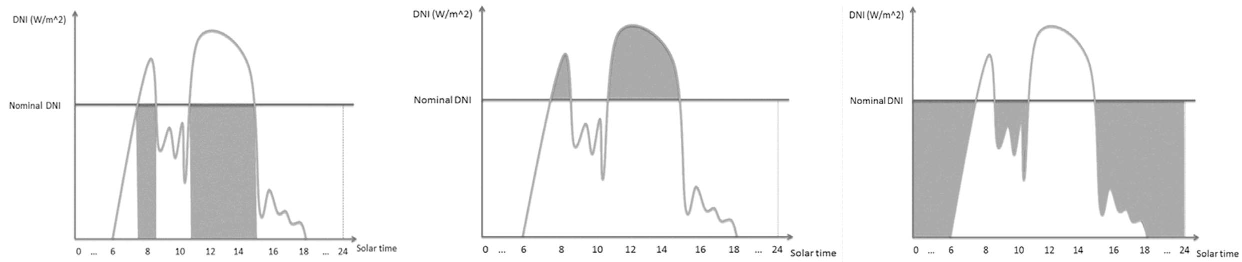

Fig. 1: From left to right: Directly useful radiant energy collected during a generic day (shadowed area), excess radiant energy collected during a generic day (shadowed area), energy needed to be supplied by the auxiliary systems to ensure an all-day operation in a generic day (shadowed area)

4. Results

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 this 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. 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%.

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%

The hybridization of the dish-Stirling by means of the installation of 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 [19], 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 a 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 mainly 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.

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):

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, hybridization seems to be the best available solution to increase the number of operating hours of a dish-Stirling system. As an example, the dish-Stirling described in the point 2 of this paper fulfilling the Spanish regulation [19] contributes to the electricity generation in an estimated additional 49.29%.

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