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### TECHNO-ECONOMIC ANALYSIS AND SIZING OF DISH-STIRLING SOLAR POWER PLANTS.

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*Abstract. The design of the solar energy conversion systems is essentially determined by the geographic location of the solar power plant and the energy demand. The geographic location establishes the primary climatic factor at design of the solar energy conversion systems, because the solar irradiation determines the energy available at the conversion system. The energy demand is another primary factor at the design of the energy conversion systems because it determines the electricity to be generated by solar power plant. The methodology of Dish-Stirling solar power plants sizing applied at this article consisting of a mathematical modeling of the geometrical and thermal performance of the Dish-Stirling system. This methodology was applied to develop a computational program to sizing the Dish-Stirling system and calculate the electricity generated, from the energy demand, the sizing the Dish-Stirling power plant is determined. The case study develop consists on design of Dish-Stirling power plants at two Brazilian location with different availability of solar irradiance to attend the same energy demand. This case study develops an economic analysis of the financial impacts by the geographic location of Dish-Stirling power plants, as well the feasibility analysis and financial sensitivity analysis of solar power plants.*

**Keywords:** renewable energy, solar energy, Dish-Stirling system, techno-economic analysis, solar power plants.

#### 1. INTRODUCTION

The solar energy is abundant in most part of the earth's surface throughout the year. Each year the earth receives about  $3.8 \times 10^{23}$  joules of solar energy, which is 50,000 times more than current world wide electricity consumption (Blakers *et al.*, 2015).

The sun provides about 1.3 kilowatts per square meter ( $\text{kW/m}^2$ ) to the upper atmosphere of the illuminated half of the earth (Blakers *et al.*, 2015). The most part of this energy (global solar energy) is transmitted from the atmosphere to the earth's surface while a small part of this energy is absorbed or reflected by the atmosphere (Baharoon *et al.*, 2015). The available solar energy at the earth's surface is 45%. The energy reflected at the earth's surface and atmosphere is 30%. The energy absorbed into the atmosphere is 25% (Blakers *et al.*, 2015).

The solar concentrators are energy conversion systems that apply lenses or mirrors and tracking systems in order to concentrate the solar irradiation in a large area and focus it on a small area. Nowadays, several solar concentrators design was developed, as the Fresnel concentrator, solar towers, parabolic trough solar concentrator and solar parabolic dish concentrator (Baharoon *et al.*, 2015).

The parabolic dish concentrator has a truncated paraboloid shape, obtained by rotating a parabola about its axis (Coventry and Andraka, 2017). The parabolic solar concentrators are usually applied at the conversion of energy to heat supply, water heating, power supply for irrigation, desalination and water distillation. The main application of parabolic dish solar concentrators consists of the conversion of electric energy associated with Stirling engine, creating the solar conversion systems called Dish-Stirling (fig.1) (Baharoon *et al.*, 2015). This solar energy conversion system is commonly acknowledged as the most efficient concentrator technology in order to conversion the solar energy into electrical energy. (Coventry and Andraka, 2017).

The Dish-Stirling systems are commonly designed for a net power by 1 to 50 kilowatts. This solar conversion system is usually applied at solar power plants for an installed capacity of 0.5 to 2 megawatt. The Tooele Army Depot solar power plant (fig.1) and Maricopa solar power plant (fig.2) are made up of Dish-Stirling systems, both designed for an installed capacity of 1,5 megawatt.



Figure 1. (Coventry and Andraka, 2017) - Dish-Stirling system (left) and Tooele Army Depot solar power plant (right).

The Tooele Army Depot solar power plant is made up of 430 Power Dish IV. The Power Dish IV is a Dish-Stirling system with a net power of 3,5KW (Coventry and Andraka, 2017).

The Maricopa solar power plant is made up of 60 SunCatcher™. The SunCatcher™ is a Dish-Stirling system with a net power of 25KW (Coventry and Andraka, 2017).

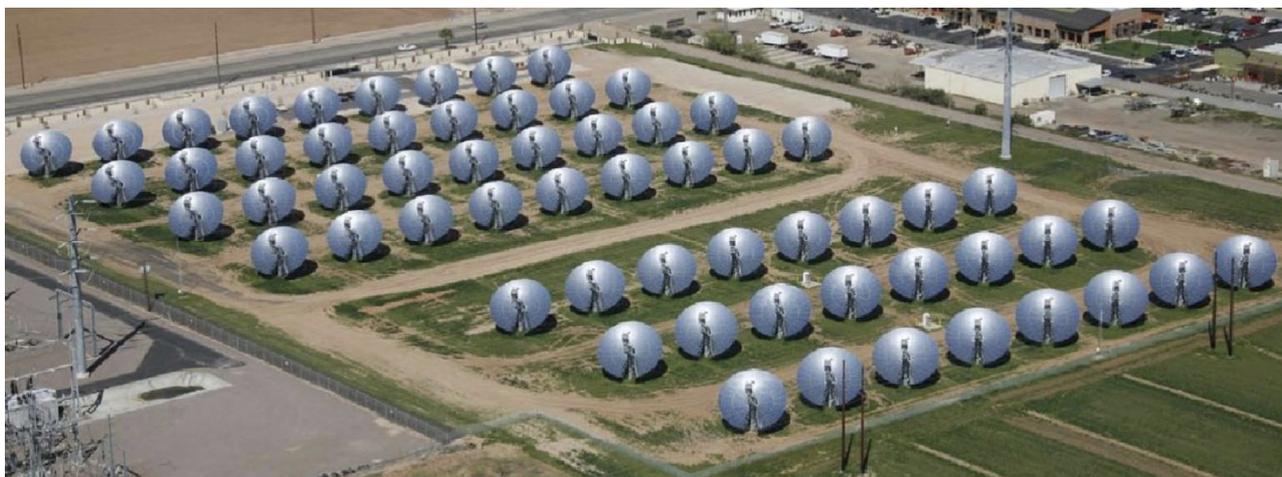


Figure 2. (Coventry and Andraka, 2017) - Maricopa solar power plant.

## 2. METHODOLOGY.

### 2.1 The geometrical and thermal sizing of Dish-Stirling solar power plants.

The methodology adopted at this article was proposed by (Castellanos *et al.*, 2017) and (Hafez *et al.*, 2016). The methodology applied at this article consists in a geometric and thermal sizing of the Dish-Stirling system through the data of climatic conditions (solar irradiance, wind speed and ambient temperature) and constructive features of parabolic solar dish (diameter, material and rim angle). The geometric and thermal sizing of the Dish-Stirling system calculates the electricity generated by the conversion system, and from the energy demand, the Dish-Stirling power plant is sizing.

The geometrical and thermal sizing of the Dish-Stirling solar power plants is obtained by solving of many equations, therefore a Maple® computational program was developed in order to make it operational. This computational program was validated by the application of the data from (Castellanos *et al.*, 2017) with the maximum variation of the 1.3% between the results of developed program and the adopted reference.

The solar irradiation affords the energy available to the conversion system, therefore it is a main factor in the design of Dish-Stirling systems. The solar irradiance (I) at noon on a sunny day on the Earth's surface is approximately one kilowatt per square meter [ $\text{kW} / \text{m}^2$ ], but this value changes according to geographic and climatic factors (Blakers *et al.*, 2015). The value of the solar irradiance (I) should be obtained from data according to the location of the installation of the Dish-Stirling power plants. The direct normal solar irradiance ( $\text{IDN}^2$ ) was obtained from the (SWERA, 2017) at the following unit [ $\text{kW} \cdot \text{h} / \text{m}^2 \cdot \text{day}$ ].

The computer program applies the direct normal solar irradiance ( $IDN^1$ ) at the following unit [ $kW/m^2$ ]. Therefore, the unit of the data obtained from (SWERA, 2017) needs to be converted by application of the Eq. (1).

$$IDN^1 = \frac{IDN^2}{HSD} \quad (1)$$

The conversion of units proposed through of equation 1 needs the average monthly duration of the day (HSD) at the following unit [h/day]. The average monthly duration of the day (HSD) was determined by the spreadsheet developed in Excel<sup>®</sup> which applies latitude and longitude values of the Dish-Stirling solar power plants location.

The wind speed ( $v$ ) and the ambient temperature ( $T_a$ ) applied at the computational program must be specified from the meteorological information's of the Dish-Stirling system location.

The parabolic solar dish diameter ( $D_c$ ) afford the energy available to the receiver, therefore this geometric feature must be defined according to the power required and the intensity of the solar irradiance ( $I$ ) available. The numeric value of parabolic solar dish diameter ( $D_c$ ) commonly applied at projects varies between three and fifteen meters. The parabolic solar dish diameter ( $D_c$ ) applied at this case study for both Dish-Stirling solar power plants is 15 meters.

The reflector material is one of the most important features in a parabolic solar dish design. The materials properties of reflector establish the efficiency of the solar conversion system. These properties are reflectivity ( $\rho$ ) and emissivity ( $\epsilon$ ), which can be expressed in terms of percentage [%]. The aluminum it was the material applied at design of the Dish-Stirling power plants because it is widely used in the manufacture of this solar conversion system.

The rim angle ( $\phi$ ) is an important geometric feature because it establishes the solar irradiation available in parabolic solar dish. The rim angle ( $\phi$ ) can be defined as the angle measured between the focal point and the edge of the parabolic solar dish. The numerical value of rim angle ( $\phi$ ) applied to design of the Dish-Stirling solar power plants is  $45^\circ$ , according to (Hafez *et al.*, 2016).

The tracking error ( $\theta$ ) has it numeric value in radians resulting from the error of the solar tracking system. The tracking error ( $\theta$ ) determines the focal diameter of the parabolic solar dish. The value of tracking error ( $\theta$ ) commonly applied at projects of the parabolic solar dish can reach up to  $10^\circ$ . The numerical value of tracking error ( $\theta$ ) applied to design of the Dish-Stirling solar power plants is  $1^\circ$ , according to (Hafez *et al.*, 2016).

The value of electric generator efficiency ( $\eta_{ger}$ ) applied to design of the Dish-Stirling solar power plants is 90%, according to (Castellanos *et al.*, 2017).

The receiver angle ( $\psi$ ) in radians corresponds to receiver position during the operation of the parabolic solar dish. The value of the receiver angle ( $\psi$ ) applied at this case study to design of the Dish-Stirling solar power plants is  $45^\circ$ .

The geometrical and thermal sizing of the Dish-Stirling system applies several factors, constants and coefficients at its equations. The numerical values, nomenclature and symbols of this factors, constants and coefficients are described in table 1.

Table 1. (Castellanos *et al.*, 2017) - Numerical values, symbols and nomenclature of the factors, coefficients and constants applied at the geometrical and thermal sizing of the Dish-Stirling system.

Symbols	Description	Numerical value
$K_{ar}$	Thermal conductivity of air	0.06525
$F_s$	Shading factor	0.96
$\alpha_{abs}$	Absorber of the receiver	0.97
$\tau_{abs}$	Transmittance-absorptance	0.95
$\Gamma$	Intercept factor	0.96
$F_d$	Deterioration factor	0.9
$K_s$	Stirling constant	0.55
$F_r$	Cooling factor	0.6

The focal length of the parabolic solar dish ( $f$ ) is defined as the distance from the vertex of paraboloid to the focus. Its value is calculated by Eq. (2).

$$f = \frac{D_c^2}{4 \times \tan(\sigma/2)} \quad (2)$$

The aperture area of concentrator ( $A_c$ ) is defined as the total surface area of the solar concentrator upon which solar energy is incident (Hafez *et al.*, 2016). Its value is calculated by Eq. (3).

$$A_c = \frac{\pi}{4} \times D_c^2 \quad (3)$$

The receiver diameter ( $D_{rec}$ ) is defined as the focal area of the parabolic solar dish. It's calculated by Eq. (4).

$$D_{rec} = \frac{f \times \theta}{\cos \varphi \times (1 + \cos \varphi)} \quad (4)$$

The receiver aperture area ( $A_{rec}$ ) is calculated by Eq. (5).

$$A_{rec} = \frac{\pi}{4} \times D_{rec}^2 \quad (5)$$

The concentration ratio of the parabolic solar dish ( $C_g$ ) is defined as the ratio of the concentrator aperture area and the receiver aperture area. Therefore, its numeric value is calculated by Eq. (6).

$$C_g = \frac{A_c}{A_{rec}} \quad (6)$$

The concentrator efficiency ( $\eta_{con}$ ) determines the power supplied at the receptor It's calculated by Eq. (7).

$$\eta_{con} = \cos \theta \times \rho \times F_s \times \tau \times 100 \quad (7)$$

The attenuation constant ( $Katt$ ) is applied to calculate the receptor temperature It's calculated by Eq. (8).

$$Katt = \eta_{conc} \times F_d \times R_{ref} \quad (8)$$

The receptor temperature ( $T_{rec}$ ) is calculated by Eq. (9).

$$T_{rec} = \sqrt[4]{\left( \frac{I \times C_g \times abs}{\sigma \times \varepsilon} \right)} \times katt \quad (9)$$

The film temperature ( $T_f$ ) is defined by the average of the receiver temperature ( $T_{rec}$ ) and ambient temperature ( $T_a$ ). Therefore, its numeric value is calculated by Eq. (10).

$$T_f = \frac{T_{rec} + T_a}{2} \quad (10)$$

The coefficient of volumetric expansion of the air ( $\beta$ ) is defined as the inverse of the film temperature ( $T_f$ ). Therefore, its numeric value is calculated by Eq. (11).

$$\beta = \frac{1}{T_f} \quad (11)$$

The Grashof number ( $G_r$ ) is a dimensionless quantity which is applied to calculate the Nusselt number ( $Nu$ ). It's calculated by Eq. (12).

$$G_r = \frac{g \times \beta \times (T_{rec} - T_A) \times D_{rec}^2}{\nu^2} \quad (12)$$

The Nusselt number ( $Nu$ ) is a dimensionless quantity which is applied to calculate the natural convection coefficient ( $h_{c_n}$ ). Its value is calculated by Eq. (13).

$$Nu = 0.88 \times Gr^{\frac{1}{3}} \times \left( \frac{T_{cav}}{T_a} \right)^{0.18} \times \cos \psi^{2.47} \times \left( \frac{D_r}{D_{cav}} \right)^s \quad (13)$$

The natural convection coefficient ( $h_{c_n}$ ) is calculated by Eq. (14).

$$h_{c_n} = \frac{Nu \times K_{ar}}{D_r} \quad (14)$$

The receiver inclination factor (F) is calculated by Eq. (15).

$$F = 0.164 + 0.7498 \times \sin \psi - 0.5026 \times \sin(2 \times \psi) + 0.3278 \times \sin(3 \times \psi) \quad (15)$$

The forced convection coefficient ( $h_{c_f}$ ) is calculated by Eq. (16).

$$h_{c_f} = F \times v^{1.004} \quad (16)$$

The overall convective coefficient ( $h_{c_o}$ ) is defined by the sum of the forced convection coefficient ( $h_{c_f}$ ) and natural convection coefficient ( $h_{c_n}$ ). Its value is calculated by Eq. (17).

$$h_{c_o} = h_{c_f} + h_{c_n} \quad (17)$$

The receptor efficiency ( $\eta_{rec}$ ) is calculated by Eq. (18).

$$\eta_{rec} = \left[ \tau_{abs} - \frac{h_{h_g} \times (T_{rec} - T_a) + \varepsilon \times \sigma \times (T_{rec}^4 - T_a^4)}{\eta_{conc} \times C_g \times I} \right] \quad (18)$$

The Stirling engine efficiency ( $\eta_{st}$ ) is calculated by Eq. (19).

$$\eta_{st} = \left( 1 - \sqrt{\frac{T_a}{T_{rec}}} \right) \times ks \times 100 \quad (19)$$

The overall efficiency ( $\eta_o$ ) is defined as efficiency of the solar conversion system or the product of the efficiencies of the conversion system components Therefore, its numeric value is calculated by Eq. (20).

$$\eta_{overall} = \eta_{con} \times \eta_{rec} \times \eta_{sti} \times \eta_{ger} \quad (20)$$

The available power ( $P_{av}$ ) is defined as the solar power supplied at the concentrator, and calculated by Eq. (21).

$$P_{av} = \frac{I \times A_c}{1000} \quad (21)$$

The net power ( $P_{net}$ ) is defined as the electric power produced by Dish-Stirling system, and calculated by Eq. (22).

$$P_{net} = \eta_{overall} \times P_{disp} \quad (22)$$

The geometrical and thermal sizing shows that the solar irradiance and wind speed are important factors at the design of the Dish-Stirling solar power plants. The local solar irradiance defines the useful energy available to the conversion system and wind speed determines the losses by convection at the receiver (Reddy *et al.*,2016). The feasibility depends mainly on solar irradiance and wind speed at the location of the Dish-Stirling solar power plants (Blakers *et al.*,2015).

## 2.2 The geographical locations applied at the case study.

The relevance of the correct geographical location applied at Dish-Stirling solar power plants sizing is the main proposal of this case study. Therefore, the geometric and thermal sizing of Dish-Stirling was applied at the locations with the highest and lowest values of the normal direct solar irradiance at the Brazil. Brazil is a country with high levels of solar irradiation because its area is very extensive with appreciable latitude variation resulting in large variations of solar irradiance intensity along its length.

The Brazilian location applied at the case study was carried out through surveys at (SWERA, 2017) which resulted in the following locations with a high and low normal direct solar irradiance:

- Location with a low average annual value of normal direct solar irradiance: Sete Barras - São Paulo.
- Location with a high average annual value of normal direct solar irradiance: Brotas de Macaúba - Bahia.

The average annual of winds speed and temperature at the both location was obtained by (SWERA, 2017).

## 2.3 Economic analysis.

The risk of investing in solar power plants at Brazil is high, as this is technology never applied in the country. It results at highest interest rates applied at the financing of this project. The methodology applied at the economic analysis of this case study was the same adopted by (Mantilha, 2017). The proposed plants will be analyzed under the conditions of fiscal and funding offered by BNDES. The table 2 describes the financial parameters adopted.

Table 2. Financial parameters (Malagueta *et al.*, 2017).

Analysis period [years]	30
Amortization period [years]	16
Inflation rate [%]	0
Real discount rate [%]	10
Tributes [%]	27
Loan rate [% per year]	7,4
Debt fraction [%]	70
Minimum required internal rate of return [% per year]	15

The economic analysis of the Dish-Stirling solar power plants developed at this case study applies costs according to international standards, disregarding nationalization costs. The costs were analyzed in two groups, the direct and indirect costs. The unit costs of the Dish-Stirling system are described in table 3.

Table 3. Unit costs of Dish-Stirling system (Mantilha, 2017).

Direct unit costs [millions USD\$]	
Site improvements	0,0045
Parabolic collector cost	0,0351
Receiver cost	0,0062
Stirling engine cost	0,0125
Contingency (10% of the direct costs)	0,0058
Overall direct costs	0,0642
Indirect unit costs [millions USD\$]	
Engineering, design and construction cost	0,0077
Site	0,0001
Several indirect costs	0,0028
Overall indirect costs	0,0106
Overall installation costs (direct + indirect costs)	0,0748

The levelized cost of electricity (LCOE) was determined for the solar power plants analyzed at the case study. The LCOE determines the unit of electricity generated in USD\$/kWh. The LCOE is calculated by equation 23:

$$LCOE = \frac{FCR \times CC + FOC}{AEP} + VOC \quad (23)$$

The variables of equation 23 are defined as described in following topics:

- CC - Capital cost in US\$;

- FOC - Fixed operating costs in US\$/kW. The value applied at this case study is 131,7 (Mantilha, 2017).
- VOC - Variable operating cost in US\$/kWh. The value applied at this study is 0,03 (Mantilha, 2017).
- AEP - Annual energy produced in kWh;
- FCR - The fixed charge rate;

The fixed charge rate (FCR) is calculated by equation 24:

$$FCR = CRF \times PFF \times CFF \quad (24)$$

The construction finance factor (CFF) is calculated by equation 25:

$$CFF = \sum_{c=0}^C CON \times \left(1 + (1 - TAX) \times \left((1 + NINT)^{(C+0.5)} - 1\right)\right) \quad (25)$$

The variables of equation 25 are defined as described in following topics:

- CON - Fraction of capital spent per year;
- c - Year of construction;
- C - Construction period in years;
- NINT - Nominal interest rate;
- TAX - Federal taxes;

The capital recovery factor (CRF) is calculated by equation 26:

$$CRF = \left( \frac{WACC}{1 - \frac{1}{(1 + WACC)^{N_1}}} \right) \quad (26)$$

The variables (N and WACC) of equation 26 are defined as described in following topics:

- $N_1$  - Analysis period;
- WACC - Weighted average capital cost is calculated by equation 27:

$$WACC = \left( \frac{1 + ((1 - DF) \times ((1 + RROE) \times (1 + i) - 1)) + DF \times ((1 + RIR) \times (1 + i) - 1 \times (1 - TAX))}{1 + i} \right) - 1 \quad (27)$$

The variables (DF, i, RROE and RIR) of equation 27 are defined as described in following topics:

- DF - Debt fraction of project;
- i - Inflation rate;
- RROE - Rate of return on equity (real) is calculated by equation 28:

$$RROE = \frac{1 + IRR}{1 + i} - 1 \quad (28)$$

The variable (IRR) of equation 28 is defined as described in following topic:

- IRR - Internal rate of return;
- RIR - Real interest rate is calculated by equation 29:

$$RIR = \frac{1 + NINT}{1 + i} - 1 \quad (29)$$

The project finance factor (PFF) is calculated by equation 30:

$$PFF = \frac{1 - (TAX \times PVDEP)}{1 - TAX} \quad (30)$$

The variable (PVDEP) of equation 27 is defined as described in following topic:

- PVDEP - Present value of depreciation is calculated by equation 31:

$$PVDEP = \sum_{n=0}^{N_2} \frac{DEP}{((1 + WACC) \times (1 + i))^{(n+1)}} \quad (31)$$

The variable (DEP) of equation 27 is defined as described in following topics:

- DEP - Fraction of capital depreciated;
- $N_2$  - years in MACRS depreciation schedule.

The results of the LCOE is obtained by solving of many equations, therefore a Maple® computational program was developed in order to make it operational. This computational program was validated by the application of the data from (Mantilha, 2017) with the variation around 0,18% between the results of developed program and the reference.

The LCOE of the Dish-Stirling solar power plants will be applied at the economic feasibility analysis. The financial sensitivity analysis will be developed in order to determine how different values of the financial parameters impact at LCOE. However, if the economic feasibility analysis concludes the Dish-Stirling solar power plants is an economic non-feasibility, the sensitivity financial analysis will be developed in order to determine the value of the financial parameters to become an economic feasibility power plant.

### 3. RESULTS:

The computational program carried out the sizing of the Dish-Stirling solar power plants. The sizing results of the Sete Barras solar power plant are shown in table 4, and Brotas de Macaúba solar power plant are shown in table 5.

Table 4. Sizing of the Sete Barras solar power plant.

Sete Barras solar power plant.												
Annual average net power of the each Dish-Stirling system [kW]												9,3
Stirling engine net power [kW]												35
Dish-Stirling system net power [kW]												31,5
Amount of Dish-Stirling systems												108
Installed capacity [MW]												3,40
Monthly average solar irradiance [kW /m <sup>2</sup> ]												
Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
487,6	288,4	263,4	393,9	314,3	228,2	300,4	232,8	176,9	269,9	197,0	274,4	291,6
Monthly net power of Dish-Stirling power plant [kW]												
Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1791	990	893	1407	1092	758	1037	773	566	916	641	935	983
Monthly electricity generation of Dish-Stirling power plant [MWh]												
Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
738,4	354,8	337,7	481,2	365,6	238,8	344,0	268,4	202,1	357,8	253,8	391,3	4.334

Table 5. Sizing of the Brotas de Macaúba solar power plant.

Brotas de Macaúba solar power plant.												
Annual average net power of the each Dish-Stirling system [kW]												17,6
Stirling engine net power [kW]												35
Dish-Stirling system net power [kW]												31,5
Amount of Dish-Stirling systems												58
Installed capacity [MW]												1,83
Monthly average solar irradiance [kW /m <sup>2</sup> ]												
Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
641,8	460,1	596,5	554,1	489,2	486,4	378,2	439,2	644,9	618,9	485,7	378,2	516,6
Monthly net power of Dish-Stirling power plant [kW]												
Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
1307	900	1142	1109	966	957	722	854	1311	1252	957	722	1016
Monthly electricity generation of Dish-Stirling power plant [MWh]												
Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual average
511,3	312,2	427,3	390,3	342,9	324,7	254,5	307,4	469,6	476,6	360,6	284,0	4.461

The data at table 3 were applied to calculate the costs of the solar power plants. The results are shown in table 6.

Table 6. Direct and indirect cost, overall and overall costs by net capacity of the Dish-Stirling solar power plants.

Dish-Stirling solar power plants	Brotas de Macaúba	Sete Barras
Direct costs [millions USD\$]	3,7208	6,9284
Indirect costs [millions USD\$]	0,6163	1,1476
Overall costs (direct and indirect) [millions USD\$]	4,3371	8,0760
Overall costs by net capacity [USD\$/kW]	4.337	8.076

The computational program calculated the LCOE of the solar power plants. The results are shown in table 7.

Table 7. Levelized cost of electricity of the solar power plants.

Dish-Stirling solar power plants	Brotas de Macaúba	Sete Barras
LCOE [USD\$/kWh]	10,20	14,17

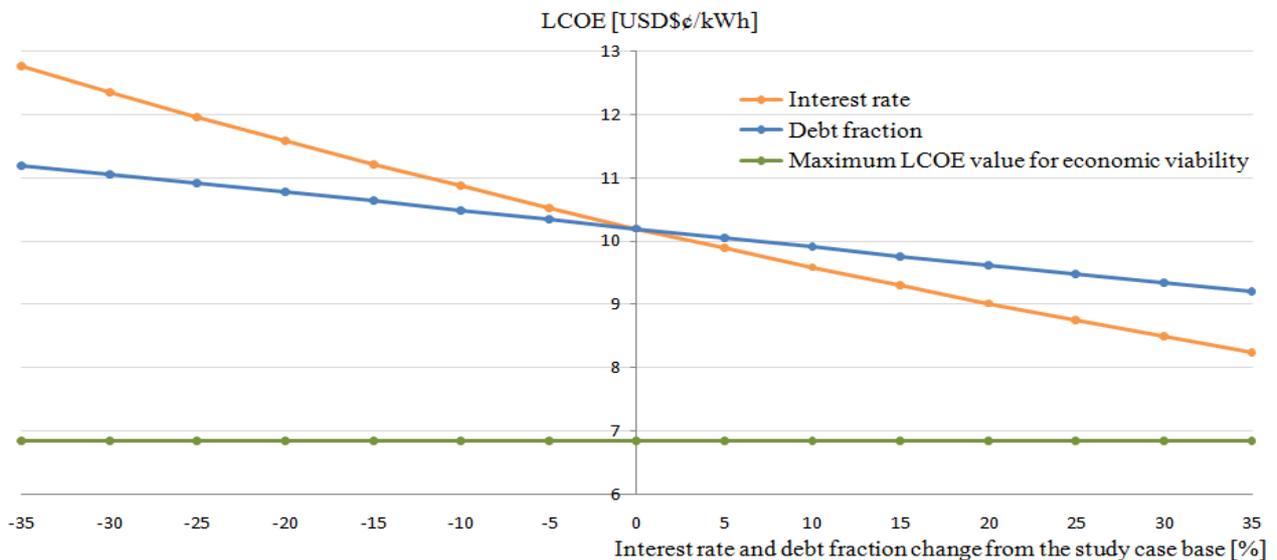


Figure 5. Diagram of financial sensitivity analysis of the Brotas de Macaúba solar power plant.

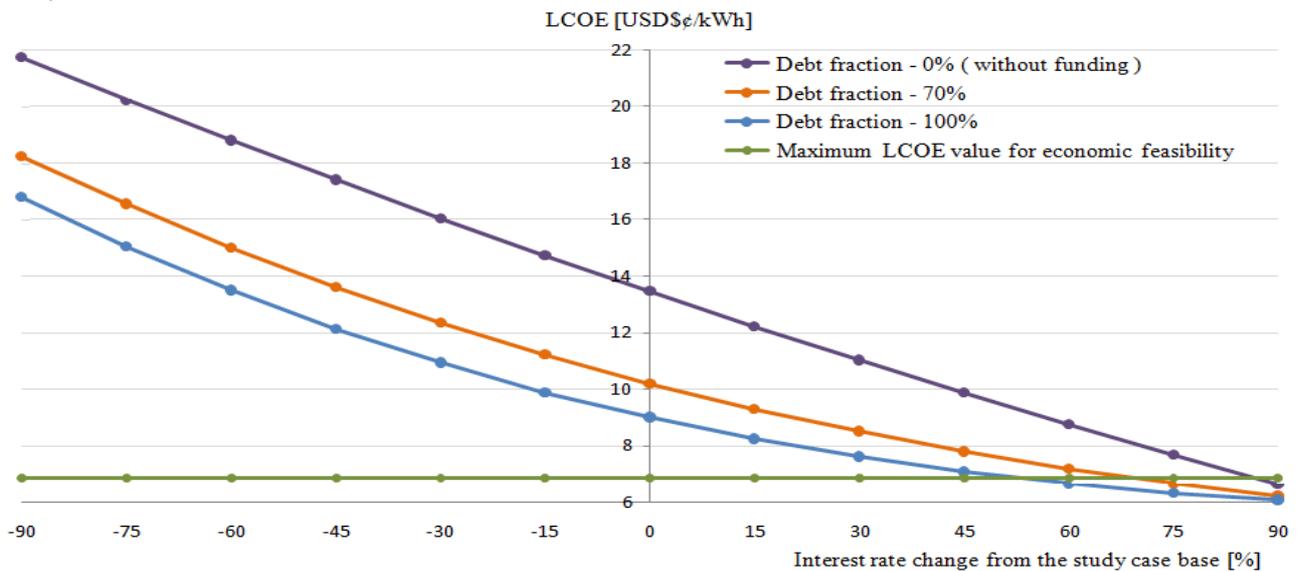


Figure 6. Diagram of financial sensitivity analysis of the Brotas de Macaúba solar power plant.

A Brazilian auction at 2016 applied a LCOE value of the 6,85 USD\$/kWh for gas turbine power plants (Mantilha, 2017). This value was adopted as the maximum LCOE for economic feasibility of the Dish-Stirling power plants.

The financial sensitivity analysis of the Brotas de Macaúba power plant proposes changes in financial parameters (interest rates and debt fraction) from study case base. The figure 5 shows the financial sensitivity analysis by changing interest rates or debt fraction independently each other. The figure 6 shows the financial sensitivity analysis by changing the interest rates and debt fraction together to determine the financial parameters at economic feasibility condition. The table 8 shows financial parameters at economic feasibility condition.

Table 8. Financial sensitivity analysis of the the Brotas de Macaúba solar power plant.

Debt fraction [%]	Maximum interest rate for economic feasibility [%]
0 (without funding)	0,97
70	2,28
100	3,48

#### 4. CONCLUSIONS

The results obtained at the sizing of the Brotas de Macaúba and Sete Barras solar power plants shows a variation around 86 % at the number of Dish-Stirling systems and the installed capacity between theses solar power plants. However, the electricity generation capacity of the Dish-Stirling solar power plants has a variation around the 3% between them. The variation on electricity generation capacity of the solar power plants occurred by the application of monthly average solar irradiance and the average monthly day duration at the sizing of Dish-Stirling power plants. In short, Sete Barras power plant needs 86% more Dish-Stirling systems than Brotas de Macaúba power plant to generate around 3% less electricity than power plant of Brotas de Macaúba.

The results obtained for the number of Dish-Stirling systems, the installed capacity and the electricity generation capacity for both solar power plants was as expected. The solar irradiance (I) is the mainly factor at the solar power plants sizing, defining the useful energy available at the conversion system. The annual average solar irradiance at Brotas de Macaúba is around 78% higher than Sete Barras. Therefore, the Dish-Stirling systems at Sete Barras receives in average 78% less power per unit area than the Dish-Stirling systems at Brotas de Macaúba to develop a electricity generation capacity only 3% less than Brotas de Macaúba. The collector area of the Dish-Stirling systems applied at both solar power plants are the same, therefore, receiving in average 78% less power per unit area, Sete Barras power plant needs 86% more Dish-Stirling systems to develop a electricity generation capacity 3% less than Brotas de Macaúba. The analysis at the sizing of the Dish-Stirling power plants indicates that results are according to expected and the purpose of this case study.

The cost financial analysis shows an 86% variation between of the plants of Brotas de Macaúba and Sete Barras. The percentage variation at the costs financial analysis is the same obtained at the solar power plants sizing. This equal percentage variation is a result was as expected, since the number of Dish-Stirling systems has the same proportionality ratio of the costs at the solar power plants. However, the costs at the Sete Barras power plant are 86% high than costs at the Brotas de Macaúba power plant and produce around 3% less electrical energy than Brotas de Macaúba power plant. In short, the costs financial analysis shows that Brotas de Macaúba power plant has higher economic feasibility than Sete Barras power plant.

The financial analysis of the levelized cost of electricity (LCOE) obtained a result at Sete Barras power plant 38% high than Brotas de Macaúba power plant. This result was as expected, since the cost financial analysis shows the Sete Barras power plant has 86% high than value costs at the Brotas de Macaúba power plant. However, LCOE at the Sete Barras power plant are 38% high than Brotas de Macaúba power plant and produce around 3% less electricity energy than Brotas de Macaúba power plant. In short, the financial analysis of the levelized cost of electricity shows that Brotas de Macaúba power plant has higher economic feasibility than Sete Barras power plant.

The cost financial analysis and the analysis of the levelized cost of electricity shows Brotas de Macaúba power plant more economic feasibility than Sete Barras power plant, but isn't enough to define the economic feasibility of the Brotas de Macaúba power plant. The economic feasibility t will be analyzed by the levelized cost of electricity of the Brotas de Macaúba power plant and electricity auctions in Brazil, adopted as the maximum LCOE for economic feasibility of the Dish-Stirling power plants.

The Brotas de Macaúba power plant has the LCOE 49% higher than the maximum LCOE for economic feasibility. Therefore, the conclusion is the Brotas de Macaúba is a non-economic feasibility power plant. Thus, Sete Barras also is an non-economic feasibility power plant.

Although Brotas de Macaúba is a non-economic feasibility power plant, the sensitivity financial analysis affords to determine how different values of the financial parameters impact at LCOE. The results of the sensitivity financial analysis developed at the diagram of the figure 5 shows the interest rate is the financial parameter with highest impact at

LCOE. The debt fraction is a financial parameter with less impact than interest rate at LCOE, but the results sensitivity financial analysis shows this financial parameter has the great relevance at LCOE.

The sensitivity financial analysis developed at the diagram of the figure 5 presented a maximum variation of 35% in the financial parameters, but it was not enough to determine the economic feasibility condition (at the 35% of variation in interest rate, the LCOE is around 20% above of the maximum LCOE for economic feasibility). Thus, the sensitivity financial analysis developed in order to determine the value of the financial parameters to become an economic feasibility power plant (the diagram of the figure 6) presented the expected results at variation between 45% and 90% in the interest rate base of the study case. The debt fraction also analyzed by this sensitivity financial analysis, and the results shows the high impact of this financial parameter in LCOE, through the variations around of 350% at the interest rate of economic feasibility condition. In short, the Brotas de Macaúba is an economic feasibility solar power plant at interest rates between 3,48% and 0,97%, depending on the debt fraction applied.

The results shows the both solar power plants are non-economic feasibility by applying the financial parameters adopted in this case study. However, the Brotas de Macaúba solar power plant would be economically feasible if the interest rate was between 3,48% and 0,97%, depending on the debt fraction applied.

In short, the financial parameters adopted at this case study represent the funding conditions (BNDES) currently applied in Brazil. Under these financial parameters, the Brotas de Macaúba and Sete Barras are non-economic feasibility power plants. The sensitivity financial analysis developed at this case study shows that Brotas de Macaúba might be an economic feasibility solar power plant if the funding parameters were change. In order for the funding parameters were changed according to the economic feasibility conditions, the Brazilian government should to create a special funding for the development of solar power plants with lower interest rates (between 3,48% and 0,97%) depending on the debt fraction available.

The results show the relevance of this case study that develops designs of Dish-Stirling power plants under conditions of distinct and antagonistic solar resources. These same results validate the methodology applied at this case study, as well the application of correct geographical location and the real climatic conditions at the design of Dish-Stirling power plant.

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