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NEW CONCEPT OF SOLAR-WIND HYBRID DISH CONCENTRATOR

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Abstract. Dish-Stirling is a solar concentrating system commonly installed at open fields; therefore, exposed to strong winds. The incidence of high speeds winds in these solar concentrators requires its deactivation, so the increasing availability of wind energy determines a decrease in their utilization rate. Based on this scenario, this research aims to assess the possibility of wind energy recuperation using a modified solar parabolic concentrator, creating a new concept of solar-wind hybrid dish concentrator. The technical proposal consists in applying wind turbine blades on a parabolic concentrator, defining the hybrid dish concentrator, which is based on the concept of the funnel concentrator. The proposed system is analyzed based on optical studies and through computational fluid dynamics simulations. Aiming to technical validate the proposed concept, its electricity generation potential is compared with an analogous traditional solar dish-Stirling. The comparative analysis proves the technical feasibility of the solar-wind hybrid dish concentrator.

Keywords: Renewable energy, hybridization, Dish-Stirling system, concentrating solar power, wind turbine.

1. INTRODUCTION

Electricity generation from non-renewable sources produces environmental impacts that increase the earth's temperature by the greenhouse effect (Baharoon et al., 2015). The key to solving this problem is the application of renewable sources, which permit a clean and sustainable energy conversion.

Hybrid renewable energy systems combine conventional and renewable energy sources or multiple renewable energy sources (Khare et al., 2014). These systems are advantageous by combining two or more power generation technologies, achieving higher efficiencies than from a single power source (Khare et al., 2014)

Solar and wind renewable energy are widely applied in electricity generation. The combining of solar and wind conversion systems (hybridization) results in a hybrid solar-wind system with large capacity for electricity generation and a long period of operation (Tao et al., 2011). The hybrid dish concentrator proposed in this research promotes the hybridization of the Dish-Stirling system by integrating wind blades in the solar concentrator.

Dish-Stirling (Figure 1) consists of solar energy conversion systems composed of a reflector (Figure 1), a receiver (Figure 1), a solar tracking system, a Stirling engine (Figure 1), and a supporting structure (Figure 1) (Coventry and Andraka, 2017). These systems use lenses or mirrors in solar dish concentrator (reflectors), which is associated at solar tracking systems to collect solar irradiation in a large area and focus it on a small area at the receiver. The concentrated solar energy is used to heat the working fluid of the Stirling engine, which is used to generate electricity (Coventry and Andraka, 2017).

Energy has been extracted from the wind over hundreds of years through primitive devices named windmills (Figure 2), which were primarily composed of wood, cloth, and stone (Schubel and Crossley, 2012). These primitive devices were typically large, heavy, and inefficient. However, they were largely used for pumping water or grinding corn (Schubel and Crossley, 2012). The development of aerodynamics and advances in materials have led to an increasing interest in wind energy harvesting in the latter half of the 20th century (Schubel and Crossley, 2012). The wind energy harvesting devices are now used to produce electricity at large scales (Figure 2) and are commonly termed wind turbines (Schubel and Crossley, 2012).

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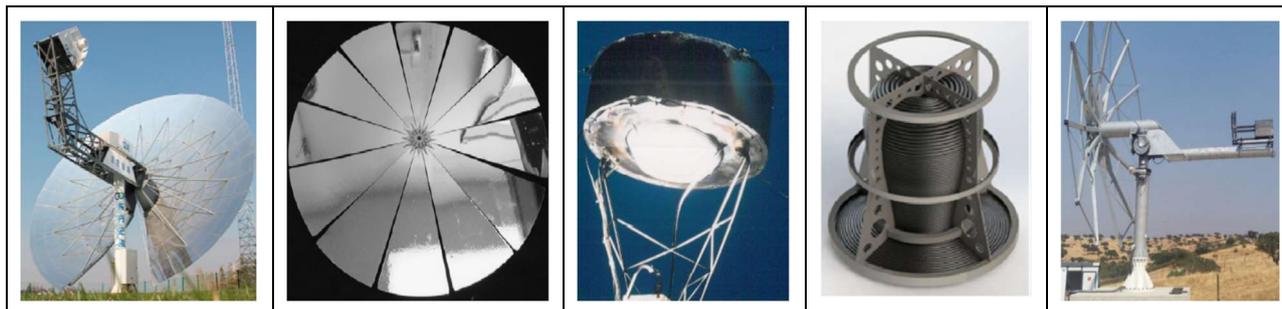A new concept of hybrid (solar/wind) dish concentrator

Figure 1. From the left to right: Dish-Stirling system (Coventry and Andraka, 2017), Reflector (Li and Dubowsky, 2011), Receiver (Coventry and Andraka, 2017), Stirling engine (Coventry and Andraka, 2017) e Structure (Coventry and Andraka, 2017).

Figure 2. Windmill (Burton *et al.,* 2011) (left) and Three blades wind turbine (Larwood *et al.*, 2011) (right)

The CSCWA solar-wind hybrid renewable system (Su *et al.,* 2011) (Tao *et al.,* 2011) was developed under a new concentrator concept (funnel solar concentrator). CSCWA (combined solar concentration/wind augmentation), shown in figure 3, is composed of a concentrator, a photovoltaic cell, and a wind turbine.

Figure 3. CSCWA Solar-wind hybrid renewable system (Tao *et al.,* 2011)

The results obtained by Su *et al.* (2011) and Tao *et al.* (2011) demonstrate the feasibility of the solar-wind hybrid renewable system under the same availability of wind and solar resources. These results demonstrate that hybridization of solar systems provides increases of up to 50% in its power capacity. Therefore, Su *et al.* (2011) and Tao *et al.* (2011) research prove the technical feasibility of the hybrid solar-wind systems.

2. CONCEPT OF SOLAR-WIND HYBRID DISH CONCENTRATOR

The concept of the hybrid dish concentrator consists of a solar dish concentrator with wind turbine blades integrated into its structure and of gaps (apertures) created by removing part of its reflecting surface. The figure 4 (left side) shows the conceptual design of the hybrid dish concentrator using an arbitrary number of blades, only to demonstrate the proposed concept.
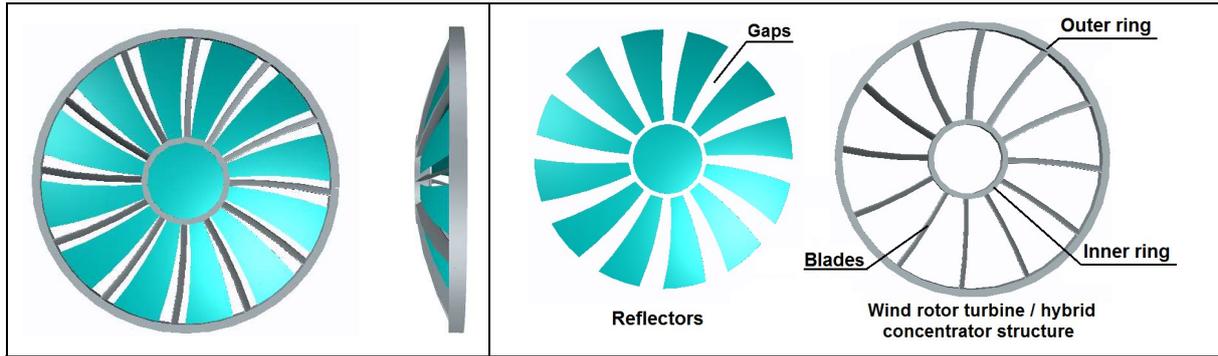
Figure 4 - Conceptual model of hybrid dish concentrator (left) and its reflectors, wind rotor turbine and structure (right)

2.1 Analogous solar dish concentrator

The analogous solar dish is a concept concentrator with the same geometric size as the hybrid dish concentrator. This solar dish was used to compare the power and electricity generation of the hybrid and analogous solar concentrators.

3. METHODOLOGY

The design of the hybrid dish concentrator applied the geometrical and thermal sizing of the Dish-Stirling systems, blade element momentum (BEM), 3D modeling and computational fluid dynamics (CFD).

3.1   The geometrical and thermal sizing of the Dish-Stirling systems

The geometrical and thermal sizing of the Dish-Stirling systems proposed by Hafez *et al*. (2016) and Castellanos *et al.* (2017) determines their geometric and thermal parameters based on data of climatic conditions (solar irradiation, wind speed and ambient temperature) and technical premises of solar dish concentrator (diameter, material and rim angle).

The methodology of geometrical and thermal sizing of a Dish-Stirling systems is composed by many equations; therefore, a computational program was developed to process these calculations. The computational code developed was validated by comparing the generated results with the ones presented by Castellanos *et al.* (2017). The maximum relative deviation between the results obtained using computational code and the adopted reference was 1.3%.

The main parameters of renewable energy sources (wind/solar) applied to design the hybrid and analogous solar concentrator are the wind speed (U_∞) and solar irradiances (I). Therefore, the location used as a reference to design the hybrid and analogous solar concentrator must be determined considering its local wind and solar energies availabilities. In this case, the city used as the reference for the design of hybrid and analogous solar concentrators was Laguna-SC. According to Dalmaz, Lagoon.

According to Dalmaz (2007), Laguna-SC has a high wind availability with an annual average wind speeds (U_∞) of 8 m/s, wind capacity factor (F_{CE}) 0,4 at 48 metros (database from Laguna´s wind farm). This height is not feasible for the application of dish concentrators, so this research uses the annual average wind speeds (U_∞) of 6 m/s, which a typical value of Santa Catarina state. According to wind profile power law, the annual average wind speeds (U_∞) of 6 m/s on Laguna is obtained at height bellow of 20 meters, with wind capacity factor (F_{CE}) 0,3 (Dalmaz, 2007).

Solar irradiances used to design the hybrid and analogous solar concentrator are the daily average solar irradiance of the isolation period (I_{DIS}), which is 450W/m² in Laguna-SC The solar capacity factor (F_{CS}) without energy storage, considering maintenance, is about 0,25 for 8 hours of insolation (Lovegrove and Stein, 2012). Laguna has 7 hours of insolation, so its solar capacity factor (F_{CS}) is 0,22.

The diameter of the concentrator (D_c) determines the energy available at the receiver, so this parameter must be defined according to required system power and solar irradiation available. The design of the dish concentrator commonly applies diameters between three and fifteen meters (Coventry and Andraka, 2017), so the diameter (D_c) used in this analysis for both the hybrid and analogous solar concentrator was six meters.

 Reflector material is one of the most important technical specification in a solar dish concentrator design. The materials properties of reflector determine the efficiency of the solar conversion system. These properties are the reflectivity (ρ) and the emissivity (ε), which are expressed in terms of percentage [%]. The aluminum was the material applied to design the hybrid and analogous solar concentrator, since it is widely used in the manufacture of this solar conversion system.

The geometrical and thermal sizing of the Dish-Stirling system uses many constants and coefficients which are shown in table 1.

Table 1. Coefficients and constants applied to geometrical and thermal sizing of Dish-Stirling systems (Castellanos *et al.,* 2017).

SYMBOL	DESCRIPTION	VALUE
F_S	Shading factor	0.72
α_{ABS}	Absorber of the receiver	0.96
$\tau_i\,\alpha_{ABS}$	Transmittance-absorptance	0.90
τ	Intercept factor	0.96
F_D	Deterioration factor	0.9
K_S	Stirling constant	0.5
F_R	Cooling factor	0.5

The focal length of the concentrator (f) is the distance from the vertex of the paraboloid to its focus. It was calculated by Eq. (1) (Hafez et al., 2016):

$$f = \frac{D_c^2}{4 \times \tan(\sigma/2)}$$ (1)

The rim angle (φ) is formed between the focal point and the edge of the dish concentrator. The value of rim angle (φ) applied to design the hybrid and analogous solar concentrator is 27 °. A small rim angle (φ_C) was adopted because the proposed hybridization determines the application of the curvature rim angle (φ_C) on the blade; however, the wind turbine blades commonly doesn´t have curvature.

The tracking error (θ) or error of the solar tracking system defines the focal diameter of the dish concentrator. According to Castellanos *et al.* (2017), the tracking error (θ) can be considered equal to 0,008 rad.

The receiver diameter (D_{rec}) is defined as the focal area of the dish concentrator, which was calculated by Eq. (2) (Hafez et al., 2016):

$$D_{rec} = \frac{f \times \theta}{\cos\varphi \times (1 + \cos\varphi)}$$ (2)

The aperture area of the concentrator (A_c) consists in total the surface area of the dish concentrator upon which solar energy is incident (Hafez *et al.,* 2016). The receiver aperture area (A_{rec}) is defined as the focal area of the solar dish concentrator at receiver. The concentration ratio of the dish concentrator (C_g) is determined by the ratio of the concentrator aperture area (A_c) to the receiver aperture area (A_{rec}).

The concentrator efficiency (η_{con}) determines the power supplied at receiver. It was calculated by Eq. (3) (Castellanos et al., 2017):

$$\eta_{con} = \cos\theta \times \rho \times F_s \times \tau \times 100$$ (3)

The attenuation constant ($Katt$) was obtained by Eq. (4) (Castellanos et al.,2017):

$$Katt = \eta_{conc} \times F_d \times R_{ref}$$ (4)

The receiver temperature (T_{rec}) reaches values up to 1000º C (Baharoon *et al.,* 2015). It was calculated by Eq. (5) (Castellanos et al.,2017):

$$T_{rec} = \sqrt[4]{\left(\frac{I \times C_g \times abs}{\sigma \times \varepsilon}\right) \times katt}$$ (5)

The film temperature (T_f) is determined by the mean between the receiver temperature (T_{rec}) and ambient temperature (T_a). The coefficient of volumetric expansion of the air (β) is obtained by the inverse value of the film temperature (T_f).

The Grashof number (G_r) was calculated by Eq. (6) (Bergman et al., 2011):

$$G_r = \frac{g \times \beta \times (T_{rec} - T_A) \times D_{rec}^2}{\nu^2}$$ (6)

The Nusselt number (NuNu) was obtained by Eq. (7) (Castellanos et al., 2017):

$$Nu = 0.88 \times Gr^{\frac{1}{3}} \times \left(\frac{T_{cav}}{T_a}\right)^{0.18} \times \cos \psi^{2.47} \times \left(\frac{D_r}{D_{cav}}\right)^s \tag{7}$$

The natural convection coefficient (h_{c_n}) was calculated by Eq (8) (Castellanos et al., 2017):

$$h_{c\_n} = \frac{Nu \times K_{ar}}{D_r} \tag{8}$$

The receiver angle (ψ) describes its angular position in the operation of dish concentrator. Due to wind studies, the numerical value of the receiver angle (ψ) adopted for designing the hybrid dish concentrator is 0º.

The receiver inclination factor (F) was calculated by Eq. (9) (Castellanos et al., 2017):

$$F = 0.164 + 0.7498 \times \sin \psi - 0.5026 \times \sin(2 \times \psi) + 0.3278 \times \sin(3 \times \psi) \tag{9}$$

The forced convection coefficient (h_{c_f}) was calculated by Eq (10) (Castellanos et al., 2017):

$$h_{c\_f} = F \times U_\infty^{1.004} \tag{10}$$

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}).

The receiver efficiency (η_{rec}) was calculated by Eq. (11) (Castellanos et al., 2017):

$$\eta_{rec} = \left[\tau_{abs} - \left(\frac{h_{h\_g} \times (T_{rec} - T_a) + \varepsilon \times \sigma \times (T_{rec}^4 - T_a^4)}{\eta_{conc} \times C_g \times I}\right)\right] \tag{11}$$

The Stirling engine efficiency (η_{st}) was calculated by Eq. (12) (Castellanos et al., 2017):

$$\eta_{st} = \left(1 - \sqrt{\frac{T_a}{T_{rec}}}\right) \times ks \times 100 \tag{12}$$

Generator efficiency (η_{ger}) applied to calculate the overall efficiency (η_o) of the hybrid and analogous solar concentrator is 90%, according to Castellanos *et al.* (2017). Overall efficiency (η_o) of the solar conversion system is determined by the product of the efficiencies of the conversion system components.

The available solar power (P_{SD}), defined as the solar power supplied to dish concentrator, was calculated by Eq. (13) (Castellanos et al.,2017):

$$P_{SD} = I \times A_C \tag{13}$$

The net power (P_{net}), or electric power of the Dish-Stirling system, was obtained by Eq. (14) (Castellanos et al.,2017):

$$P_{net} = \eta_{global} \times P_{disp} \tag{14}$$

The annual electricity generation period (T_S) was obtained by Eq. 15 (Lovegrove and Stein,2012):

$$E_{AGS} = P_{net} \times F_{CS} \times 8760 \tag{15}$$

3.2   Blade element momentum (BEM)

The blade element momentum is widely applied to wind turbine design. This methodology determines the geometrical sizing of the blade element based on local weather (wind speed), technical premises (diameters, number of the blades, aerodynamic profile), operational parameters (rotation) and the number of blade sections analyzed.

BEM is composed by many equations; therefore, a computational code was developed to process these calculations. The computational code program was validated through the application of the data presented by Tammaruckwattana *et al.* (2015). The maximum variation of the 0.1 % between the results of developed program and the adopted reference.

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The wind speed (U_∞) affords the energy available to wind turbine; therefore, it is a main factor in design of hybrid dish concentrator. This design parameter must be specified from the atmospheric condition of the hybrid dish concentrator location (Laguna-SC). It was previously specified at 6 m/s.

The internal and external diameters of the hybrid dish concentrator are respectively the diameter of the blade root or base and the diameter of the blade tip. The external diameter was previously specified at six meters. The internal diameter was specified through analysis of the hub-to-tip ratio based on wind turbines similar to the hybrid dish concentrator, mainly as concerns to the high solidity of its rotors. Therefore, the internal diameter was specified at 33% of its external diameter, resulting in 2 meters.

The number of blades (N_{pa}) used in hybrid dish concentrator was specified (twenty blades) based on analysis of relationship between blades numbers and tip speed ratio for wind turbine rotors, as recommended by Manwell et al. (2010). The number of blades elements used in the hybrid dish concentrator was specified (ten blade elements) according to average value recommended by Hau (2013).

The NACA 4415 is widely applied to design wind turbine, therefore this aerodynamic profile was used in the hybrid dish concentrator. Javafoil® was applied to define the angle of attack (α), drag coefficient (C_d) and lift coefficient (C_l) for aerodynamic profile NACA 4415. These dimensionless coefficients quantify the lift and drag generated by aerodynamic body. The angle of attack (α) must be constant along blade, keeping the best ratio between the lift and drag coefficients, therefore the same efficiency along blade.

Blade element momentum determines the geometrical sizing of the blade element essentially based on aerodynamic profile and two geometric parameters: pitch angle (β_{BEM}) and chord (c_{BEM}) (The BEM index indicating that it´s calculated for each blade element). However, to obtain these parameters, it is required to determine the flow angle (ϕ_{BEM}) and local tip speed ratio (λ_{BEM}).

Local tip speed ratio (λ_{BEM}) is the ratio between the tangential speed and the wind speed. It was obtained by Eq. (16) (Burton et al., 2011).

$$\lambda_{BEM} = \frac{2 \times \Omega \times D_{BEM}}{U_\infty} \tag{16}$$

Flow angle (ϕ_{BEM}) is formed between the turbine rotation plane and relative wind speed. It was obtained by Eq. (17) (Burton et al., 2011).

$$\phi_{BEM} = arctan \left(\frac{1-a}{\lambda_{BEM}(1+a')} \right) \tag{17}$$

Pitch angle (β_{BEM}) is formed by inclination angle of blade chord relative to rotor plane. It was calculated by Eq. (18) (Burton et al., 2011).

$$\beta_{BEM} = \phi_{BEM} - \alpha \tag{18}$$

Relative velocity (W_{BEM}) was calculated by Eq. (19).

$$W_{BEM} = \sqrt{U_\infty^2(1-a) + r^2\Omega^2(1+a')^2} \tag{19}$$

Chord (c_{BEM}) is the linear dimension between leading and trailing edge of the aerodynamic profile. It was calculated by Eq. (20) (Burton et al., 2011).

$$c_{BEM} = \frac{8\pi a'(1-a)\mu^2 R U_\infty^2 \lambda_{BEM}}{N_{P\dot{A}} W_{BEM}^2 (C_L \sin(\varphi_{BEM}) + C_D \cos(\varphi_{BEM}))} \tag{20}$$

3.3   3D modeling

The CFD analysis of the airflow through concentrator blades cannot be performed by 2D drawing. Therefore, the 3D modeling was applied to design of the hybrid dish concentrator.

3.4   Computational fluid dynamics (CFD)

The computational fluid dynamics was applied to determine the torque generated by the hybrid dish concentrator. The CFD applied the SST k-ω turbulence model at steady state, both premises are suitable for the physical characterization of the analyzed system.

The CFD analyses was based on periodicity, so a fraction (1/20) of 3D model was considered on analyses. The application of two domains were required (general domain and the rotating domain), which were defined as cylinder,

according to Rajendran and Madhu (2010) and Massouh and Dobrev (2007). The domains dimensions were specified as a scale of concentrator diameter (D_c), according to Rajendran and Madhu (2010) and Massouh and Dobrev (2007). Due to periodicity, those domains were applied at CFD analyses as a fraction (1/20) of their total volume. The subtract Boolean operation was applied on periodic 3D model of the hybrid dish concentrator and domains.

4. RESULTS

4.1 Blades design

The results of blade design are shown in table 2.

Table 2. Chord (C_{BEM}) and pitch angle (β_{BEM}) of the blade elements.

Symbol	Unit	Blade element										
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
β_{BEM}	[°]	39,35	38,98	38,92	38,01	36,83	35,51	34,11	32,69	31,29	29,92	28,61
c_{BEM}	[m]	0,27	0,26	0,26	0,26	0,25	0,25	0,24	0,23	0,22	0,22	0,21

4.2 3D model of the hybrid dish concentrator

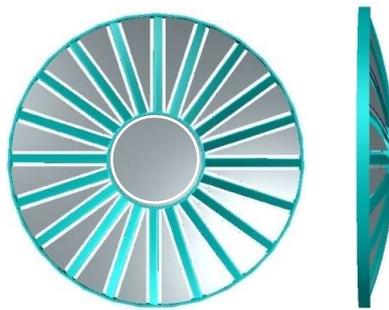The 3D model of the hybrid concentrator is shown in figure 5.

Figure 5. 3D drawing of the hybrid dish concentrator

The 3D model of the hybrid concentrator (figure 5) was designed based on results of the table 2, technical premises and methodology described on 3.1 and 3.2 sections. The geometric analysis validates the 3D model obtained, therefore, validates the results of the table 2, the technical premises and the methodology applied to design.

4.3 Computational fluid dynamics (CFD)

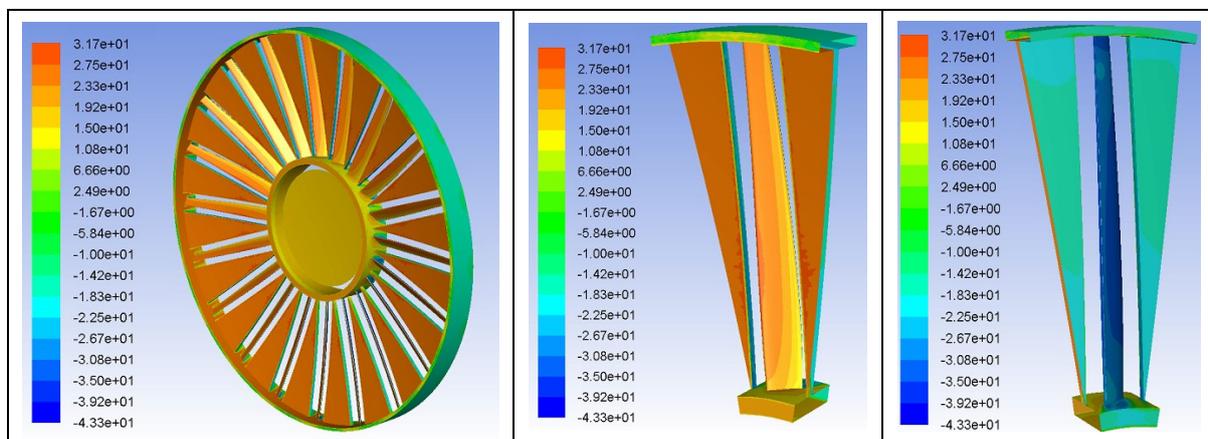The pressure distribution on hybrid concentrator surface is shown on figure 6.

Figure 6. Pressure distribution on hybrid concentrator surface

The pressure distribution on wind blades surface (figure 6) demonstrates a difference pressure between its downwind and upwind sides, therefore the torque generation from hybrid concentrator was proven. The torque developed by periodic hybrid concentrator according to CFD results is 13,4 N m. Therefore, the torque developed by hybrid dish concentrator is 268 N m. The generator efficiency (η_{ger}) used to calculate the net torque of the hybrid dish concentrator is 90%, as previously adopted for solar energy conversion systems.

4.4   Solar design of the hybrid dish concentrator and analogous solar dish concentrator

The results of solar design are shown in table 3, for hybrid and analogous solar concentrator.

Table 3. Solar design of the hybrid dish concentrator and analogous solar dish concentrator.

Symbol	Unit	Hybrid dish concentrator	Analogous solar dish concentrator
D_R	[m]	0,19	0,19
A_C	[m²]	17,28	28,27
A_R	[m²]	0,03	0,03
C_G	-	593	971
η_C	[%]	59,44	59,44
η_R	[%]	88,35	88,53
η_S	[%]	15,70	17,75
η_G	[%]	7,55	8,4

The results of the aperture area (A_C) and concentration ratio (C_G) from analogous solar and hybrid concentrators has a percent change about 40%, generated by gaps of the hybrid concentrator. The results of the Stirling engine efficiency (η_{st}) and overall efficiency (η_o) from analogous solar and hybrid concentrators has a percent change between them generated by results of the aperture area (A_C) and concentration ratio (C_G). Therefore, the gaps of hybrid concentrator change the solar conversion efficiency on proposed hybrid system.

4.5   Solar-wind electric power generation by the hybrid and analogous solar dish concentrator

Results of solar-wind electric power generation form hybrid dish concentrator and analogous solar dish concentrator are shown on table 4.

Table 4. Solar-wind electric power generation from hybrid dish concentrator and analogous solar dish concentrator

	Unit	Hybrid concentrator	Analogous solar concentrator
Electric power generation (Solar)	[kW]	0,59	1,07
Electric power generation (Wind)	[kW]	0,51	-

4.6   Electricity generation from hybrid dish concentrator and analogous solar dish concentrator

Results of electricity generation from hybrid dish concentrator and analogous solar dish concentrator are shown on table 5.

Table 5. Electricity generation from hybrid dish concentrator and analogous solar dish concentrator

	Unit	Hybrid concentrator	Analogous solar concentrator
Electricity generation (Solar)	[MWh/year]	1,13	2,06
Electricity generation (Wind)	[MWh/year]	1,03	-

The results of the electric power generation and electricity generation demonstrate a decrease in solar energy conversion due to the hybridization proposed. However, the conversion of wind energy increases the electric power generation and electricity generation of the hybrid system.

5. CONCLUSIONS

The CFD results and the pressure distribution on the blades confirm the torque generation in hybrid dish concentrator. Therefore, these results attest the wind energy conversion and validate the concept of the hybrid dish concentrator.

The results of the electric power and electricity generation for hybrid and analogous solar concentrator showed a decrease about 45% in solar conversion by the proposed hybridization. The hybrid dish concentrator has the reflector area about 40% less than the analogous solar dish concentrator, therefore the decrease obtained in results of the electric power and electricity generation is consistent.

The comparative analysis of the electric power and electricity generation for hybrid and analogous solar concentrator demonstrate a little increase about 5%. The results of electric power and electricity generation from the wind source were based on premise; the wind energy conversion was only performed when the solar conversion is not available. Therefore, the hybrid dish concentrator has a greater potential to electric power and electricity generation through hybrid energy conversion (simultaneous wind and solar).

The blade design of the hybrid dish concentrator was based on references of the standard wind rotors. However, its concept has a singular flow configuration through of the gaps under rotational motion, which is different from wind rotors. Therefore, the recommendations for future study consist in an optimization for blade design and the gaps dimensions provides an increase in electric power and electricity generation by wind energy conversion.

Additionally, the results showed the relevance of the gaps dimensions on solar energy conversion. Therefore, the recommended study increases the electric power and electricity generation by solar energy conversion (optimizing the reflection area) and wind energy conversion.

The hybrid dish concentrator is an innovative concept. The results of this research showed its feasibility and relevance of the further studies to determine its maximum potential for electricity generation.

6. ACKNOWLEDGEMENTS

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