Simulation and financial assessment of three types of solar energy for the generation of steam.

Simulación y evaluación financiera de tres tipos de energía solar para la generación de vapor.

*Luisa María Cadena-Triana[a], Mariana Campos Padilha Lopes[b], Laura Guerrero-Martin[c], Erik Montes-Páez[d], Camilo Guerrero-Martin[a,e]

[a] *Energy Department, Fundación Universidad de América, Bogotá, Colombia. lu.mariatriana@gmail.com*
[b] *Electrical Engineering Program, Federal University of Rio de Janeiro, Rio de Janeiro, RJ, Brazil. E-mail: mariana.padilha@ppe.ufrj.br.,*
[c] *Environmental Engineering, Universidad Distrital Francisco José de Caldas. Bogotá, Colombia. g.laura05@hotmail.com*
[d] *Universidad Industrial de Santander. Bucaramanga, Colombia. erimonpa@uis.edu.co*
[e] *Centre for Energy and Environmental Economics (CENERGIA), Energy Planning Programme, PPE/COPPE, Universidade Federal Do Rio de Janeiro, Brazil. camilo.guerrero@ppe.ufrj.br*

Abstract

In this article three types of alternative energies were evaluated, which are High Concentration Photovoltaic PV, Concentrated Solar Power - Direct Linear Fresnel Steam and Stirling Dish, in a Colombian field called TECA field which is located in Puerto Nare, Antioquia, to generate steam and supply it. To perform this evaluation, it was done using the simulator System Advisor Model (SAM) to obtain the respective LCOE for each type of energy, likewise different factors were taken into account, then the following results were obtained: 0.44 ¢ / kWh in High Concentration Photovoltaic, 0.40 ¢ / kWh in concentrating solar power - Direct Steam Fresnel linear and 0.40 ¢ / kWh in concentrating solar power - Stirling Dish. And finally, a financial analysis was performed in order to determine the feasibility of the project, where a payback period of approximately 34 months and an Internal Rate of Return (IRR) with a value of 27.8% were obtained, among other parameters resulting in a viable project in the medium term.

Keywords: Concentrated Solar Power, Photovoltaic, Oil Field

Resumen

En este artículo se evaluaron tres tipos de energías alternativas, las cuales son Fotovoltaica FV de Alta Concentración, Energía Solar por Concentración - Vapor Directo Lineal Fresnel y por Plato Stirling, en un campo colombiano llamado campo TECA que esta ubicado en Puerto Nare, Antioquia, con el fin de generar vapor y suministrarlo. Para realizar dicha evaluación, se realizo mediante el simulador System Advisor Model (SAM) con el fin de conocer el respectivo LCOE para cada tipo de energía, así mismo se tuvieron en cuenta diferentes factores, posteriormente se obtuvieron los siguientes resultados: 0.44 ¢ / kWh en Fotovoltaica de Alta Concentración, 0.40 ¢ / kWh en energía solar de concentración - Vapor directo Fresnel lineal y 0.40 ¢ / kWh en energía solar de concentración - Plato Stirling. Y finalmente realizó un análisis financiero con el fin de determinar la viabilidad del proyecto, donde se obtuvo un período de recuperación de aproximadamente 34 meses y una Tasa Interna de Retorno (TIR) con un valor de 27,8%, entre otros parámetros teniendo como resultado un proyecto viable a mediano plazo

Palabras clave: Energía solar concentrada, Fotovoltaica, Campo petrolífero

1. Introduction

For some years now, there has been a need to commercialize clean, cheap and efficient renewable energy sources in industrial applications, since there is currently a growing concern about greenhouse gas emissions and global warming, as well as a decrease in the use of fossil fuels in the commercial sectors. Therefore, it is required to implement green energy systems, in order to reduce over time, the aforementioned needs. Today these energies have already shown favorable results, for example in drying, cleaning, washing, water heating, steam generation, pasteurization and sterilization processes and many other foods processing applications, replacing or substituting other types of energies [1]. Through this article, the focus is to replace the generation process for steam injection in an improved recovery process in an oil field, in order to generate a cost reduction and with a more environmentally friendly bias.

It is intended to initially implement three types of clean energy, in order to demonstrate through simulation, which energy is the most appropriate with respect to the location, which is the one that has the best use with respect to its infrastructure and has better performance. The alternative energies to be simulated are: High Concentration Photovoltaic; Concentration Solar Energy - Direct Steam Linear Fresnel; and Concentration Solar Energy - Dish Stirling; which were chosen for their commercialization that is currently found, this in order to make a comparison between them in the value obtained the Levelized Cost of Energy (LCOE), for it will be shown the development of the simulation in the System Advisor Model (SAM) program taking into account their corresponding specifications in each of them.

The use of technologies that take advantage of the solar resource for applications in oil industry processes was studied, first through the Assessment of use of concentrated solar power technology for steam generation and subsequent injection in a Colombian oil field: An application of solar EOR [2], Approaches for Integrating Renewable Energy Technologies in Oil and Gas Operations [3] and an initiative towards sustainability in the petroleum industry: A review [4]. In the first one a simulation in SAM in a Colombian field with concentrated solar energy (CSP) is carried out, with respect to that an analytical model in improved recovery for the prediction of the oil production rate was made. The second one shows the integration of renewable energy technology, evidencing the reduction of operating costs. The third compared the difficulties that the oil industry is facing with respect to the three spheres of sustainability, social, economic and environmental. This present article intends to simulates three types of solar energy technologies using data of the Colombian field TECA [5], to evaluate and compare the different LCOE results for each technology. Also, it works proceeds a financial analysis, evaluating the CAPEX, OPEX and its corresponding cash flow; calculating the internal rate of return (IRR), net present value (NPV), payback period and benefit cost ratio (BCR).

2. Methods

2.1 Simulation in SAM

The energy generation and financial indicators of three different solar systems will be simulated using the System Advisor Model (SAM), version 2020.2.29. SAM is free software developed for the technical and economic evaluation focused on renewable energy projects and it was developed by the

National Renewable Energy Laboratory (NREL) in collaboration with Sandia National Laboratories and the University of Wisconsin Solar Energy Laboratory (NREL, 2020).

The Levelized cost of energy (LCOE) was calculated in SAM for three different types of energy, which are:

- Photovoltaic High Concentration PV
- Concentrating Solar Power- Linear Fresnel Direct Steam
- Concentrating Solar Power - Dish Stirling

The case study for these technologies is the sector of Puerto Nare, Antioquia – Colombia, for the simulation in the SAM software consisted initially in the configuration of the Locations and resource, where the location was the same in the three case studies.

2.1.1 Photovoltaic High Concentration PV

Initially, the Module page inputs are for the high concentration photovoltaic performance model. For the High Concentration Photovoltaic (HCPV) was proposed a 1 cm^2 area of a module cell, with 20 corresponding cells in a single module and the concentration ratio of 700, which is the ratio of lens area to cell area. For this purpose, the SAM program uses this value to calculate the overall area of the module according to the single cell area and the number of cells you specify.

In the inverter inputs, it is used the Sandia Performance Model for Grid-Connected PV Inverters. This model is an empirically-based performance model that uses parameters from a database of commercially available inverters maintained by Sandia National Laboratory. The parameters are based on manufacturer specifications and laboratory measurements for a range of inverter types. The Sandia model consists of a set of equations that SAM uses to calculate the inverter's hourly AC output based on the DC input (equivalent to the electrical output of the photovoltaic array) and a set of empirically-determined coefficients that describe the inverter's performance characteristics. The equations involve a set of coefficients that have been empirically determined based on data from manufacturer specification sheets and either field measurements from inverters installed in operating systems, or laboratory measurements using the California Energy Commission (CEC) test protocol. Because SAM does not track voltage levels in the system, it assumes that for each hour of the simulation, the inverter operates at the photovoltaic array's maximum power point voltage, given the solar resource data in the weather file for that hour. The inverter single-point efficiency model calculates the inverter's AC output by multiplying the DC input (equivalent to the array's DC electrical output) by a fixed DC-to-AC conversion efficiency that you specify on the Inverter page. Unlike the Sandia inverter model, the single-point efficiency model assumes that the inverter's efficiency does not vary under different operating conditions [6] [7].

For the Array configuration, the Concentrating Array page displays inputs for the high concentration photovoltaic (HCPV) performance model and assumes that HCPV modules are mounted on 2-axis trackers, and calculates tracking power consumption based on the tracking power that specify; it was chosen 20 trackers and 150 modules per tracker have been taken into account and in the stowage the maximum allowed value of wind speed in front of these is 11m/s.

Finally, the financial and operational parameters were configured. A system capacity of 1,126.66 kW, a capital cost of 5000 USD/kW, and a fixed operating cost (annual) of 66 US/kW were sized. For the calculation of the LCOE (Levelized Cost of Energy), 25-year financing was assumed with an inflation rate of 2.5% per year and a nominal internal rate of return of 13% per year.

2.1.2 Concentrating Solar Power- Linear Fresnel Direct Steam

Initially, for the Solar Field, SAM provides two options: option 1 (multiple solar mode), SAM calculates the total aperture required and the number of loops based on the entrance value for the solar multiple and the option 2 (field aperture mode), calculates the solar multiple based on the field aperture entrance value. In this case, option 1 is almost chosen. The configuration of a CSP plant is best described by the so-called Solar Multiple (SM) [8].

In the Solar Filed the following parameters were used as shown in Table 1, where the irradiation design point is the one that reaches the thermal output including thermal and piping losses. This value is the position of the sun at noon in the summer solstice. The solar multiple is required to satisfy the thermal load and the field inlet temperature and the field outlet steam quality [2].

Table 1. Design Point Parameters

Design point irradiation	950 W/m^2
Solar multiple	1,8
Design point ambient temperature	42°C
Loop flow configuration	Recirculated boiler
Number of modules in boiler section	12
Number of modules in superheater section	4
Field inlet temperature	230°C
Field outlet temperature	440°C
Boiler outlet steam quality	0,65

Source: The Authors.

Among the Table 1, it should be noted that the reference ambient temperature for the solar field is used as the basis for calculating the thermal losses of the receivers and pipes. Also, the loop flow configuration determines whether the boiler is configured as once-through or recirculated. In the recirculated boiler design, a portion of the collectors in the loop are dedicated to boiling the subcooled feedwater, but the boiler mass flow rate is controlled such that the boiling mixture exits the boiler section with a vapor fraction (quality) equal to the specified value in the Boiler outlet steam quality input on the Solar Field page. The liquid fraction is extracted and recirculated to the inlet of the solar field loop where it mixes with the subcooled liquid from the power cycle outlet. The saturated steam at the outlet of the boiler section does not recirculate, but instead passes into the dedicated superheater section where it continues to increase in temperature before entering the power cycle [9]. The most used configuration in these systems is the recirculated boiler design, although developments in technology show that the single pass design is favorable.

The solar position table was chosen for the collector and receiver, as it allows specifying the optical efficiency of the solar field as a function of the azimuthal and zenith solar angles. The zenith solar angle is zero when the sun is directly overhead and 90° when the sun is on the horizon, with a reflective aperture area of 513,6 m^2 and length of collector module of 44,8 m. The solar position may contain any number of rows and columns, but should contain enough information to fully define the performance of the solar field at all sun positions for which the field will operate [10].

In the power cycle, in the design plant tab, it hats the qualified cycle efficiency, where it is defined as the thermal to electrical conversion at design conditions, where it has a value of 0.371 and respectively SAM models the partial load behavior with normalized performance curves as a function of steam inlet temperature, mass flow rate and ambient temperature.

Finally, the financial and operational parameters were configured. A system capacity of 6,000.00 kW and with the same data used in the first solar energy simulation.

2.1.3 Concentrating Solar Power – Dish Stirling

The solar field is assumed to be a rectangular field with collectors oriented north-south and east-west [8]; initially for the field layout, 50 collectors were used from North to South with a separation of 15 m and 80 collectors from East to West with the same separation. The SAM program uses the number of collectors and the distance of them to determine the area of the solar field, the shading factor and the distance of the pipes, also calculating the pumping losses. In addition, the total surface of the mirror is 91 m^2 and this is the reflected parabolic surface.
The receiver absorbs thermal energy from the parabolic concentrator and transfers the energy to the working fluid of the Stirling engine. Stirling engine consists of an aperture and an absorber. The receiver aperture is located at the focal point of the parabolic concentrator. SAM models a type of direct illumination receiver, in which the solar radiation is absorbed directly by absorber tubes containing the working fluid; these are the most commonly used in this system. [11] In relation to the receiver, there are four important factors: first, the Receiver Aperture Diameter, with a value of 0.0184; second, the insulation thickness 0.075 m; third, the Absorber Surface Area with the adopted value of 0.6 m^2; and finally, the Cavity Surface Area with the value of 0.6 m^2. The receiver aperture diameter allows solar radiation to reach the absorber and also, that the radiation convection losses to escape from the receiver cavity. The thickness is required to calculate conduction losses and the absorber surface area. The cavity surface area is used to calculate the internal cavity area.

The Stirling engine converts heat from the receiver's absorber to mechanical power that drives an electric generator [11]. Generally, a single unit Nameplate Capacity of 25 kW is used, where the engine parameters of heater Head Set Temperature are 993 Kelvin and heater Head Lowest Temperature is 973 Kelvin.

By means of the simulator, the reference condition parameters are used in an iterative process to calculate the total collector error for a given set of values for the aperture diameter, the focal length, and collector diameter. With the error, a new intercept factor is calculated for different aperture diameters [11]. The reference inputs are divided into three sections, being the first two will be explained and the third one is Parasitic Variable which the SAM program gives the parameters of the reference conditions and the other two sections are shown below.

1. Collector Reference Condition Inputs: it has the intercept factor with a value of 0.995, which is the fraction of energy reflected by the parabolic mirror that enters the receiver aperture and the mirror focal length of 7.45 m (7.45 ft).

2. Receiver Reference Condition Inputs: is has an aperture diameter of 0.184 m and a Receiver Temperature Delta (DIR Type) of 90 Kelvin.

Finally, the financial and operational parameters were configured as previously mentioned, as a proposed system capacity of 100,000.00 kW.

2.2 Financial Analysis

A financial analysis was carried out to determine the profitability of each alternative energy in the medium term (5 years), in order to see which of the three alternatives would be the best.

Initially the CAPEX was determined, the first value is the 5000 USD, where these were pre-determined in the SAM program in order to perform the simulation and then for the assembly of each corresponding system according to the energy, it is recommended to hire four construction technicians, where these will take approximately 6 months, therefore a salary was calculated for each one during that time, taking into account all its parameters required by Colombian law. Finally obtaining a value of 14,325 USD.

Having the CAPEX, we proceeded to the OPEX where for the development it is recommended that two operators work in shifts in the system and for safety reasons be assisted by a technician, so in case of any emergency or breakdown. Taking into account the above, an OPEX of 1 927.06USD was determined.

Finally, it proceeds to determine the corresponding indicators in order to evaluate their viability, where through these financial tools we can make a decision to invest. The indicators to be used are as follows:

- The internal rate of return (IRR)
- Net present value (NPV)
- The payback period
- The benefit cost ratio (BCR)

3. Results and discussion

After having carried out the three simulations in the program SAM, by means of the previous methodology mentioned in the Colombian field TECA, we proceed to evidence the revealing results and their behavior during a year

Initially we have the Photovoltaic High Concentration PV energy, where the results can be seen in Table 2.; which are the kWh per year, the capacity factor in the first year, that means the ratio of the system's predicted electrical output in the first year of operation to the nameplate output and the levelized cost or energy, that is the total project lifecycle cost expressed in cents per kilowatt-hour of electricity generated by the system over its life; and also for the other alternative energies.

Table 2. Results for Photovoltaic High Concentration PV Energy

Metric	Value
Annual energy (year 1)	1,226,874 kWh
Capacity factor (year 1)	12.4%

Levelized cost of energy	0.44¢/kWh

Source: The Authors.

Figure 1 shows the energy production in the different months, where it can be seen that between November and December there will be a better performance with values between 120000 to 140000, unlike the other months, although it should be noted that in most of the months more than 80000kWh is produced, so it can be supplied.

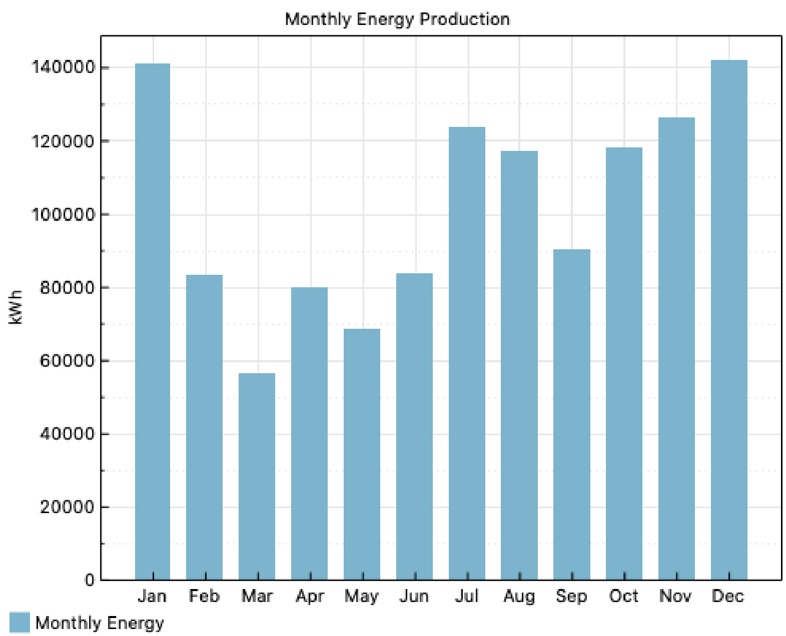

Figure 1. Monthly Energy Production- Photovoltaic High Concentration PV
Source: The authors

Figures 2 show the power generated by the system in all months, as mentioned above, in January, November and December there are high values, although in July and August there are values equal to or slightly higher than those of the other months, although there is a decrease in the middle of the month, this may be due to the fact that in the previous months there has not been a good performance and the efficiency module % has a behavior similar to this.

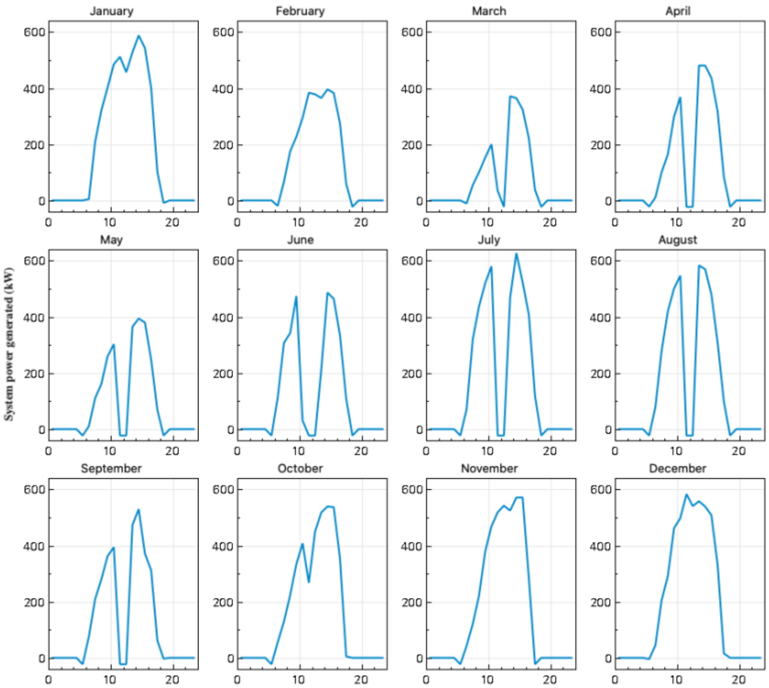

Figure 2. System power generated (kW)
Source: The authors

Energy generated using solar panels that take advantage of the photovoltaic effect is a clean and efficient way to use one of the most abundant renewable sources in our universe. [12]. In addition, it could be observed that its behavior is highly good and also that its efficiency, that is because a photovoltaic system of high concentration was used, which has more performance unlike the one that has no concentration, it should be noted that this depends on the location.

Likewise, this is a young energy, which currently has already been implemented in 133 countries and its growth is increasing every day due to its competitiveness in relation to other energy sources, in 2014 systems of this technology have already been presented, where it is seen that its LCOE value is much cheaper at a price of kWh than a domestic value supplied by the electricity supplier. [13]

Then there is the Concentration Solar power - Linear Fresnel Direct Steam, where in table 3 shows the corresponding results.

Table 3. Results for Concentration Solar power - Linear Fresnel Direct Steam

Metric	Value
Annual energy (year 1)	167,564,176 kWh
Capacity factor	19.0%
Annual Eater Usage	20,355 m^3
Levelized cost of energy	0.40¢/kWh

Source: The Authors.

Figure 3 shows the field thermal efficiency for each month, where the highest value obtained would be in July and the lowest in May, although the May value is approximately 2/3 of the highest value obtained.

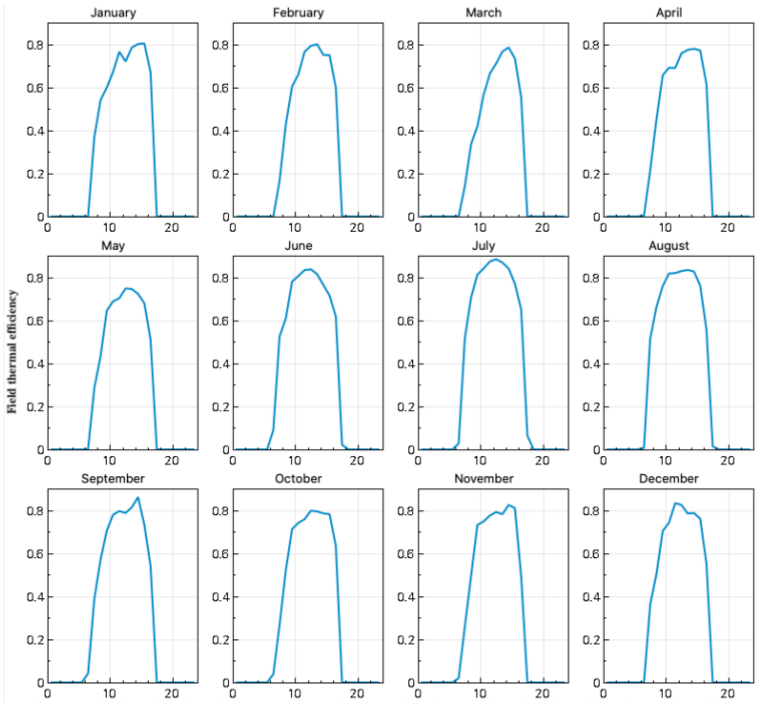

Figure 3. Field thermal efficiency
Source: The authors

Figure 8 also shows the power generated by the system (kW), which presents a similar behavior, due to the fact that the efficiency of the thermal field helps in the system.

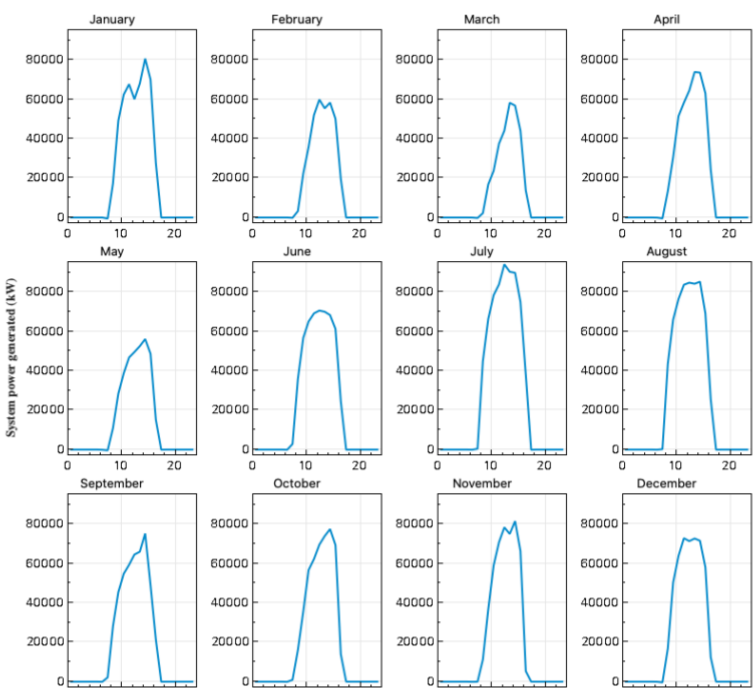

Figure 4. System power generated (kW)
Source: The authors

Produce superheated steam for industrials process has been presented as one of the main advantageous applications of Concentrated Solar Power (CSP) plants particularly Linear Fresnel Concentrator (LFC) [14]. It can be seen in the results, that it does not present drastically falls unlike the previous technology mentioned, otherwise it has a stable behavior over the months, in addition, it is about maintaining approximately the same range in most of the months.

Finally, there is the Concentrating Solar Power - Dish Stirling, where the following results are shown in the table 4.

Table 4. Results for Concentrating Solar Power - Dish Stirling

Metric	Value
Annual energy (year 1)	125,295,264 kWh
Capacity factor (year 1)	14.3%
Levelized cost of energy	0.40¢/kWh

Source: The Authors.

Figure 5 shows that the highest energy production was in the month of July; In the same way, the same behavior is presented with respect to energy production, where it can be observed that July has a better performance with a value greater than 60,000, unlike the other months and the lowest values are between February and March, although after these months there is a growth to reach the range of the month of July.

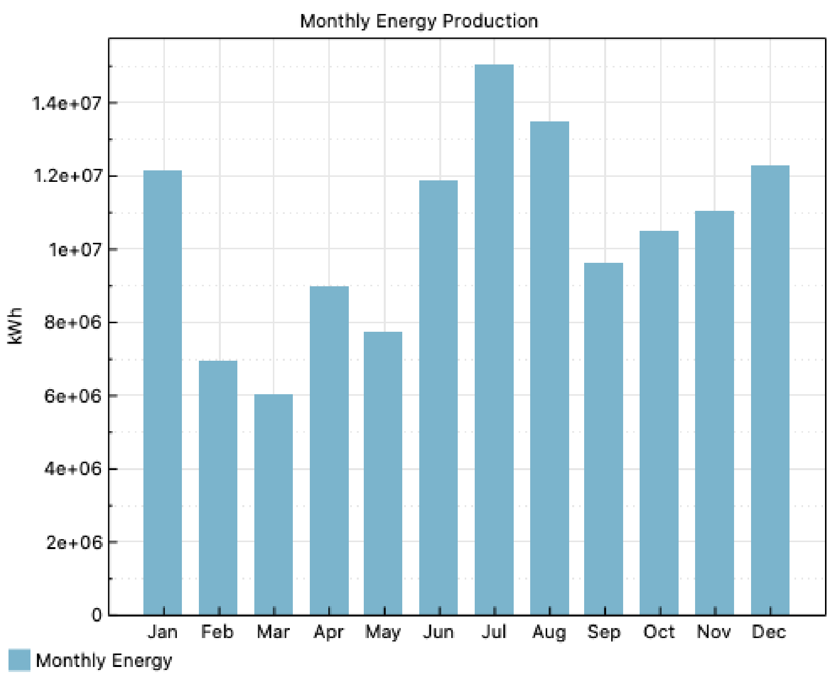

Figure 5. Monthly Energy Production
Source: The authors

Regarding the efficiency of the collector over the months, each month presents a number of ups and downs, however its behavior always tends to remain homogeneous at high values; this gives us to understand that the efficiency can be considered relatively good.

The Solar Dish-Stirling Systems (SDSS) have been successfully developed for fulfilling electrical power and heat for high-temperature applications. [15] Although in general, these systems are highly attractive, due to their environmental impact and their infrastructure, they are currently not highly marketable. Therefore, more efforts are required to promote the viability of your commercial applications, thereby increasing global demand while dropping the costs of new installations.

Observing the behavior of the three simulated energies in the SAM program, we have two energies, which are Stirling Solar Power Plate Concentrator and Direct Linear Fresnel Steam with the same LCOE value with a value of 0. 40 ¢ / kWh, difference that one of these would have to be chosen, it would be the Annual Energy, which in this case for Linear Fresnel has a higher value per kWh. For this it would be better, although these two energies have a good behavior and a stable efficiency throughout the months, making them profitable and favorable for an adequate supply.

For the financial analysis in the first instance, summary tables were previously shown for each alternative energy, where the annual kWh capacity is found, it should be noted that this capacity is the maximum that the system can produce, it is known that electricity is constantly being produced and for its best use is due to the utilization systems, the three clean energies have a high capacity, where it favors us, where this project would only use the energy needed to heat water, where it would be used for steam injection to an oil field. The second value is the capacity factor, which is equivalent to the quantity of energy the system would generate if it operated at its nameplate capacity for every hour of the year. In the case of the linear Fresnel system, we have an additional data which is Annual water Usage, where SAM reports the total annual water consumption in cubic meters for cooling and mirror washing. And finally, we have the LCOE value for each energy, this value is calculated by the SAM program, taking into account different parameters such as capital cost, operating and maintenance costs.

Initially, the possible income per year was calculated taking into account the value that each initial kWh is worth compared to the market price, thus obtaining the income per year. Taking this income and the OPEX, the profit per year was obtained through the 5 years with its percentage of inflation. The values can be observed in the following table.

Table 5. Utility during the 5 years

Year	Utility
0 (CAPEX)	-$ 14,325
1	-$ 14,325
2	$ 4,696
3	$ 5,281
4	$ 5,903
5	$ 6,566

Source: The Authors.

Then the Internal Rate of Return (IRR) was performed, where a value of 27.8% was obtained, which means that it is greater than 5% (market IRR). Following the net present value (NPV) with a value greater than 0 and the benefit-cost relation with a value of 1.40, these three parameters show that the project is viable, because it would be more fruitful to invest in this project than in the market current, higher income will be obtained with respect to your expenses, therefore its payback period is approximately 34 months, which makes it profitable with respect to the years.

4. Conclusions and recommendations

With concentrated solar power, either Linear Fresnel Direct Steam or Dish Stirling, you get the same lower LCOE value compared to high concentration photovoltaics, although the maximum capacity of the three are different, all three have the required minimum capacity.

The project has an approximate payback period of 34 months, and also has low costs relative to revenues.

The three energies present a good performance in their system in the area of the TECA Field, it can be observed that its location is very favorable.

A high energetic capacity is obtained; therefore, it is recommended the installation of an electric system for the oil field, in order to supply light or other options to reduce costs.

The implementation of solar energy, in order to generate steam for injection into the oil field in an improved recovery process in the TECA oil field will increase sustainability, reduce pollution, avoid excessive use of fossil fuels and also provides the option to implement other systems in order to have a better use of energy.

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LUISA MARÍA CADENA TRIANA, MARIANA CAMPOS PADILHA LOPES, LAURA GUERRERO MARTIN, ERIK MONTES PÁEZ, CAMILO GUERRERO MARTIN

We here by introduce the manuscript entitled: " **Simulation and financial assessment of three types of solar energy for the generation of steam.**" for the consideration of the Editorial Board. The manuscript´s authors are LUISA MARÍA CADENA TRIANA, MARIANA CAMPOS PADILHA LOPES, LAURA GUERRERO MARTIN, ERIK MONTES PÁEZ, CAMILO GUERRERO MARTIN.

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Below, (in no more than 5 lines) the innovative topic of the article is shown: (different to the summary included in the article):

In the article, a simulation was carried out in the SAM System advisor Model program of three alternative energies, which are high concentration photovoltaic, concentrated solar energy - direct linear Fresnel steam and Stirling dish; in order to generate steam for the implementation of an improved recovery process in an oil field and also a financial evaluation through different parameters that demonstrate its profitability and sustainability.

Sincerely

Signed (Author 1): Luisa María Cadena Triana

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Signed (Author 3): Laura Guerrero Martin

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MAIN AUTHOR

Names and surnames: Luisa María Cadena Triana
Institutional filiation: Fundacion Universidad de America
Cell phones: +57 3142315898
Institutional e-mail: Luisa.cadena@estudiantes.uamerica.edu.co
Personal e-mail: Lu.mariatriana@gmail.com
Postal address: 110016
Country: Colombia City: Bogotá, DC state/province: Cundinamarca

Co-author

Names and surnames: Mariana Padilha Campos Lopes
Institutional filiation: Post-doc at Electrical Engineering Program, Federal University of Rio de Janeiro, CT, I-156, Cidade Universitária, Rio de Janeiro, RJ, Brazil
Fixed telephone numbers: Ext: (55) (21) 3938 8637 Fax: (55) (21) 3938 8638
Cell phones: +55 (21) 981222619
Institutional e-mail: mariana.padilha@ppe.ufrj.br
Personal e-mail: mariana.padilha10@gmail.com
Postal address: Centro de Tecnologia, bloco I, sala I - 156, Cidade Universitária - Rio de Janeiro - RJ - Brasil, CEP: 21.949-900
Country: Brazil City: Rio de Janeiro, state/province: RJ

Co-author

Names and surnames: Laura Estefanía Guerrero Martín
Institucional filiation: Universidad Distrital Francisco José de Caldas
Cell phones: +57 3118148017
Institutional e-mail: leguerrerom@correo.udistrital.edu.co
Personal e-mail: g.laura05@hotmail.con
Postal address: 10001
Country: Colombia City: Bogotá, DC state/province: Cundinamarca

Co-author

Names and surnames: Erik Montes Páez
Institutional filiation: Universidad Industrial de Santander
Cell phones: +57 300 427 7634
Institutional e-mail: erimonpa@uis.edu.co
Postal address: 680006
Country: Colombia City: Bucaramanga state/province: Santander

Co-author

Names and surnames: Camilo Andrés Guerrero Martin
Institutional filiation: Fundacion Universidad de America
Cell phones: +57 321 420 7332
Institutional e-mail: camilo.guerrero@profesores.uamerica.edu.co
Personal e-mail: camilo.guerrero@poli.ufrj.br
Postal address: 10001
Country: Colombia City: Bogotá, DC state/province: Cundinamarca

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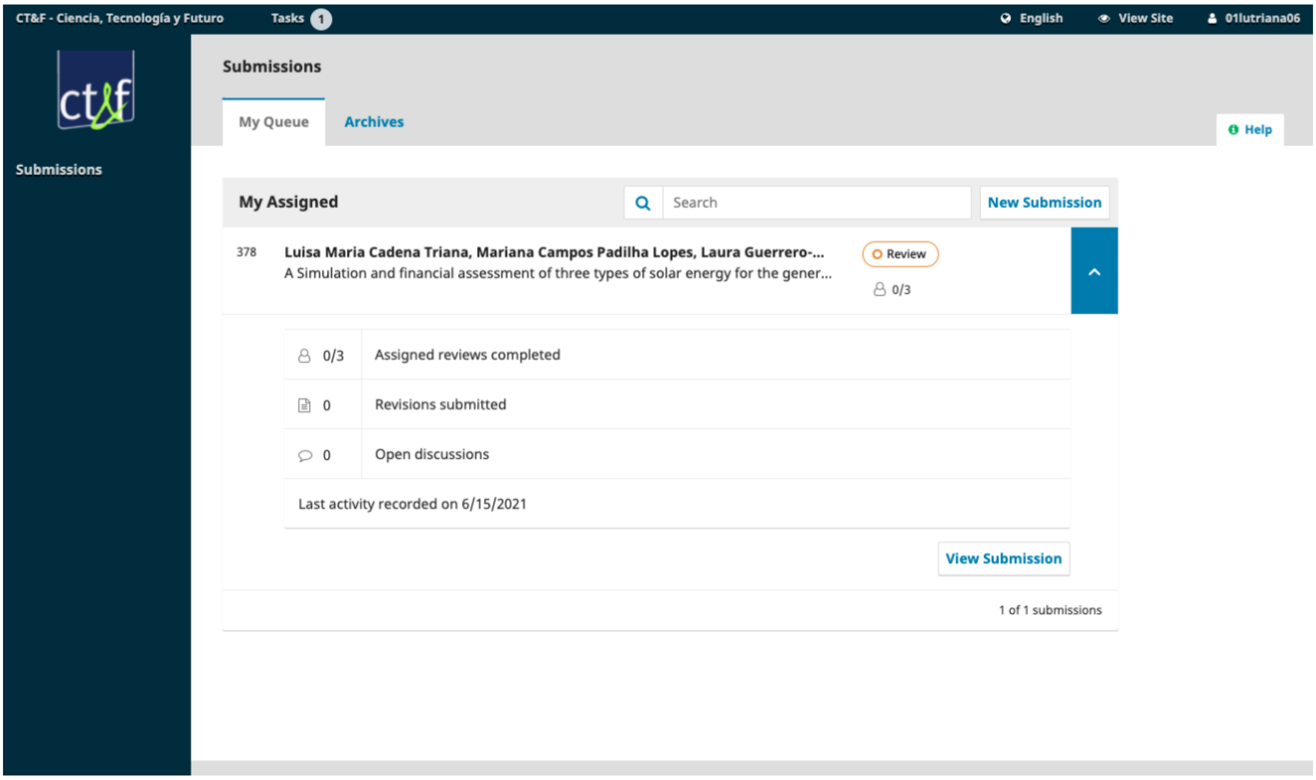
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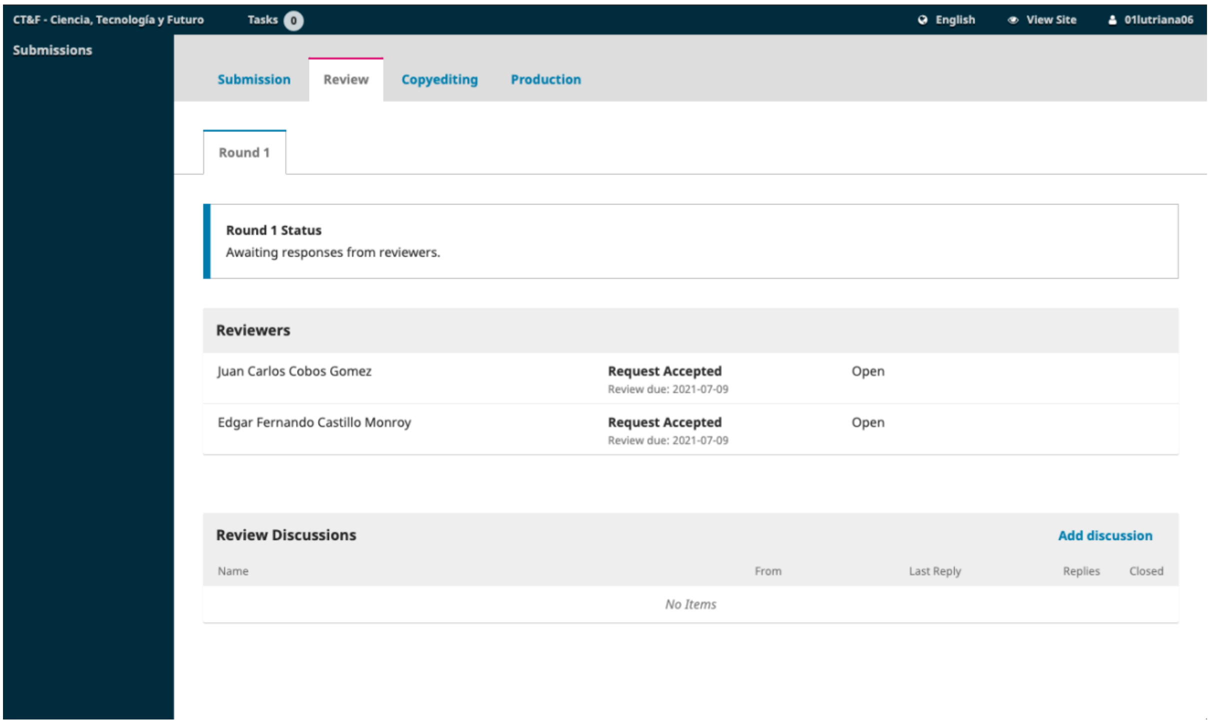
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