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A Predictive Performance of Future Central Tower Receiver and Linear Fresnel Solar Thermal Power Plants in Algeria

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Abstract*-- This paper gives a methodology and procedure to determine the optimum design and configuration of future solar thermal power plants with minimum levelized cost of electricity (LCOE) and maximum annual electricity output using different models, technologies and scenarios in Hassi R'mel City, in the south of Algeria for given capacity (50MW). In this methodology, the size of the solar field, the Fossil Fill Fraction of hybridization and Full Load Hours of storage are optimized for the minimum LCOE using the concept of solar multiple. Moreover, different models for Linear Fresnel, and Central Tower Receiver Solar Thermal Power Plant have been developed and presented .LCOE presents a basis of comparison for weighted average costs of different power generation technologies. This concept [1]allows the accurate comparison of different technologies, but sometimes it became insufficient, so it's necessary to use other factors like efficiency of plant, economic analysis (total installed cost). With all this background, and making use of SAM (System Advisor Model) tool, the Central Tower Receiver Solar Thermal Power Plant with 48% of hybridization and 8 hours of storage is the best attractive and optimum plant design.

***Keywords* -- Central Tower Receiver; Cost of Electricity; Linear Fresnel Plant; Solar Multiple; Thermal Energy Storage.**

Nomenclature

CSP	Concentrating Solar Power
RES	Renewable Energies
FNERC	National Fund of Renewable Energy and Cogeneration
DNI	Direct Normal Irradiation
NREL	National Renewable Energy Laboratory
TMY3	Typical Meteorological Year 3
HTF	Heat Transfer Fluid
TES	Thermal Energy Storage
SM	Solar Multiple
FFF	Fossil Fill Fraction
CF	Capacity Factor
FLH	Full Load Hours
CTRSTPP	Central Tower Receiver Solar Thermal Power Plant
TIC	Total Installed Cost
LCOE	Levelized Cost Of Electricity
SAM	System Advisor Model
NPV	Net Present Value

I. Introduction

It is universally acknowledged that two of the key technological and economic challenges of the 21st century are energy and the environment **[1].** Consequently, considerable efforts are being made to effect a gradual transition from systems based on fossil fuels to those based on renewable energies. Electricity generation from solar energy is currently one of the main research areas in the field of renewable energy. To extract electricity from solar radiation, the power plants use the technology of solar concentration. Concentrating solar power (CSP) technologies now constitute feasible commercial options for large scale power plants as well as for smaller electricity and heat generating devices. CSP has an inherent capacity to store heat energy for short periods of time for later conversion to electricity. When combined with thermal storage capacity, CSP plants can continue to produce electricity even when clouds block the sun or after sundown. CSP plants can also be equipped with backup power from combustible fuels [**2-3**]. With these factors, CSP is set to take its place as an important part of the world's energy mix, such as Algeria, notably with the National Plan of Renewable Energies Development and Energy efficiency. In this ambitious program, CSP plants represent about 70% of the total power to be installed [**4-5**]. Moreover CSP can be a competitive source of bulk power in peak and inter mediate loads in the sunniest regions by 2020 and of base load power by 2025 to 2030 **[6].**

The utilization of CSP isn't limited to electricity production but it can be used in several ways as hydrogen production. The development of the methods of hydrogen production based on

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renewable energy sources takes place as much as possible without releasing the greenhouse gas [**7**].Fig 1 shows The different techniques involved for the production of hydrogen from solar origin, and in all these techniques three things must be taken into consideration: The raw material, the energy necessary for the production and the process of production. For most of the processes, there exist relatively many important variants [**8**].

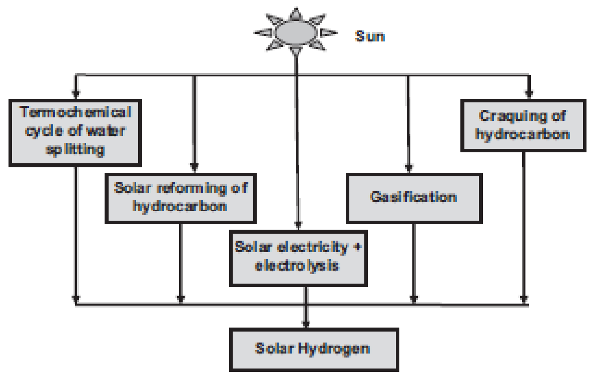


Fig 1: the techniques production of hydrogen from solar energy [**8**]

A. *New Policy and incentives*

The implementation of this program benefits from substantial and multifaceted contribution of the State intervening mainly through the National Fund for Renewable Energy and Cogeneration (FNERC), supplied by a levy of 1% of oil royalties. An incentive mechanism based on feed-in tariffs is established by regulation. Thus, the producer of renewable energy enjoys purchase tariffs which are guaranteed for a period of 20 years for photovoltaic installations and wind power. The sectors not covered by the guaranteed purchase price will be financed by FNERC for 50% to 90% of the investment cost according to the selected technology and industry **[9-10].**

B. *Objectives of the study*

Sensitivity analysis of LCOE, CF, and annual energy to SM, FFF and FLH) for plant models with 50MWe , for each technology with different scenarios have been simulated using SAM software, in order to determine optimum plant configuration in Algeria with minimum LCOE and maximum annual energy.

II. Methodology

A. *Off-design model description*

In this work, the selected location is Hassi R'mel (ALGERIA); weather data of this location, such as DNI and ambient temperature are taken from NREL database; an hourly timeframe is selected due to TMY3 standard format. Table I shows parameters of our site.

Table I.

Hassi R'mel location Parameters **[11]**

Parameters	Values
Latitude (*Degree*)	33.8
Longitude (*Degree*)	3E
Altitude (*m*)	776
Climate	Tropical
Direct Normal Irradiation (DNI) kWh/m2	2008.4

B. *Design parameters*

B.1.Solar field sizing and design requirements

The components of CSP plants should have an optimized design to better fit with HTF, Thermal Energy Storage (TES) system, and parameters of solar field, storage and power block. Then, to provide the required heat storage capacity, the solar field (i.e. mirrors and heat collectors) of the CSP plant must be oversized with respect to the nominal electric capacity (MW) of the plant. Thus, from a technical point of view, design requirements are the solar multiple factor, Fossil Fill Fraction of hybridization, capacity factor (efficiency), and storage system capacity (Full Load Hours).

- The solar multiple is the ratio of the actual size of the solar field to the solar field size needed to feed the turbine at nominal design capacity with maximum solar irradiance (about 1 kW/m2) **[12].**
- The capacity factor is the ratio of the system's predicted electrical output in the first year of operation to the nameplate output, 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.

- Full Load Hours is the number of hours that the storage system can supply energy at the power block design turbine input capacity
- Fossil Fill Fraction is a fraction of the power block design turbine gross output that can be met by the backup boiler. It used to calculate the energy from the backup boiler.

B.2.Mathematical models

B.2.1 Levelized Cost Of Electricity (LCOE)

The method of LCOE makes it possible to compare power plants of different generation and cost structures with each other. The basic thought is that one forms the sum of all accumulated costs for building and operating a plant and comparing this figure to the sum of the annual power generation. The calculation of the average LCOE is done on the basis of the net present value method, in which the expenses for investment and the payment streams from earnings and expenditures during the plant's lifetime are calculated based on discounting from a shared reference date **[13].** For calculating the LCOE for new plants, the following applies **[14]:**

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}} \qquad (1)$$

Where:

LCOE Levelized cost of electricity
I_0 Investment expenditures
A_t Annual total costs in year t
$M_{t,el}$ Produced quantity of electricity in the respective year in kWh
i Real interest rate in %
n Economic operational lifetime in years
t Year of lifetime (1, 2, ...n)

Annual total costs At= Fixed operating costs + Variable operating costs (+ residual value/disposal of the plant).

B.2.2 Net Present Value (NPV)

A project's net present value is a measure of a project's economic feasibility that includes both revenue and cost.

The NPV is the present value of the after tax cash flow discounted to year one using the nominal discount rate [**15**]:

$$NPV = \sum_{n=0}^{N} \frac{C_{Aftertax,n}}{(1+d_{nominal})^n} \qquad (2)$$

Where

$C_{\text{After Tax}}$ is the after tax cash flow in Year *n*,
N is the analysis period in years.
d_{nominal} is the nominal discount rates.

C. Plants optimization (configurations, technologies, models and scenarios)

The optimization method used in simulation that is integrated in SAM software. Different configurations have been chosen for all plants based on loop flow configuration (once trough, recirculated boiler), condenser type (wet cooling: evaporative, dry cooling: air cooled), and receiver type (external, cavity), in order to determine the optimum configuration, for different models:

- Model 1(**M1**): solar field only (without storage and without hybridization).
- Model 2 (**M2**): integration of hybridization (without storage).
- Model 3 (**M3**): integration of solar thermal storage STE (without hybridization).
- Model 4(**M4**): integration of hybridization and STE.

Table II shows these configurations and scenarios:

Table II
Overview of proposed technologies and scenarios of proposed models

CSP technology	**Technology options and configuration**	**scenarios**
LFSTPP	T1: Superheated steam as HTF T2: Saturated steam as HTF	S1:wet cooling and recirculated boiler configuration S2: dry cooling and recirculated boiler configuration S3: wet cooling and once trough configuration S4: dry cooling and once trough configuration
CTRSTPP	T1: Molten salt as HTF and external receiver T2: Molten salt as HTF and cavity receiver	S1: wet cooling S2: dry cooling

D. Financial data

The base case scenario represents the anticipated financial terms for the investment in normal conditions with no incentives provided by the government.

In all models, plants have been simulated by base case financial scenario, and the fixed financing parameters for base case scenario used in simulation are given in table III.

Table III
Fixed Financing Parameters **[16]**

Financing data	**value**	**unit**
Base Case		
Analysis Period	30	*years*
Loan Term	20	*years*

Loan Rate	8	*%/year*
Inflation Rate	8.9	*%/year in 2013*
Real Discount Rate	4	*%/year in 2013*
Nominal Discount Rate	13.26	*%/year*
Minimum Required IRR	12	*%*
Assessed Percent	80	*% of installed cost*
Insurance Rate	0.30	*% of installed cost*
Sales Tax	5	*% of installed cost*
State Income Tax Rate	15	*%/year*

III. RESULTS AND DISCUSSION

In these sections, and using the input parameters of **table III**, sensitivity analyses of CF, LCOE, and annual energy delivered from plants with and without storage and hybridization for capacity of 50MW, with different configurations and scenarios of table II have been optimized by changing SM, FFF of hybridization and FLH of storage. The simulation was done with a project’s lifetime of 30 year, as estimated by most studies **[17-18]**. Moreover, an inflation rate of 2,5%/ year was used in the economic calculations and with no incentives provided by the government(base case). In addition, the process for defining the system design follows the general procedure: first define the fixed design-point parameters, then fixe design gross output, finally parametrically optimize the solar multiple.

A. Sensivity analysis of collector‘s and receiver’s geometry

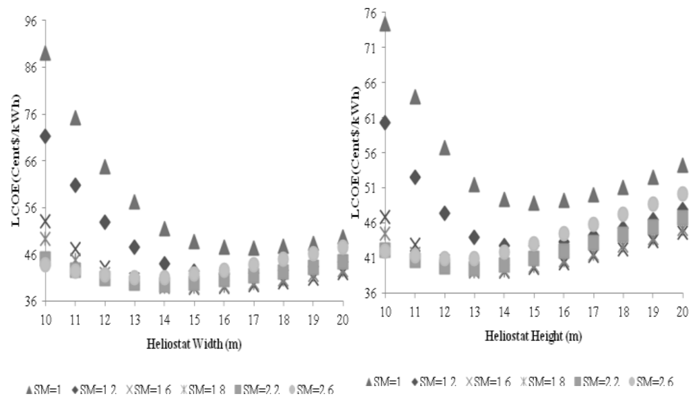
Unlike parabolic system designs, which can be based on modular designs of individual components, central tower receiver system designs require optimization of the tower height, receiver and heliostat geometry, Similarly linear Fresnel system designs require optimization of total aperture area, and length of collector.

. Based on these, the optimal geometries of collector and receiver have been determined for CTRSTPP and LFSTPP.

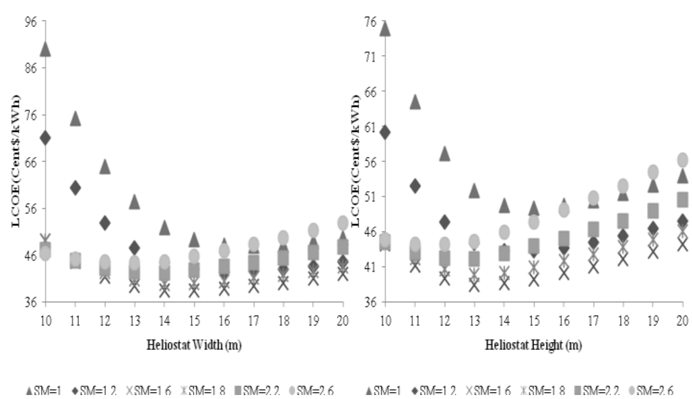
Fig 2 shows the effect of heliostat’s size on LCOE with different values of SM for different technologies and scenarios. The shape of heliostat chosen is rectangular due to its maximum ground coverage of 58% than other shapes. Then a span angle equal to 120° is chosen for cavity receiver and 360° for external receiver. In addition, the optimal distribution of heliostats is done by optimal technology (optimization wizard) used in SAM software, and heliostat’s width and height are simulated for range from 10 to 20 m. The results show that LCOE decreases when heliostat field (SM) and length of heliostat increase because the energy produced increases due to the big amount of flux reflected on receiver, and it is clear that increasing SM beyond two is only marginally beneficial .The optimum SM is 1.6 for all technologies and scenarios corresponding to heliostat width of 15m. Concerning the heliostat height, for cavity receiver is 13m, and for external receiver is 14m, but LCOE is lower for cavity receiver.

From **Fig 3** which corresponds to LFSTPP, it was found that LCOE decreases with increasing length of collector and reflective aperture area until SM=2, beyond this value, LCOE returns to increase. Then, it can be seen that the optimal SM, length of collector and RAA are same for all technologies and scenarios, and are respectively 1.9, 30 m, 540 m2.

Finally, the optimum plant with optimum designs is T2-S1 (cavity receiver and wet cooling technology), with 18m and 18.4m of width and height for receiver respectively.



(a)



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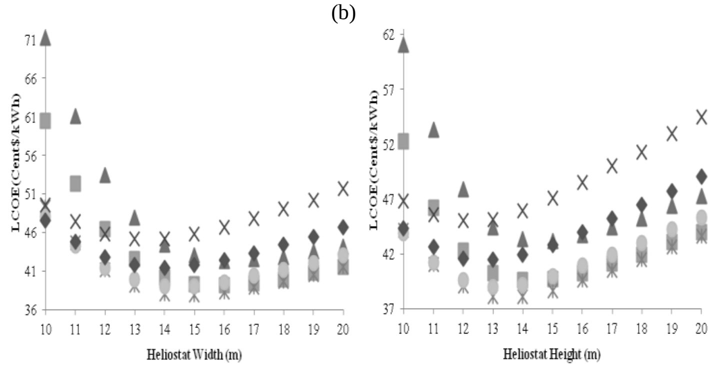

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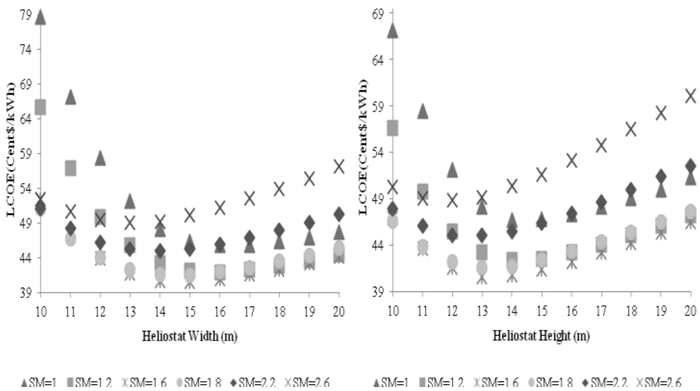
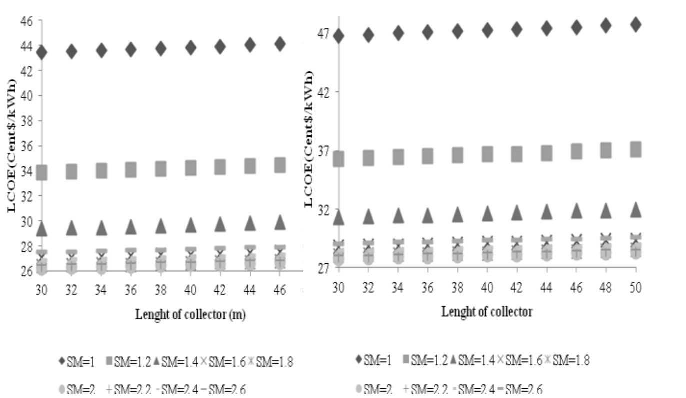
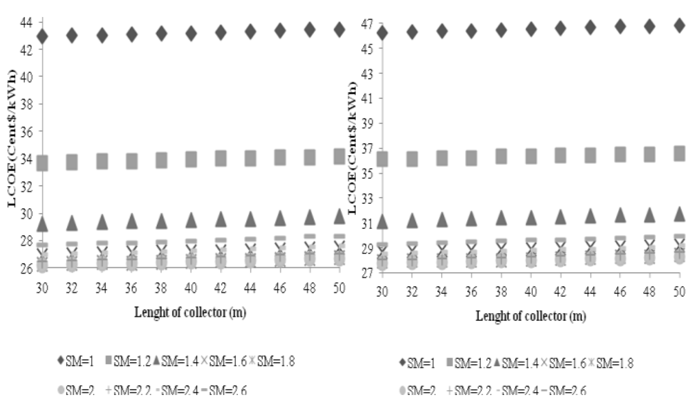


(d)

Fig 2: Optimum collector’s geometry for CTRSTPP

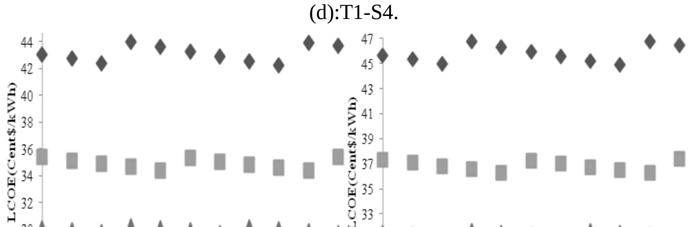


(a) (b)



(c) (d)

Fig3.1 .Optimum length of collector; (a): T1-S1 ;(b):T1-S2; (c):T1-S3; (d):T1-S4.



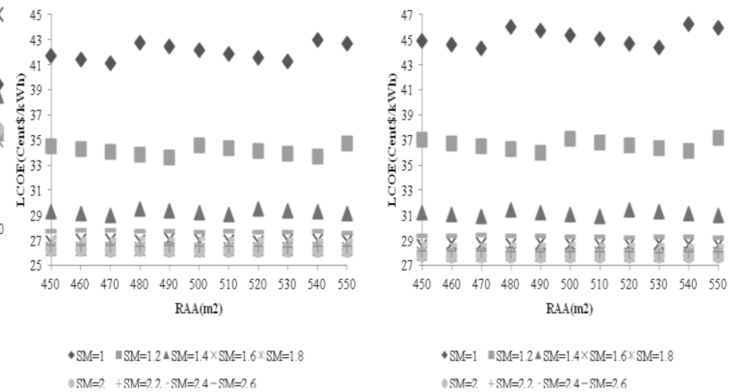


Fig.3.2: Optimum reflective aperture area of collector; (a): T1-S1;(b):T1-S2; (c):T1-S3; (d):T1-S4.

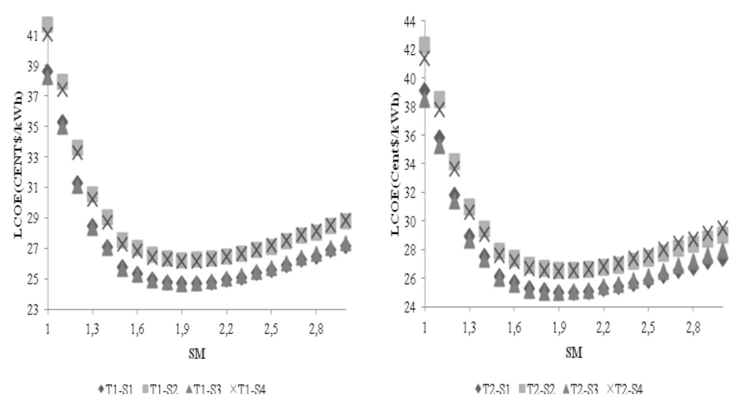
Fig3: Optimum collector’s geometry for LFSTPP

B. *Model 1: solar field only (no storage and no hybridization)*

Using the optimum parameters of section A for different plants, effect of solar field (SM) on efficiency (CF), and levelized cost of electricity (LCOE) have been simulated for solar field only without storage and without hybridization, and for different technologies and scenarios. Then the optimum configurations have been obtained and given in **table IV**, for each plant with low LCOE and optimal SM.

Fig 4, 5 show these effects for LFSTPP and CTRSTPP respectively. From these figures, it is clear that LCOE decreases with increasing SM until optimal value, which net electricity generated is higher than life cycle cost, beyond this value LCOE increases due to high investment and maintenance costs of large solar field of plant.

Concerning efficiency increases with increasing SM according to high thermal energy dumping from large solar field.



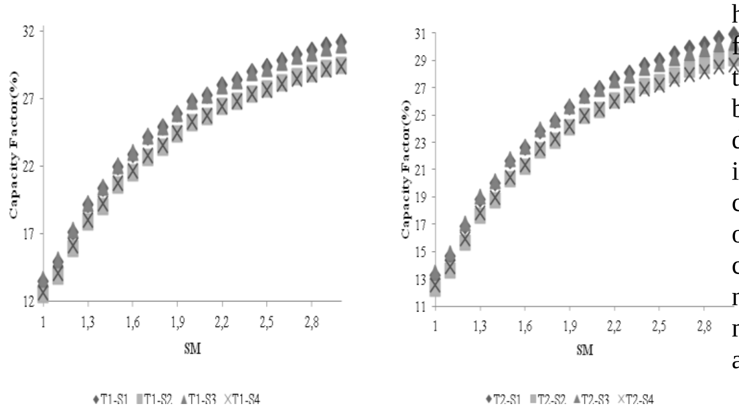


Fig.4**:** Effect of SM on LCOE and CF of M1 for LFSTPP

C. Model 2: solar field and hybridization (no storage)

In this section, we have determined the effect of hybridization on performances of optimum plants of Model 1 for different values of FFF. From **fig 6and 7**, it can be seen that the effect of hybridization began seen beyond FFF=0.2 for both plants. Moreover, LCOE decreases when increasing FFF, due to enough thermal energy produced, but it increases with increasing SM. In the solar only (model 1), the energy conversion efficiency and solar field are lower than in the case of hybrid (model 2). The need to develop more suitable components, such as turbines and heat exchangers, is necessary in order to increase the competitiveness of solar only mode. We get an optimum FFF and SM for each plant, which are illustrated in **Table V**.

For same SM of model 1, the integration of hybridization leads to an increase of annual energy of 25% for LFSTPP and 42% for CTRSTPP, which can used in other applications as: production of hydrogen, heating..

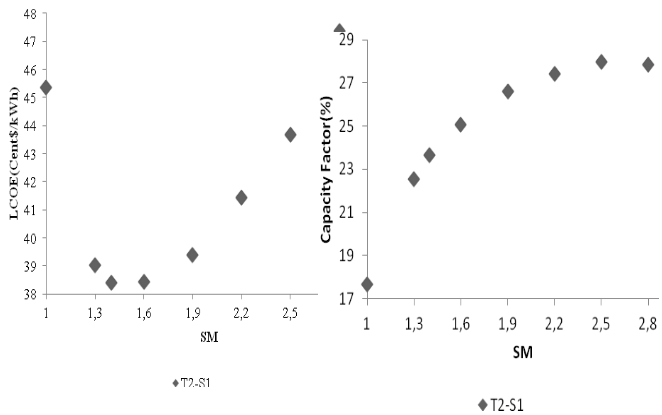


Fig5: Effect of SM on LCOE and CF of M1 for CTRSTPP

Table IV shows the optimum configurations and it can be seen that wet cooling is the best solution to all plant than dry cooling, and LFSTPP requires large solar field which represents 22% to CTRSTPP, because it uses less-expensive reflector materials and absorber components, which it has lower optical performance and thermal output but this is offset by lower investment and operation and maintenance costs.
The annual energy produced by LFSTPP is higher by 4%than CTRSTPP.

Table IV
Optimum configurations of M1

Plant	Technologies and scenarios	SM_{Opt}
LFSTPP	T1-S3	1.9
CTRSTPP	T2-S1	1.6

In next steps, all simulations have been done with an optimum configurations obtained in Model 1.

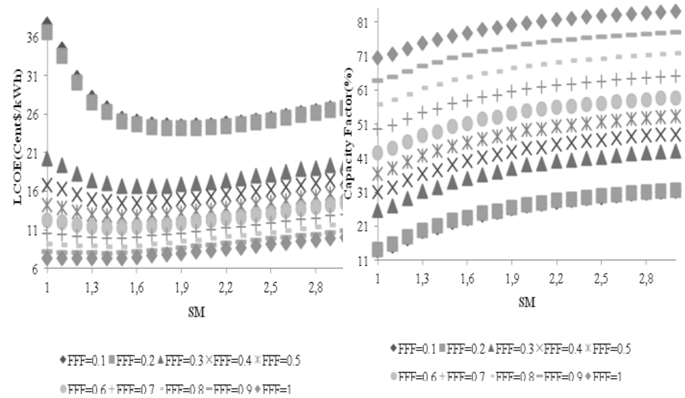


Fig6: Effect of SM on LCOE and CF of M2 for LFSTPP

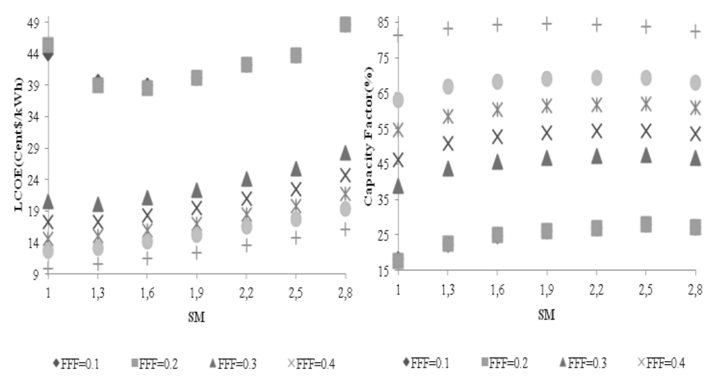


Fig 7**:** Effect of SM on LCOE and CF of M2 for CTRSTPP

D. Model 3: solar field and storage (no hybridization) for CTRSTPP only

Using optimum plant of Model 1 for CTRSTPP, this section is a sensitivity analysis of SM and FLH on LCOE and efficiency. We have used two kinds of storage which are two tank and thermocline, and then all simulations were done with Generic Summer Peak Thermal Storage Dispatch Schedule, the storage dispatch and FFF for different period of the day and the year.

Fig 8 shows that LCOE increases with increasing FLH for each value of SM, but decreases with increase in SM, This means that the solar field area increased with increasing storage capacity in order to capture enough energy for the TES system. Moreover efficiency of plant increases with increase in SM and FLH according to high thermal energy produced with large solar field, but increases approximately with constant values for SM ranging from 1 to 1.6.

The optimum configuration for this model is: the optimum configuration of Model 1 with two tank storage technology. The optimum parameters (SM, FLH) of each configuration are summarized and given in **table V**.

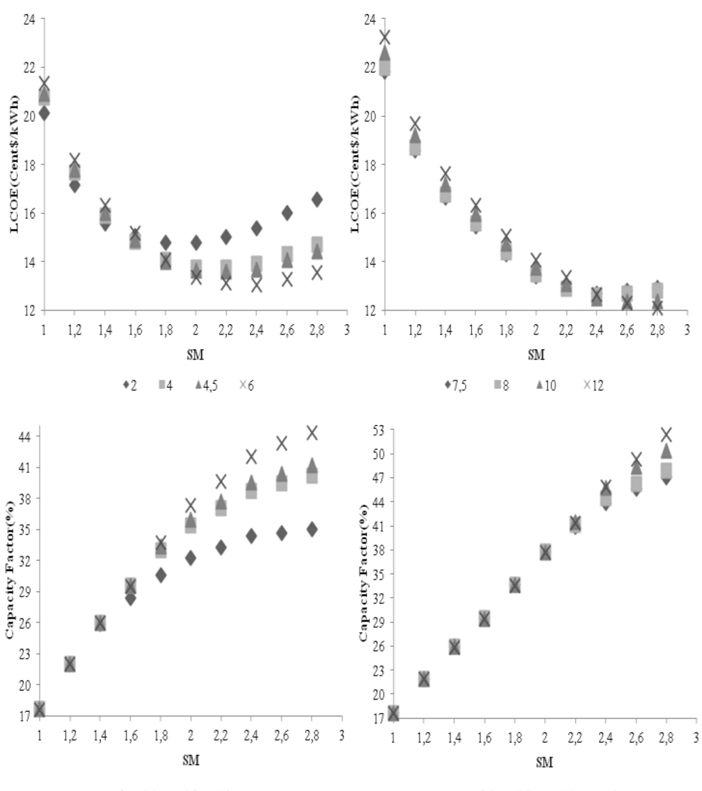
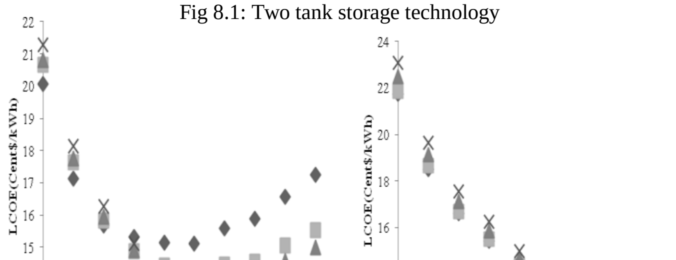
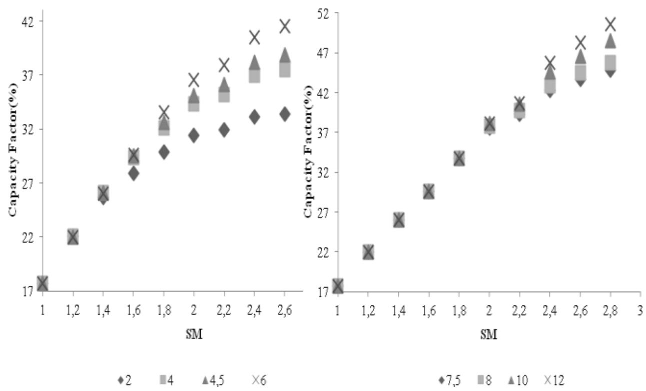


Fig 8.1: Two tank storage technology





E. Model 4: solar field with storage and hybridization (for CTRSTPP only)

In last step, we have determined the interest of storage and hybridization for CTRSTPP on LCOE and CF. The optimum configuration of Model 3 was used for storage, and FFF of hybridization have been optimized for different values of SM and FLH. Moreover the storage dispatch and optimum FFF for different period of the day and the year were introduced here.

The variation of LCOE and CF with SM, FLH for optimum FFF were computed and plotted in **Fig 9** . It was found that the optimum FLH is not changed and it's as Model 3, SM is as Model 1, but FFF increases which demonstrate the benefit of hybridization.

From **Fig 9.1**, LCOE decreases with FFF and increases with SM, but the benefit of hybridization is maximum for FFF=0.6.

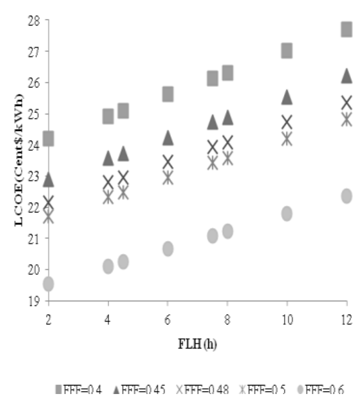


Fig 9.1**:** Optimization of FFF

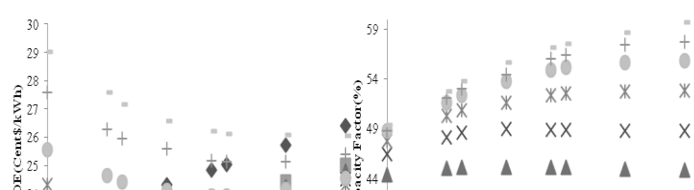


Fig 8.2: Thermocline storage technology

Fig 8: Effect of SM and FLH on LCOE and CF of M3 for CTRSTPP

Fig 9: Effect of SM, FLH on LCOE and CF of M4

Finally, the optimum parameters of optimum configurations for all plants are given in **table V.**

Table V

Optimum results of different configurations for all plants

	CTRSTPP				**LFSTPP**	
	M1	**M2**	**M3**	**M4**	**M1**	**M2**
SM_{opt}	1.6	1.3	2.2	1.6	1.9	1.5
FLH_{opt}(h)	-	-	8	8	-	-
FFF_{opt} (%)	-	0.3	-	0.48	-	0.24
LCOE (cent$/kW)	37.9	20.15	29.88	23.57	24.67	16.26
CF (%)	25.9	43.6	41.1	45	25.9	34.7
Annual Energy (GWh/year)	109	188	172	193	97	183

F. Economic analysis

Levelized cost of electricity presents a basis of comparison for weighted average costs of different power generation technologies. In addition, this concept allows the accurate comparison of different technologies.

Based on this and simulation results presented above, two optimum plants should be selected, which are:

CTRSTPP: solar field with storage and hybridization (M4).

LFSTPP: solar field with hybridization (M2)

Sometimes LCOE became insufficient to make best comparison. So it's necessary to use other factors.

For our study, we have used CF, annual energy, and Total Installed Cost (TIC) as other factors, in order to compare between these two optimum plants and select the optimum plant for Algeria.

From **table VI**, it's clear found that:

1-for all plants, the solar field was the most expensive component, contributing between 28 % and 52 % of the TIC. It decreases in M2 and M4, and decreases also TIC of plants, which prove the benefit of hybridization in CSP plants.

2- The next largest component cost is the cost of power block for CTRSTPP.

3- Linear Fresnel power plant with hybridization is in part a considerably less expensive solution compared to other plants, due to NOVATEC innovations (cleaning system, and lower land use due to simple light structure using standard steel profiles).

Table VI

Economic results

	CTRSTPP				LFSTPP	
	M1	M2	M3	M4	M1	M2
Site Improvements (%)	2	1.8	2	1.8	4.8	4.7
Solar field (%)	47.3	44	47	42	43	42
HTF system (%)	-	-	-	-	13	12.5
Power Plant (%)	25	28	18.4	22	21	22
Balance of Plant (%)	7	8	5	6.5	3	3
Storage (%)	-	-	8.2	9.66	-	-
Indirect Cost (%)	18.5	18.2	19.2	18	15	15
Total Installed Cost(Moi$)	274	243	370	309	215	204.2

Based on these results, CTRSTPP with 48% of hybridization and 8 hours of storage is the best and optimum solution under Algerian climates, with minimum LCOE and TIC, and maximum efficiency and annual energy output.

G. Validation of model and results:

Based on simulation results represented above, we have compared our models to existing operating plants considering thermal storage and hybridization with same capacity.

Table VII
Comparison of optimum models with plants data.

	LCOE(Cent$/kWh)	FLH(h)	CF(%)
	LFSTPP		
Our model	16.14	0	38.7
Ming Liu [19]	19-38	0	22-24
	CTRSTPP		
Our model	20.72	8	45
Ming Liu [19]	20-29	6-7.5	40-45

IV. CONCLUSION

In this study, we have presented a methodology of determining the optimum design and operation of 2 kind of CSP plant in Algeria, which are Central Tower Receiver and Linear Fresnel Solar Thermal Power Plant based on different technologies and scenarios, using the concept of solar multiple, solar thermal storage and hybridization. The tool SAM (System Advisor Model) developed at NREL, Sandia National Laboratories, the University of Wisconsin, and other organizations facilitates to determine the optimum parameters (SM, CF, Annual Energy, and TIC) of plants.

From the results presented in this paper, we can reach the following conclusions: (i) the solar field of central tower receiver and linear Fresnel solar thermal power plant depend on geometry and cost of maintenance of collector and receiver, which are important to optimize it in order to improve and strengthen the economic viability of the plants. The optimum length of collector of LFSTPP is 30 m, then width of heliostat is 15 m and heights are 14 and 13 m for external and cavity receiver respectively.(ii): the integration of hybridization leads to an increase of efficiency of plant and annual energy of 25 % for LFSTPP, and 42 % for CTRSTPP, which can be used in other applications as: production of hydrogen, heating…,which allows the power block to operate at better part load conditions. (iii): Linear Fresnel Solar Thermal Power Plant is in part a considerably less expensive solution compared to other plants, due to NOVATEC innovations (cleaning system, and lower land use due to simple light structure using standard steel profiles).(iv): sometimes Levelized Cost Of Electricity became insufficient to take decision in comparing between solar technologies, so it's necessary to use other factors as efficiency of plant, annual energy output and total installed cost.(v): Central Tower Receiver Solar Thermal Power Plant with 48% of hybridization and 8 hours of storage is the best and optimum solution under Algerian climates, with minimum LCOE and TIC, and maximum efficiency and annual energy output .

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VI. REFERENCES

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