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Optimization Analyses of Parabolic Trough (CSP) Plants for the Desert Regions of the Middle East and North Africa (MENA)

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Abstract

The objective of this study is to investigate the effectiveness of installing concentrating solar power plants in Middle East. A case study is performed for this purpose in the Ma'an area in southern Jordan. Due to water scarcity in most MENA region, contrasting analogy between hot and dry cooling is performed. The performance of CSP plant is simulated using SAM software. The simulation results predict that solar field size and thermal energy storage systems play major role in determining the energy cost. Moreover, it is found that larger plant size has lower values of levelized cost of energy (LCOE). Furthermore, LOCE for 50 MW using dry cooling ranges between 12.88 and 13.40 c$/kW, while it ranges between 11.23 c$/kW and 13.56 23 c$/kW for wet cooling. Finally, it is found that dry cooling option has a great economical potential for generating energy in water scare regions. Therefore, implementing optimal CSP plants in Maan area has great economic impact in Jordan's economic and reduces its dependent on imported oil.

Keywords: *Solar Energy; Electricity generation; Levelized Cost of Energy; LCOE, SAM..*

1. Introduction

Jordan depends on imported fossil fuels to meet its national energy demand [1]. The demand for primary energy has increased from 2.4 million toe in 1982 to 11.5 million toe in 2017. Jordan is experiencing an increased pressure on primary energy demand reaching up to 5.5%. It is expected that the demand for primary energy amounts will reach up to 15 million tons of oil equivalent in 2020 compared to 7.5 million tons of oil equivalent in 2008. The total electricity generation was approximately 8,447 GWh in 2004 while it reached 17,261 GWh in 2013 [5]. The electricity demand increase in Jordan is estimated around 7.4% [6]. On other word, an average of 300 MW per year of additional generated capacity is needed to meet the high electricity demand.

Jordan currently facing real challenges due to the high rates of energy demand, lack of available natural resources and the increase in the public debt which touched US$ 34 billion for the year of 2016 [7]. One promising way of facing these serious problems is utilizing renewable energy sources, which will help the government to achieve the national goals of a brighter future [8]. Jordan has great potential sources of renewable energy, particularly solar and wind energy. Until recently, Jordan experience in generating electricity from renewable energy sources is limited to laboratory scales [2-9]. It has been reported that only 2% of the total electricity is generated from renewable energy resources in 2005 [9-10]. Jordan's Energy Master Plan aims to increase the share of RE to 10% of Jordan's primary energy consumption by the year of 2020.The Jordanian government has estimated the size of investment in renewable energy to meet that share to 15 billion US$ [11].

The RE targets reported by the MEMR are 1000MW of Wind, 600MW of Solar, and 50MW by Biomass by 2020 [12]. According to annual report 2016 published by The Ministry of Energy and Mineral Resources MEMR, there are a long list of RE projects currently have been completed in the last few years (2013-2016) summarized as follows:

- 12 photovoltaic projects with a capacity of 200 MW to generate electricity have been achieved in 2016.
- The commercial operation of Philadelphia Solar Power Company PV project direct proposals Round I has been achieved in 22/10/2015 with a capacity of 10 MW in Mafraq.
- Jordan Wind Project Company JWPC has started the commercial operation of Tafila Wind Farm in 2015 with 117 MW of capacity
- Hundreds of small-scale renewable energy schemes (on-grid roof tops PV systemshave been installed reaching a total of 80 MW.

Other large RE generation projects of about 1600–2000 MWp are expected to follow before 2020 and the estimated capital investment in these projects exceeding US$ 3–4 billion [13].Figure 1 shows the energy mix in Jordan for the period between 2008 and 2020.

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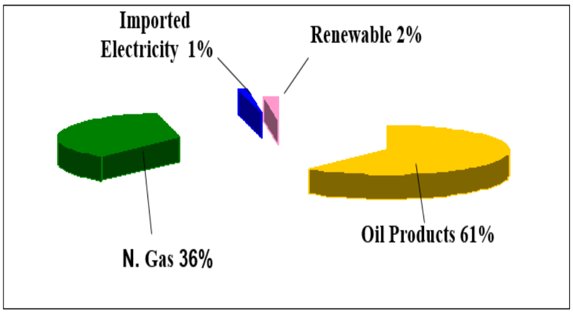
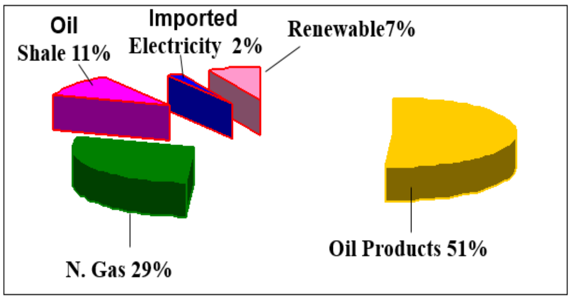
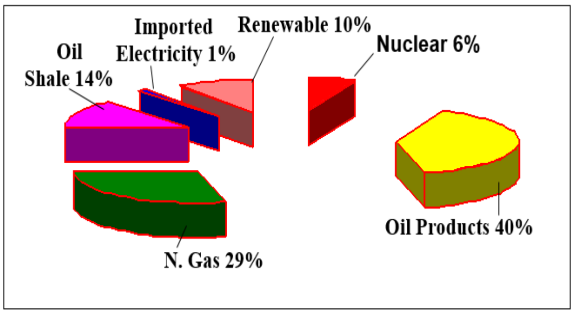


2008, Domestic Resources 4%, Imported 96%



2015,Domestic Resources 25%, Imported 75%



2020, Domestic Resources 39%, Imported 61%

Figure 1: The Energy Mix in Jordan (2008 – 2020) [12]

Recently, several studies for generating electricity utilizing different RE options are conducted in Jordan. Among all renewable energy resources available in Jordan to generate electricity, solar energy is found the most attractive option for generating electricity [14-16]. Although solar energy is totally renewable, but the solar power generates environmental impacts that need to be identified, quantified and evaluated. Life Cycle Assessment (LCA) has been successfully used to evaluate the environmental performance of renewable technologies [18, 19]. Furthermore, the environmental impacts of conventional CSP plants have been previously evaluated by the scientific based on LCAmethodology [20-25].

Electricity can be produced by different type of CSPP. The selection of CSP technologies depends mainly on working fluid, the desirable power output and the operating temperature [26-28]. The most widely used solar technology around the world is parabolic trough solar power plant (PTPP)[29]. It has been reported that for solar-thermal power plants operating at temperatures below 500°C, solar Rankine cycles using parabolic trough are appropriate [30-31].

The objective of this study is to assess the economic potential of installing parabolic trough solar power plant PTSPP in Jordan. For this purpose, a 50MW PTSPPis simulated using System Advisor Model program (SAM). Optimization of the main power plant components is carried out. The effect of thermal energy storage system (TES), type of cooling (dry or wet),and the size solar field on the plant performance and energy costare studied.Levelized cost of energy is used as the main criteria for optimization analysis. The objective of optimization is to determine the optimal configurations and components size that gives lowest LCOE.

2. Site

It has been reported that CSPP is economically viable when the average annual direct normal irradiation (DNI) above 2000 kWh/m2 [30]. Jordan is blessed with large amount of solar radiation reaching on average above 2000 kWh/m2 annually. The southern part of the country receives on average above 2500 kWh/m2[33]. Jordan is located in the middle east (31.5^0 N degree latitude, 36.1^0 E longitude), the annual average temperature and wind speed is 22°C,4 m/s at 10 m height respectively. Studying the map of solar irradiation over Jordan is a very crucial step in selecting potential sites for CSP plants.

Maan area which is located in the southern part of Jordan and receive around 2700 kWh/m2 is chosen for this study. The electricity transmission system in Jordan passes through this area. Considering the huge amount of solar radiation and the vicinity of the national electric grid, this selected site is considered the most attractive site in Jordan.

3. Methodology

The plant is geographically located at Maan city latitude 30.15^0N and longitude 35.75^0E. The elevation of the site ranges between 1065m and 1075m with flat terrain. A simulated CSP plant of 50 MW located in southern part of Jordan is considered in this study. The solar field size, the thermal energy storage size, and cooling options are considered optimization variables. The system advisor model (SAM) is used to simulate the CSP plant. It has been used by many researchers to simulate hourly transient behavior of CSP plant [34-37]. It allows investigating the effect of variations in physical, cost, and financial parameters on the performance outcome [34-35]. It produces comprehensive list of financial metrics for assessment[36]. The hourly data for the global, diffuse and direct irradiation, dew point, relative humidity, wind speed, atmospheric pressure and surface albedo are input to the SAM model. The measured weather data for the Maan for the year of 2014 is used in this study [31]. Results of solar radiation measurement are shown in Figure 2. The annual amount of global horizontal solar radiation is 6.46 Kwh/m²/day.

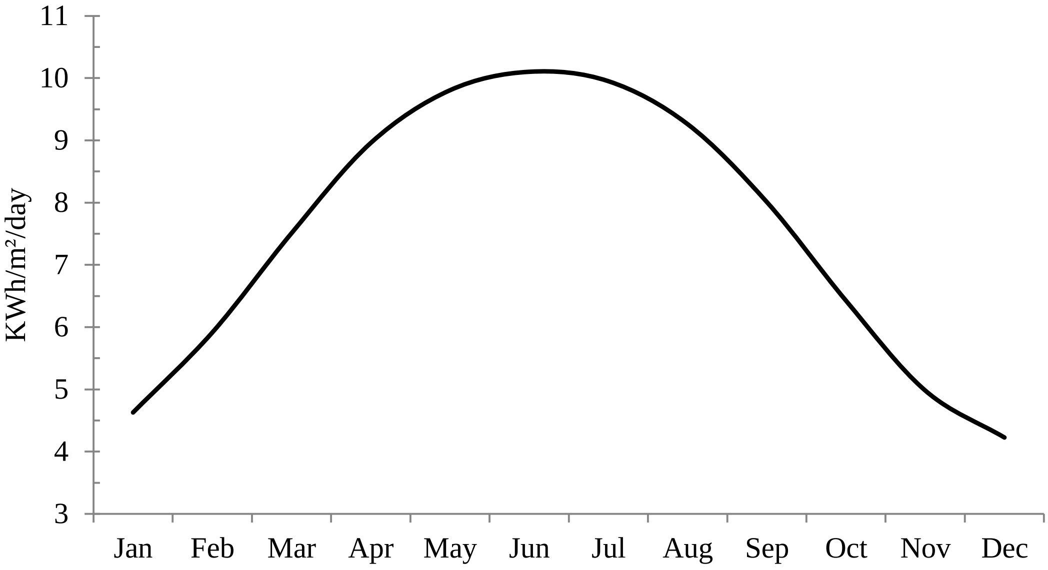


Figure 2: The amount of global horizontal solar radiation for each month.

4. Simulation and Optimization

A CSP plant with TES is simulated using SAM software. Table 1 lists the specifications for the main components of the simulated CSP plant in the selected site of Ma'an Jordan. A 50 MW plant capacity is considered. Dry and wet cooling are investigated. Table 2 lists the ranges of optimization variables simulated to determine the optimal configurations. The LCOE is taken as the objective function for the optimization problem. Furthermore, the relation between the plant size and the cost of energy production is studied. The plant costs for different configurations are listed in Table 3. High-performance cost effective Euro Trough parabolic trough collector models ET150 and ET151 have been chosen for solar collector assembly. Table 3 lists the cost of the main component of CSP. The cost of the components obtained from several sources have been updated in SAM. It is worth mentioning NREL’s System Advisor Model (SAM) has updated the baseline cost for CSP plants in November 2015 [38]. According to the report the resulting new cost numbers reflect innovation and improvements in solar collector technology during the past several years. On the other hand, HTF, TES, and power block subsystems have been largely unchanged and have costs affected only by market and inflationary factors. Moreover, the site improvements and O&M fixed cost categories are dominated by labor costs. Construction and engineering labor cost indices have changed very little between 2012 and 2015.The Physical Trough Model “SkyTrough”was used to examine the impact of the revised cost values on LCOE, which is redefined in SAM 2015. This adjustment led to a change in the estimated real levelized power purchase agreement price from 14.9 ¢/kWh to 13.9 ¢/kWh.

The outputs of SAM simulation are validated against actual data obtained from Andasol plant located in Spain. Published plant data used is obtained from Herrmann et al. [34].To conduct plant simulations, all published plant specifications are simulated with SAM. Table 4 lists contrasting points between actual data and simulated data. It is clear that SAM was successfully able to predict actual data of the Andasol plant. Moreover, the percentage errors shown in the last column in table 4 indicate that SAM results are more conservative than actual data (all errors are negative).

Table 5 lists the LCOE values for each simulation runs. Figure 3 shows LCOE as function of SM for several values of a storage capacity in full load hours. As can be seen from table 5, for all TES sizes studied, the LCOE values decreases with increasing SM until certain value and starts rising again with further increase in SM. As can be seen from figure 3 for each TES size, there is an optimum value of SM where LCOE is minimum.

Table1: Specification for the main components of the CSP plants

Option	Heat Transfer Fluid	Collector	Receiver	Storage Media	Power Cycle
1	Molten Salt	Euro Trough ET150	Schott PTR70	Molten Salt	Nexant 450C HTF
2 ,3 &4	Molten Salt	Euro Trough ET151	Schott PTR71	Molten Salt	Dry Cooled SEGS Turbine

Table 2: Ranges of optimization variables

Option	Turbine Size (MW)	Cooling Option	Solar field size (solar multiple)	Thermal energy storage capacity (h)	Turbine gross efficiency (%)
1	50	Wet	1–2.5	0–12	39
2	50	Dry	1–2.5	0–12	37.3
3	100	Dry	1–2.5	0–12	38.1
4	150	Dry	1–2.5	0–12	38.25

Table 3: Cost data Input [34-38].

Economic inputs toSAM		
Direct Capital Cost	**Wet Cooling**	**Dry Cooling**
Site Improvements	30 \$/m²	30 \$/m²
Solar Field	150 \$/ m²	150 \$/ m²
HTF System	70 \$ / m²	70 \$ / m²
Storage	75 \$ / m²	75 \$ / m²
Power Plant	940 \$ /Kw	1160 \$/ Kw
Balance of plant	100 \$ / KWe	100 \$ / KWe
Contingency	6 % of direct capital cost	6 % of direct capital cost
Indirect Cost		
Engineer -Procure – Construct and owner cost	12% of direct capital cost	12% of direct capital cost
Land Cost	2 \$ / m²	2 \$ / m²
Sales Tax	6%	6%
Operation and maintenance Cost		
Fixed Cost By Capacity	60 \$ / KW – year	60 \$ / KW – year
Other Cost	60 \$ / KW – year	
Project Period (Year)	30	30
Discount rate %	6%	6%

Table 4: Simulation validation data.

Description	Unit	Simulated	Published data (Herrmann et al., 2002)	% (Simulated-published)/simulated
Annual DNI	KWh / m²	2052	2202	-7.31%
Annual electricity sold to the grid	MWh	153560	157,206	-2.37%
Annual parasitics received from the grid	MWh	0	4,307	Not applicable
Mean annual field efficiency	%	44.21	46.10	-4.28%
Annual overall efficiency	%	13.09	14.70%	-12.30%
Full load hours	h	3098	3144	-1.48%

Table 5: Optimization result.

LCOE Cent $ / KWhel		Solar Multiple - 50 MW / Wet Cooling								
		1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
Number of storage full load hours	0	13.53	12.32	12.55	13.12	13.85	14.68	15.68	16.73	17.82
	1.5	14.04	12.53	12.34	12.67	13.18	13.85	14.61	15.45	16.37
	3	14.54	12.87	12.13	12.22	12.59	13.09	13.69	14.35	15.11
	4.5	15.00	13.22	12.13	11.92	12.14	12.51	13.00	13.55	14.18
	6	15.46	13.58	12.41	11.76	11.82	12.09	12.47	12.94	13.46
	7.5	15.92	13.93	12.71	11.86	11.62	11.76	12.06	12.44	12.88
	9	16.37	14.29	13.00	12.11	11.54	11.52	11.73	12.05	12.42
	10.5	16.83	14.65	13.29	12.36	11.73	11.40	11.52	11.77	12.09
	12	17.28	15.00	13.59	12.60	11.95	11.42	11.33	11.50	11.75
Number of loops		70	88	105	112	140	158	175	193	215

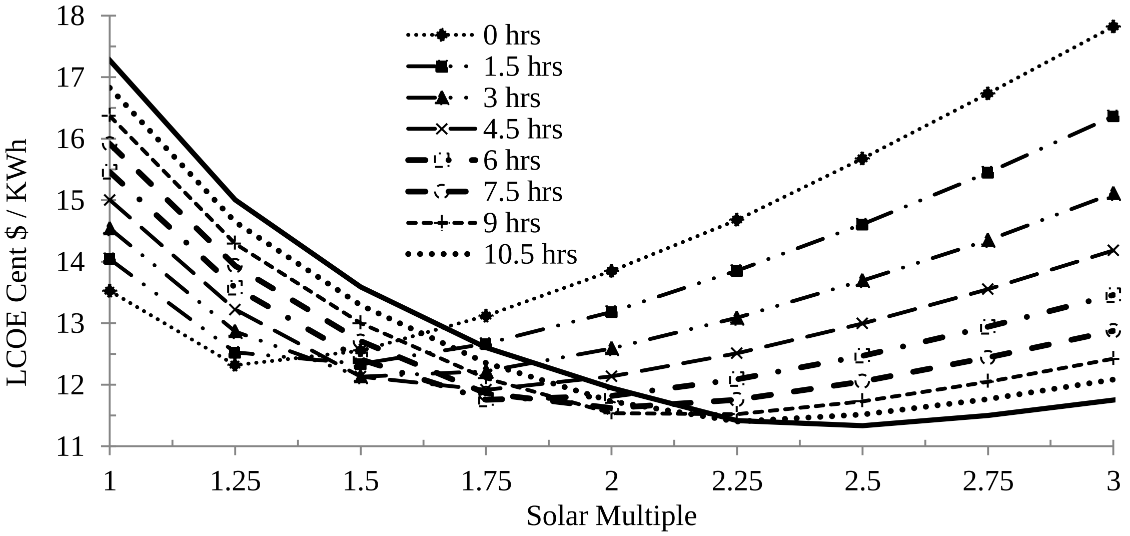


Figure 3: Variations of LCOE with solar field and TES sizes for wet cooling.

Simulation results presented in table 5 show that the minimum values of LCOE obtained for 1.5 <SM<2, and 6< TES< 9. The lowest value of LCOE is 11.54 c$/kWhel. Although practical optimum combination depends on operation schedule which are determined by national energy policy. Larger TES capacity should always be recommended. Therefore, combination of (SM = 2, TES = 9 full load hours) is considered the best combination in terms of energy cost.

Similar to the wet cooling optimization, a dry cooling optimization analyses are carried out for same plant size. Table 6 listssimulation results for several values of solar field and thermal energy storage sizes. The simulations results shown in figure 4 predict that wet and dry cooling have similar behavior. Generally, simulation runs predict that minimum values of LCOE can be obtained for combination of 1.5 <SM <2 and 6 hrs<TES< 9 hrs. Furthermore, optimal values for 50 MW that operates with dry cooling ranges between 13.08 and 14.85 c$/kWhel. The unit energy cost for dry cooling is only 1.5 c$/kWhel higher than those associated with wet cooling. Furthermore, this amount of cost should be considered when choosing between wet and dry cooling in dry hot regions.

In order to investigate the effect of size of the CSP plant on the energy cost and performance, optimizations of a dry cooled 100 and 150 MW CSP power plants are carried out. Procedure used for optimization analysis for 50 MW presented previously is repeated for larger plant size. Table7 shows the simulation results for 100 MW which are demontrated graphically in Fig.5. As can be seen in table 7 and figure5 minimum values of LOCE occur for 1.75 < SM< 2 and 6 <TES< 9. Simulation results predict that the lowest value of LCOE is 12.72 c$/kWhel for 100 MW plant. This value is lower than that corresponding to 50 MW plant size.

The simulation results for150 MW CSP plants are shown in Table 8 and Figure6. It is found that lowest values of LCOE occurs for 1.75 <SM< 2 and 6<TES<9. The LCOE varies from 12.69 to13.6 c$/kWhel, which shows a additional reduction in production costs with increasing plant size. It is worth mentioning that load management aspects and demand profiles should be considered when selecting the suitable plant size.

Table 6: Optimization results.

LCOE Cent $ / KWhel		Solar Multiple - 50 MW / Dry Cooling								
		1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
Number of storage full load hours	0	15.59	14.14	14.39	15.02	15.87	16.84	18.00	19.24	20.54
	1.5	16.11	14.34	14.11	14.49	15.09	15.87	16.76	17.72	18.80
	3	16.69	14.73	13.85	13.95	14.38	14.95	15.65	16.42	17.30
	4.5	17.24	15.15	13.84	13.58	13.82	14.25	14.82	15.46	16.18
	6	17.78	15.57	14.17	13.38	13.45	13.76	14.20	14.74	15.33
	7.5	18.32	15.99	14.51	13.49	13.19	13.34	13.68	14.12	14.61
	9	18.86	16.41	14.85	13.78	13.08	13.05	13.28	13.64	14.06
	10.5	19.40	16.83	15.20	14.07	13.31	12.89	13.02	13.29	13.65
	12	19.94	17.24	15.54	14.36	13.56	12.90	12.79	12.97	13.25
Number of loops		70	88	105	112	140	158	175	193	215

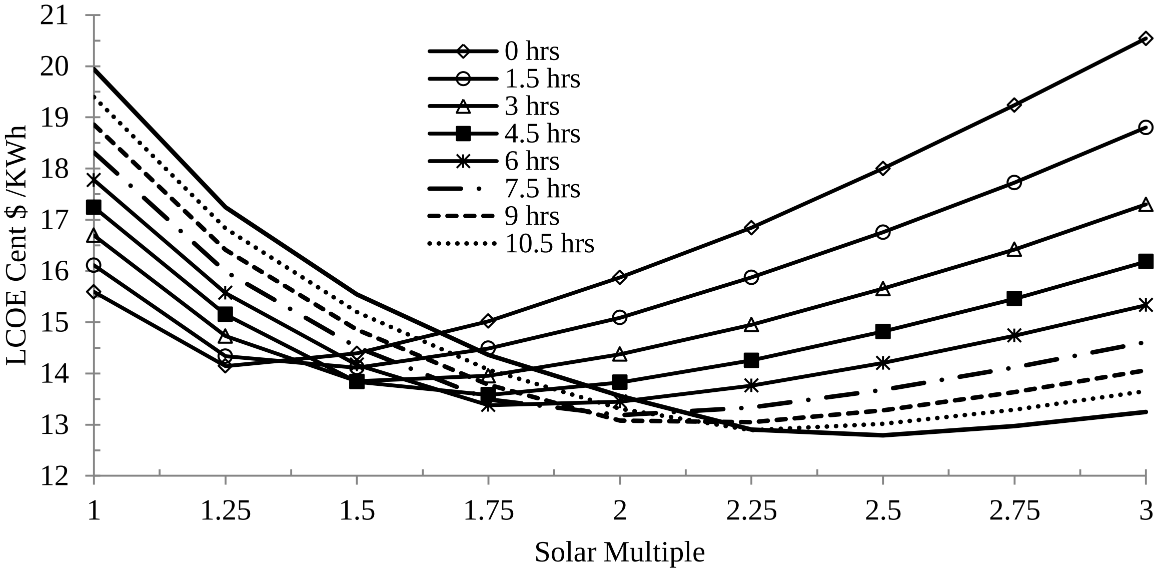


Figure 4: Variations of LCOE with solar field and TES sizes for dry cooling.

Table 7: Optimization results.

LCOE Cent $ / KWhel		Solar Multiple - 100 MW / Dry Cooling								
		1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
Number of storage full load hours	0	15.58	14.13	14.38	15.01	15.86	16.83	17.99	19.23	20.53
	1.5	15.88	14.17	13.98	14.37	14.98	15.77	16.65	17.63	18.72
	3	16.42	14.53	13.71	13.83	14.27	14.86	15.57	16.34	17.22
	4.5	16.95	14.94	13.69	13.46	13.72	14.17	14.73	15.38	16.11
	6	17.48	15.36	14.02	13.26	13.34	13.66	14.10	14.64	15.24
	7.5	18.01	15.77	14.36	13.36	13.09	13.25	13.60	14.04	14.54
	9	18.54	16.19	14.70	13.65	12.98	12.96	13.21	13.57	13.99
	10.5	19.08	16.60	15.04	13.93	13.20	12.81	12.93	13.20	13.56
	12	19.61	17.02	15.38	14.22	13.45	12.81	12.72	12.90	13.18
Number of loops		128	159	191	223	255	287	318	350	392

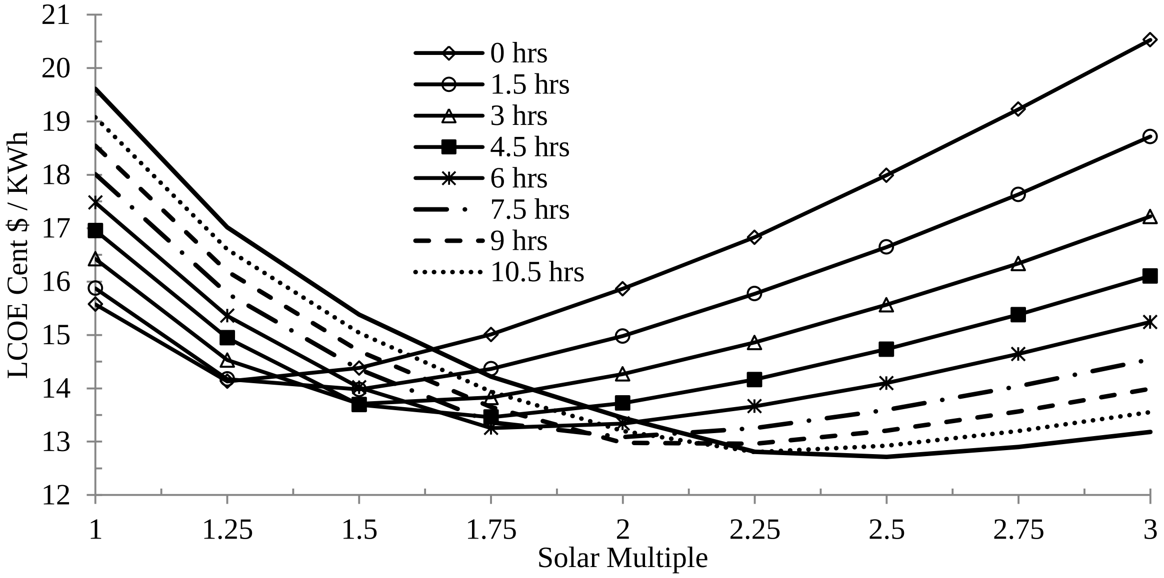


Figure 5: Variations of LCOE with SM and TES sizes for 100W plant (dry cooling).

Table 8: Optimization results.

LCOE Cent $ / KWhel		Solar Multiple - 150 MW / Dry Cooling								
		1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
Number of storage full load hours	0	15.57	14.12	14.37	15.00	15.86	16.83	17.99	19.22	20.53
	1.5	15.79	14.11	13.93	14.32	14.94	15.74	16.62	17.60	18.69
	3	16.33	14.47	13.66	13.79	14.24	14.82	15.53	16.31	17.19
	4.5	16.87	14.88	13.64	13.42	13.69	14.13	14.70	15.36	16.08
	6	17.38	15.29	13.97	13.22	13.31	13.64	14.07	14.62	15.22
	7.5	17.91	15.71	14.30	13.32	13.06	13.23	13.58	14.02	14.52
	9	18.44	16.12	14.64	13.61	12.94	12.94	13.18	13.55	13.97
	10.5	18.97	16.53	14.98	13.89	13.16	12.78	12.90	13.18	13.53
	12	19.50	16.94	15.32	14.18	13.41	12.78	12.69	12.88	13.16
Number of loops		235	294	353	412	471	530	588	653	725

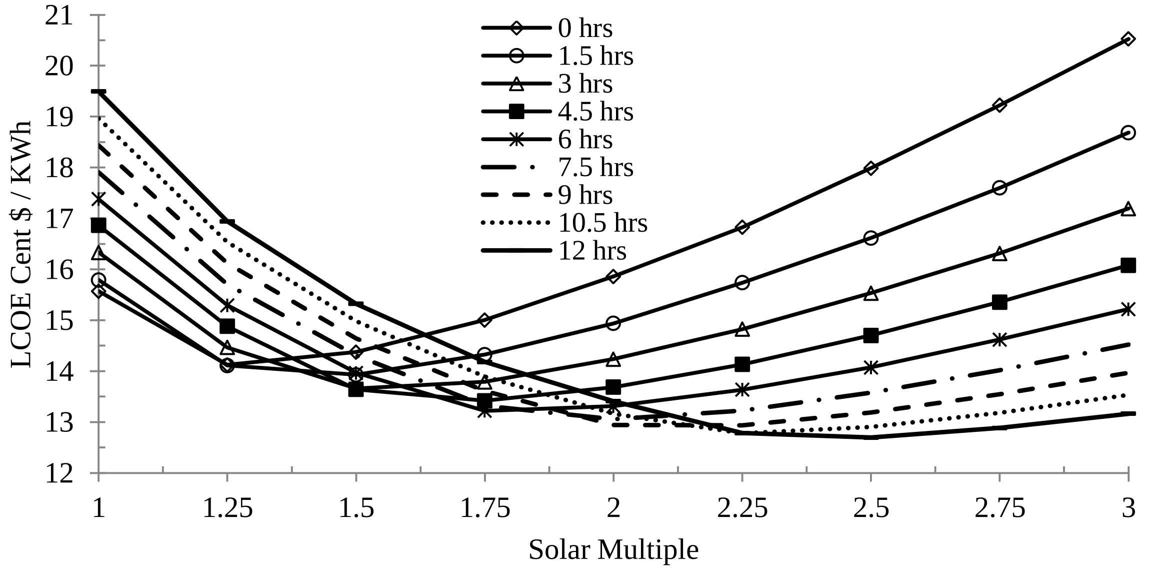


Figure 6: Variations of LCOE with SM and TES sizes for 150W plant (dry cooling).

5. Results and discussions

Simulation results presented in previous section indicate that CSP with a large TES has a great economic benefit. Generally, it is found that 9 hours of storage is the optimal size in terms of energy cost. Figure 7 shows the variation of LCOE with TES size. A large TES allows storing the surplus energy during daytime and reusing it during night. Therefore, TES has significant effect in increasing the capacity factor of the power plant and increase the economic attractiveness of CSP. Furthermore, due to high level of solar radiation in the considered site, LCOE values found attractive from economic point of view. Moreover, it is noticed that the LCOE for dry cooling is not significantly higher than the wet cooling, i.e. only in the range of 1.2 and 0.53 c$/kW h for the 150 and 50 MW CSP plants respectively as shown in Table 9. This slight increase in cost does not justify using wet cooling in dry hot arid regions.

Figure 8 shows the monthly specific net power generation (MW hel generated per MW installed) for optimized design options for all plant size studied. The simulation results predict that only small difference between cooling options in summer for different plant size, while the specific net power generation is same for the rest of the year. Figure 9 shows monthly overall plant efficiency. Simulation results show that for all power block sizes, the overall plant efficiency ranges between 7% to 20%. Moreover, simulations predict that larger power blocks have higher efficiency. This can be explained due to lower specific losses.

Due to the scarce of water in the study site, the cost of water is expected to be significant and should be included in the financial analyses. Water is used for wet cooling and cleaning of the collector mirrors. The cost of water delivery is 1.75$/m^3 (WAJ, 2015). Water cost should be added to the LCOE for both wet and dry cooled power blocks. It is assumed that washing takes place 65 times per year with amount of 0.7 L/m^2 of collector aperture area. The specific water cost for each option is calculated and added to the previously calculated LCOEs. LCOEs including water cost are shown in Table 9. For 50 MW plant, simulations predicts that about 92.6% of water use can be saved if dry cooling option is chosen. Results presented in Table 9 show that LCOEs for dry cooling is not significantly higher than that for wet cooling. Beside the water cost, the availability of water is a major problem in the waterless regions. Based on these results, dry cooling option is more economically appealing than wet cooling in hot sunny arid regions. This statement is very critical for Jordan which extremely suffers from lack of water.

Table 9 summarizes simulation results for the four different power plant options studied. Simulation predicts that the annual net electricity output for 50 MW CSP power plant for the two cooling options almost similar. The investment cost per installed kW for the four studied power plant options are shown in table 9. Including the cost of water, dry cooling option is lower than wet cooling option. The specific cost goes down as the size of the plant increases.

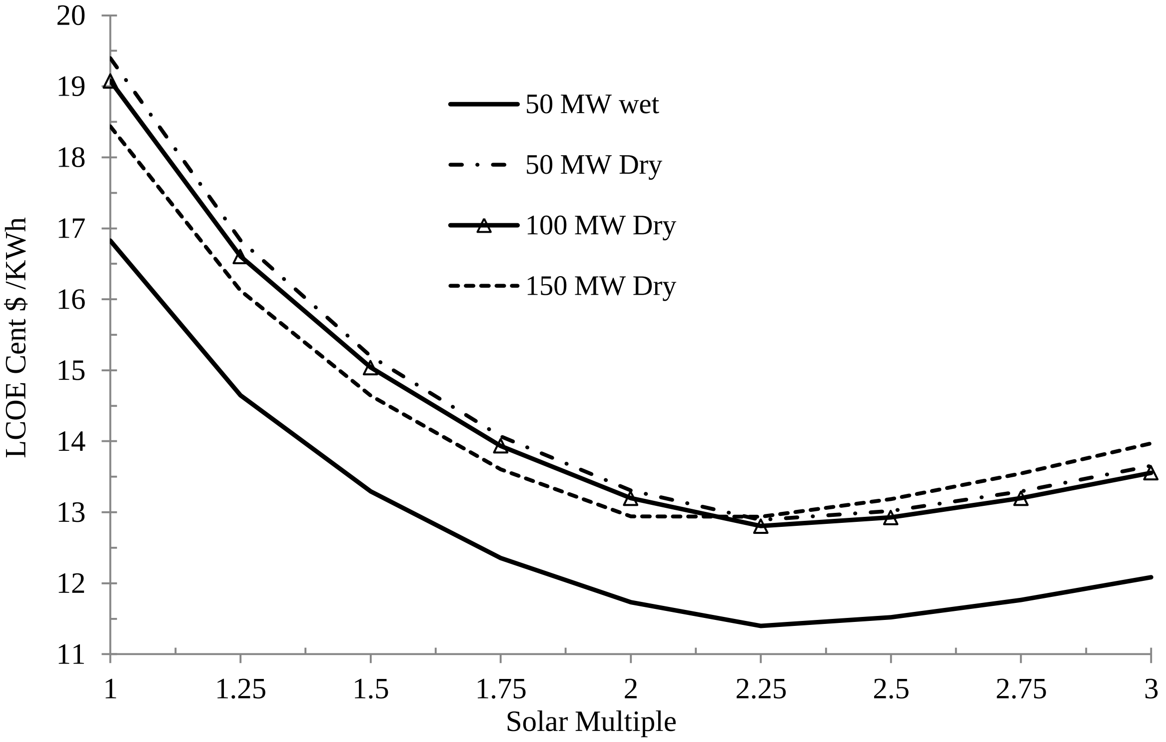


Figure7: Variation of LCOEwith SM (9 hour storage size)

Table 9: Results for different configurations

Description/ Cooling type	Unit	Plants in Maan - Jordan			
		50 MW wet	50 MW dry	100 MW dr	150 MW dry
		503,580	523,201	1,036,590	1,543,440
Collector area	m²	639,373	646,775	1,036,590	1,543,440
Annual thermal power	MWhth	210,993	206,968	1,302,438	1,972,709
Annual electricity output	MWhel	210,993	206,968	416,780	631,267
Capacity factor	%	48.2	47.6	47.7	48.1
Annual water consumption	m³	846868	61525	122571	183175
Levelized electricity cost	c$/KWh	11.54	13.08	12.98	12.94
Levelized electricity costs incl. water cost	c$/KWh	12.7	13.1	13	12.98
Net investment cost	$	277,758,272	292,801,600	577,758,272	857,715,008
Net investment cost /KW	$ / KWh	5,555	5,777	5,718	5,718
Net investment cost costs incl. water cost	$	319,678,238	295,847,088	583,825,537	866,782,171
Net investment cost /KW costs incl. water cost	$ / KWh	6393.56	5916.94	5838.26	5778.55

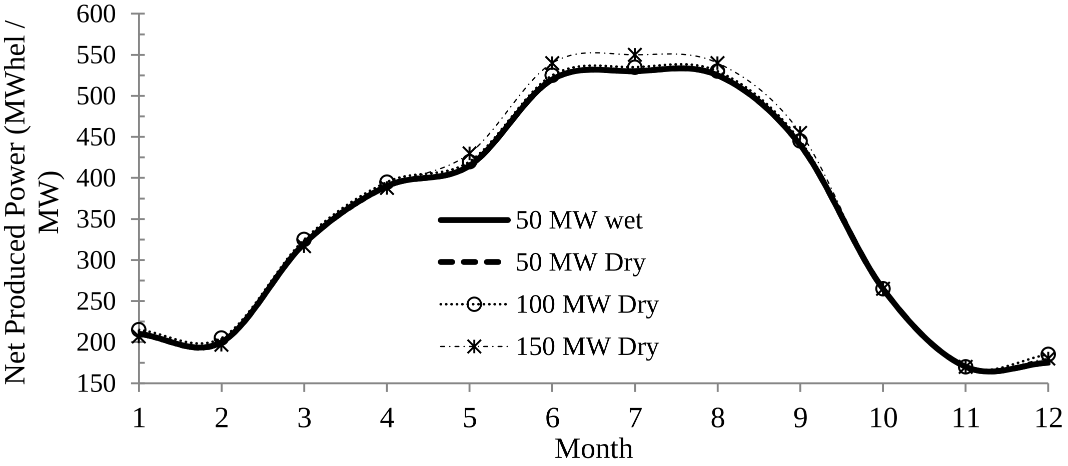


Figure 8: Monthly variations of net power generation at optimal values.

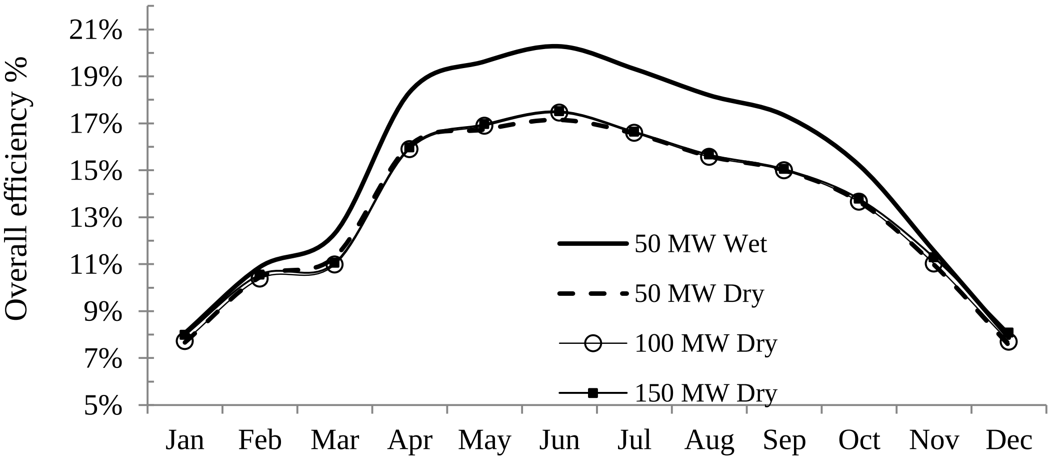


Figure 9: Overall efficiency for reference plant in Ma'an.

6. Conclusion

Optimization analyses for CSP plant located in southern part of Jordan using SAM software are presented. Size of solar field, thermal storage size, size of the power block, and type of cooling are considered the main design factors. The objective of optimization is to minimize the cost of energy production. It is found out that the thermal energy storage (TES) system has the greatest impact on CSP plants performance**.** It can be concluded that lowest values of LCOE and high capacity factor can be obtained when selecting 6<TES <9. Furthermore, LCOE decreases with increasing plant size. Moreover, dry cooling option is found feasible for regions with water scarcity. Finally, the study concluded that implementing optimal configuration of CSP plants in southern part of Jordan has great benefit to Jordan's economy, and thus it reduces its energy import.

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