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Cost Analysis of a Large Solar Plant with Parabolic Trough Concentrators Using Molten Salt Storage Tank

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ABSTRACT

Thermal storage tank is a standout amongst the most encouraging methods in solar thermal power stations operation. Accurate selection of appropriate storage system is a significant parameter to ensure the continuous working of thermal solar station during the absence of the sun. This work describes financial analysis of different locations of a 500MW Solar Plant in Egypt and also thermal tank design. The selected three locations which are investigated in this study are Aswan, EL-Arish and Hurghada to build this challenged size solar station. These locations cover the tree levels of the solar intensity in Egypt. This study is achieved by System Advisor Model (SAM) as financial analysis simulation tool. All the solar thermal power plants are working twenty-four hours per day and with sixteen full-load times of thermal energy storage (TES). Parametric design and cost analysis for each location, comparison between these locations are performed to obtain the optimum locations for 500MW solar power plants. The results of this study are considered a good orientation for feasibility study for CPS (concentrators parabolic system) projects, and it is needed in all over the world in particular, in Egypt for future to produce clean energy. The results of the cost analysis indicated that SM of Aswan is smaller value than the other cities and it equals 1.8 due to high annual irradiation 2916 kW.hr/m2.

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1. Introduction

Thermal energy storage (TES) systems stratify simple idea: abundance thermal energy is accumulated and directed from the solar medium to exchange the heat inside a heat exchanger to heat up the Heat Transfer Fluid (HTF) that streams from cold reservoir to hot reservoir. Subsequently, the heat is recuperated from the hot reservoir utilizing HTF and transmit to the steam boiler if necessary. To avoid excess heating of HTF the plant operator defocus of some undesired solar collectors in case of stopping the storage operation. While, storage sidesteps losing the day time excess energy to continue the production after sunset.

Thermal storage can be accomplished indirectly or directly. For indirect thermal storage systems, the fluids such as mineral, synthetic and silicone oils as well as molten salts are used for heat transfer sensibly. The molten salts have desirable properties (i.e. low vapor pressure, low chemical reactivity, low cost, moderate specific heat, and high density), so it is recommended for sensible heat usage. The molten salts as HTF absorb heat that collected and then it pumped to TES system. Where, the storage solid substance which in direct contact with HTF absorbs heat.

The molten nitrate salt (stable mixture with low vapor pressure) is used as HTF. It consists of 60 wt% $NaNO_3$ (sodium nitrate) & 40 wt% KNO_3 (potassium nitrate) and it is utilized in a temperature range of 260ºC - 600ºC. Nevertheless, with temperature decreasing it begins to crystallize and solidify at 238ºC and 221ºC, respectively.

Thomas et al. [1] studied the effect of inhanced component performance on LCoE (Levelized Cost of Electricity) using parabolic trough solar power plant under 2 various geographical locations; United State and MENA. Also, they studied the effect of several absorber tube diameters on LCoE by using three kinds of molten salts, two commercial types and one hypothetical. It has been found that the achievement of the three kinds of molten salts lessened the LCoE by 3-5 %. Calculations and simulations of solar power plant characteristics had been achieved via System Advisor Model (SAM); this software is obtained by the National Renewable Energies Laboratory (NREL).

Same findings for the related concentrating solar energy potential were presented in many regional studies. In the Mediterranean region, Trieb [2,3] and Poullikkas [4] described the technical viability of inter connecting Northern Africa, Europe, and Middle East for distributing the output electric energy in that region. Fthenakis et al. [5] considered a sensible a concentrated sun-oriented power (CSP) innovation improvement. They anticipate that 83 GW could be introduced in this area by 2030 and 342 GW by 2050, in addition they assessed that in the Middle East 55% of the output power has been introduced as well as 30% in northern Africa and the rest 15% in Europe. However, the ideal utilizations of an accessible solar radiation in these zones with greater assets are principal. In US, circumstance will be comparative; it was evaluated that 118,000 MW can be introduced by year 2030 and 1504,000 MW by year 2050. Moreover, Salvador et al. [6] talked about the impacts of the storage capacity and capacity factor on the output electricity price from concentering solar power. The interaction among these factors can be utilized to seek an insignificant cost target that can fill in as a specialized basis to manage in the design of financial motivations for CSP plants. Sargent and Lundy [7] concentrated on the appraisal of the thermal technologies and in addition current expenses. A financial investigation has been made to survey the current expenses of individual part and also separate the elements cost such as the CSP parts. In addition, the investigation of solar power plant for the meaning of power generation polices by Izquierdo et al [6] who presented the understanding of the interchange between various affectability factors such storage capacity, solar multiple capacity factor, solar irradiation and the subsequent practicality of the solar power station.

The probabilistic method was utilized by Ho and Kolb [8] for price assessment of solar innovation. Moreover, the impacts of affectability constraints such as capacity factor, solar irradiation, and annual productivity could be dissected as probability distributions that give outputs as the shape of ordering the yield parameter, generally the output electricity price level. Nevertheless, this work did not depict the main price contemplations and estimation of production charge. The investigation of expenses of concentrated sun powered warm power by Pranesh et al. [9], was examined a transparent technique for expecting the costs magnitude for improving a power station utilizing the CSP system innovation. They gave a straightforward framework to the produced electricity cost from CSP plant. The various variables contributing in the capital and production costs of solar power plant advances were examined. Additionally, the impacts of variety of power station dimensions, irradiance, discount rates in addition the return internal rate on the equity have been appeared. The various factors which share in the capital and generation costs of CSP technology have been presented. Otherwise, the utilization of molten salts as heat transfer fluids in the thermal solar plant field using thermal storage presents an execution impact and appealingly bring down electricity cost. Kearney et al. [10] stated that preventative heating system for solar fields is important for starting-up, maintenance. Thermal storage within thermal solar power plant covers the capability of the convey electricity without non-renewable energy source (fossil fuel) back up and to encounter peak demand and independent of climate changes [11–17].

Zhen et al.,[18] presented two temperature models for examining energy release utilizing molten salts as the HTFs and economical rocks as the filler. There are a many industrially accessible molten salt blends, for example, blends of nitrates and they likewise have been utilized for solar systems. For instance, the binary salt blend (60 wt. % $NaNO_3$ & 40 wt. % KNO_3), it has the higher thermal steadiness (600ºC) and has the lower cost, yet in addition has the higher melting point (220ºC). Ternary (40 wt. % $NaNO_2$ & 7 wt. % $NaNO_3$ & 53 wt. % KNO_3) has been utilized since a few decades in the heating treatment industries. That salt has the lower liquefying temperature which equals 120ºC. Moreover, this salt has thermal stability at temperatures rise up to 454ºC. However, the shortcomings of these liquid salts as HTF are their moderately high melting point and their limitations in CSP applications, Bradshaw [19]. Kearney et al., [20] said that though, the accessible higher temperature oil produces steam around 393ºC with an effectiveness of cycle equals 37.6%. The thermal storage by utilizing molten salts media gives a higher storage temperature and reduces the volume of the thermal storage. In addition, the molten salt is less expensive and has environmental safety than as of recent accessible high-temperature oils.

There are two kinds of thermal storage to keep up a consistent supply throughout the year; long and short-term energy storages. The short-term energy storage absorbs and saves at the day time energy for night time utilization. In other hand, long-term energy storages are including storage in spring and summer months ang usage in winter and autumn months. Recently, just sensible heat has been stored. In addition, the useful enhancement by utilizing latent and chemical heat storages are in full advancement, Fernandez et al. [21], where chemical heat storage is considered much appropriate for long-term thermal storage. A deep investigation of authors was included a simulation of the performance of the large solar thermal power station using the parabolic trough and utilizing molten salt storage. The authors studied three different locations in Egypt (Al-Arish, Aswan and, and Hurghada) and the thermal storage tank of the molten salt was used for 16 hours [22]. Yuanjing et al [23] decreased the total costs of the power plant using the parabolic trough by reducing the number of collectors in the solar field and increasing the plant efficiency. Khajepour, and Ameri [24] studied the effect of the three solar field rather than one solar field to produce super-heated steam. Their results indicated that the usage of the solar fields in these days with low price of nature gas is not economically but if the nature gas price is increased, the use of solar energy is more economically feasible. In general, a study has been provided a new method for comparing relatively of various sensible TES alternatives by Tehrani et al. [25]. That study gave acumen into the most promising alternatives for moving beyond two tanks molten salt system.

All the above discussed researches in the present survey have endeavored to comprehend the performance of the concentrating solar power plant with storage and cost investigation of those power stations, taking in considering either the traditional systems or tenuous adjustments. Moreover, there is a renewed interest for thermal power plants utilizing thermal storage in the recent year. Furthermore, numerous little adjustments and improvements were presented in the previous work survey to enhance the plant efficiency or certain particular attributes (e.g., power yield, cost rebate and power plant efficiency). Notwithstanding, an accurate modeling of the cost analysis of this system has not been completely understood up to now. Therefore, the present work aims to thermal storage system design using molten salt and cost analysis of 500 MW solar power plant with parabolic trough concentrators located in different cities in Egypt (Hurghada, Aswan, and El-Arish).

2. Cost analysis

The current study is accomplished by means of SAM 2014 as financial simulation tool. SAM (Supported by National Renewable Energies Laboratory (NREL) U.S.) is a financial and performance model developed to favor the decision-making process for individuals engaged with the renewable energy industry. In addition, SAM predicates the performance and cost analysis for renewable energy resources associated with the network. These calculations are basically depending on fixed and running costs.

CSP economically is more sophisticated knowledge than other renewable ones, with photovoltaic. Expanded difficulty is because of the concurrence, of two interconnected main elements: the collector and the power generation cycle. The cohabitation gives approximately a few exclusive attributes now not found in different renewable technologies.

The investigation of concentrating solar power plant for the meaning of energy costs gives a knowledge into the association between various parameters incorporate as like capacity factor, solar multiple, and storage capacities. The solar multiple is the more impact on cost and providing performance of thermal storages.

The solar multiple is characterized as:

$$SM = \frac{Q_{SF}}{Q_{PB}} \tag{1}$$

where:

Q_{SF} : is the nominal solar field collected thermal power

Q_{PB} : is the power block thermal input.

The solar multiple can be calculated by the overall efficiency of the solar power plant at the design point, and defined as:

$$\mathrm{SM} = \frac{\mathrm{P_{max}}}{\mathrm{P_{rated}}} \tag{2}$$

where

P_{max} : corresponding output power of Q_{SF} per unit area.

P_{rated} : nominal turbine electrical power / area.

Therefore, for (SM =1), entirely the collected solar irradiance converted into electricity in the full and part loads. The capacity factor (CF) is often utilized to be an indicator for the plant load which is defined as time fraction that a plant works at full power and given as:

$$\mathrm{CF} = \frac{3.6e6\ q_{abs}}{t.P_{rated}} \tag{3}$$

SAM organizes the costs into three categories (see Fig. 1): (i) capital cost (direct) that include equipment costs and labors, (ii) capital cost (indirect) include authorization, land related costs, and engineering, (iii) maintenance and operating costs including equipment, labors, and other costs related to the working of the project. The details of each category are presented in the following sections.

2.1. Direct capital costs

The direct capital costs are the total of site refinements, solar field, HTF system, storage system, fuel backup system, power plant operation cost, balance of plant, and eventuality cost.

a. Site Improvements ($\$/m^2$): a cost of site elaboration and other equipment per unit area of solar field.

b. Solar Field ($\$/m^2$): costs of solar field/unit area take into account the expenses associated with solar field, equipment installations, and labor.

c. HTF System ($\$/m^2$): a cost of solar field per unit area to obtain the costs associated with pumps and piping installation including equipment and labor.

D. Storage ($/MWht): a cost of thermal storage system installation per thermal storage capacity (megawatt-hour).

e. Fossil Backup ($/MWe): a cost of fossil backup system installation per electric power block gross capacity (megawatt).

f. Power Plant ($/MWe): a cost of power block installation per electric power block gross capacity (megawatt).

g. Plant balance ($/MWe): the additional costs per electric power block gross capacity (megawatt).

h. Contingency (%): the costs that considered uncertainties in direct cost evaluations which is a percentage of the summation of all direct capital costs of the components.

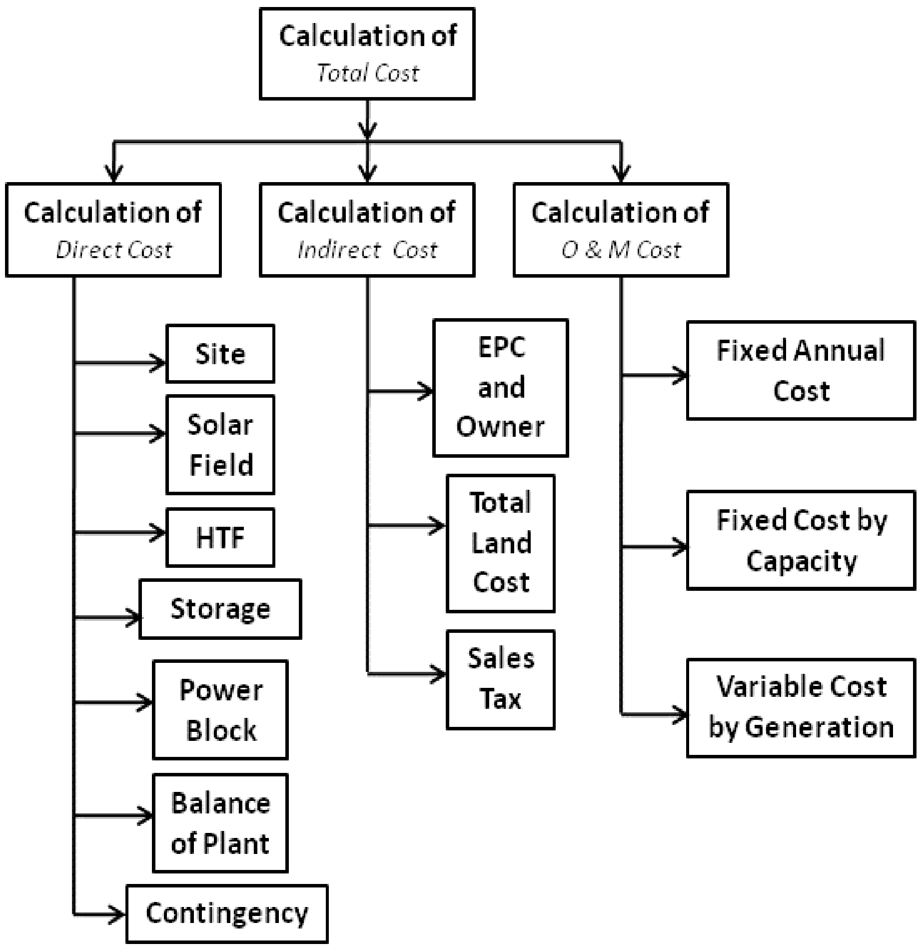

Fig. 1. Illustration diagram for cost analysis via SAM simulation tool.

2.2. Indirect capital costs

Total indirect capital cost is the summation of Engineer Procure Construct (EPC) and owner cost, sales tax, project land and various costs. The summation of installation costs are the investment of project costs that uses in first year of the project payments.

Total installed cost = Direct capital costs + Indirect capital costs

2.3. Operating & maintenance

Operation and maintenance (O & M) costs connected with the annual expenses on equipment and facilities next the system installation. SAM permits the users to insert operation and maintenance costs by three different manners: (i) fixed annual, (ii) fixed by capacity, and (iii) variable by generation.

a. Fixed Annual Costs ($/year): the costs of every year in the project cash flows.

b. Fixed Costs by Capacity ($/kW.year): the costs related to the systems rated capacity.

c. Variable Cost by Generation ($/MWh): the costs that is related to the summation annual power output of the system which is depending on both the model performance calculated at first year and the year-to-year decay in production value.

3. Storage reservoir

A lower vapor pressure of the TES permits perpendicular field-erected tanks for use. The big atmospheric pressure tank is much like industrial oil storage tank. However, the tank is manufactured by using carbon steel and using self-assisting roof. In addition, the tanks' walls are built from mineral wools and calcium silicate blocks insulation, respectively. The foundation includes the following layers: (i) concrete slab, (ii) thermal foundations, (iii) foam glass insulations, (iv) firebricks insulation, (v) liner thin steel plate, and (vi) sand. Herrmann et al. [26] stated that a border ring wall supports the weights of the tank walls and roofs.

The thermal properties of HITEC (binary) for this modeling are fluid density (ρ, kg/m^3), viscosity (μ, $Pa\ s$), thermal conductivity (k, $W/m\text{-}K$) and specific heat (C_p, $J/kg\text{-}K$) in the form temperature – dependent function, Roberta et al., [27]:

$$\rho(T) = 2090 - (0.636)\,T \qquad (i)$$

$$\mu(T) = 10^{-3}[(22.714) - (0.12)\,T + (2.281\times 10^{-4})\,T^2 - (1.474\times 10^{-7})T^3] \qquad (ii)$$

$$k(T) = 0.443 + (1.9\times 10^{-4})\,T \qquad (iii)$$

$$C_p(T) = 1443 + (0.172)\,T \qquad (iv)$$

where

T: temperature in ^{o}C

The thermal storage capacity for TES, E_{stored} in MJ h_t, the thermal storage mechanism is primarily based upon the utilization of sensible heat in various kinds of liquid material; sensible heat is brought to a material definitely via heating it up. Usually, all energies that are concerned in heat conversion of a fluid are known as sensible heat. In addition, it amounts simply to produce the specific heat and the temperature changes. So, it is given by the following equation:

$$V_{TES} = \frac{E_{stored}}{\rho_{hms} c_{ph}(T) \times (T_{hot} - T_{cold})} \tag{4}$$

where:

V_{TES}: the storage volume, m^3

T: fluid temperature [(T_{hot} + T_{cold})/ 2], ºC

Thermal capacity for TES is:

$$E_{stored} = \frac{Gross\ power}{desired\ efficicy} \times t_{full\ load} \tag{5}$$

where:

$t_{full\ load}$: total full-load hours of thermal storage, hrs.

Diameter of the tank, D_{tank} can be estimated as:

$$D_{tank} = 2 \times \sqrt{\frac{V_{TES}}{h_{tank} x\ \pi x\ N_{pairs}}} \tag{6}$$

where:

h_{tank}: The height of the tank less than 10.0 m

N_{pairs}: Number of tank pairs

Estimation of heat loss, q_{loss}, is:

$$q_{loss} = \left(h_{tank} \times \pi \times D_{tank} + \pi \times \left(\frac{D_{tank}}{2}\right)^2\right) \times N_{pairs} \times (T - 20) \times C_{ph} \tag{7}$$

The minimum fluid volume, $V_{TES,min}$, is:

$$V_{TES,min} = V_{TES} \times \frac{h_{min}}{h_{Tank}} \tag{8}$$

The thermal storage capacity may be changed to fulfill completely various load necessities, and different choices based on the storage capacity involved in:

(i) A small storage only, when the sunshine is available, electricity is only generated.

(ii) A postponed moderate load arrangement, where solar energy is gathered along day time, however with an expanded electricity generation.

(iii) A completely constant mode, using the big storage capacity to comprise power generation amongst sunrise and sunset.

3.1. System description

The tanks will be designed as vertical cylinder with flat or round roofs based on API 650.

- **Tank foundation materials**

The tank foundation materials will be built below the ready soil material. Additionally, the foundation embraces elevated tank, soil mat, foundation ring, and concrete foundation mat.

- **Foundation material insulations**

Foundation material insulations are mounted on top of the passive cooling systems and refractory brick as shown in Fig. 2. The insulation system descriptions below are typical; Table 1 shows the materials were selected for cold and hot tank.

The insulation systems of cold and hot salt tanks are involved from two separate radial zones and the insulation thickness are 420 mm and 495 mm, respectively that is the height from the highest point of the foundations cooling system to lowest point of tank floors. The construction of exemplary zone comprises of:

- Outer zones for supporting the tank side walls and adjust thermal expansion. It includes bottom layer of insulating firebricks and top layer of hard firebricks where the leak detections lining exists on hard firebrick top. Circumferentially, the refractory rings have been segmented and the space between the different segments is filled with mineral wools.
- The inner zones for supporting tank floor includes of several staggered layers of one or two leak detection liners, foamglass insulation, and a dry sand layer over that the tank's floor. The mediator within the zones is filled with mineral wools.

Table 1
Tank materials selection.

Materials	Cold Tank	Hot Tank
Tank Shell		
Plate	Carbon-Steel, ASTM A516, Gr70	Stainless-Steel ASTM A 240, Gr 321 or 347
Bar stock	Carbon-Steel, ASTM A181	Stainless-Steel ASTM A193 B8M Studs A194 B8 Heavy Hex. Nuts
Tank nozzles	Carbon-Steel, ASTM A181	Stainless-Steel, ASTM A182, Gr F321 or F347
Internal Structural		
Structural tubing	Carbon-Steel, ASTM A 500	Stainless-Steel, ASTM A249, Grade TP321H / TP347H
External Clips and Attachments	Carbon-Steel, ASTM A506	Stainless-Steel, ASTM A240, Gr 304
Corrosion Allowance (30 years)	0.4 mm	0.7 mm

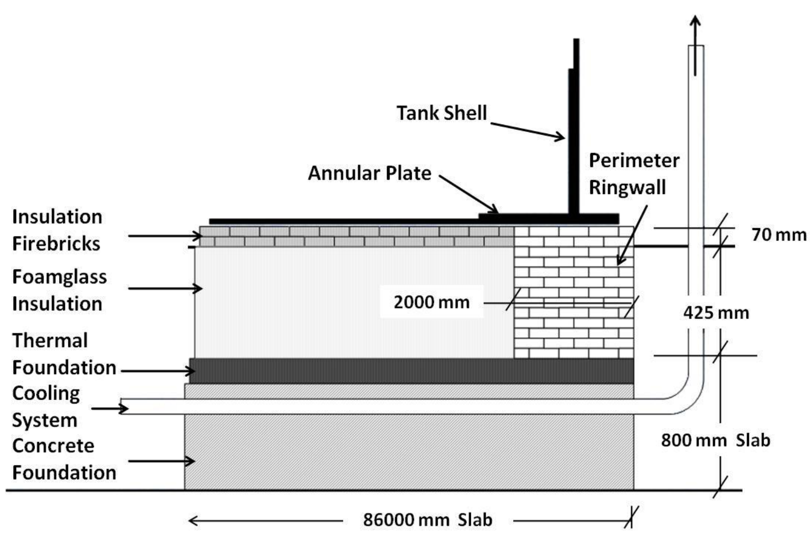

Fig. 2. The foundation insulation.

4. Results and discussions

4.1. Cost analysis

➢ **Solar multiple, SM**

Figure 3 shows the relation between solar multiple and levelized cost of energy ($/KWh) during 16 full load hours of TES, according to SAM simulation cost tool. The best of value of SM is not constant and depends on location; for Aswan SM= 1.8, Al Bahr al Ahmar SM= 2.8 and El Arish SM= 5. The solar multiple has been selected at minimum Levelized cost of energy; notice that Aswan has the minimum SM and minimum LCoE. However, the Al Bahr al Ahmar has the highest value of SM and LCoE.

Table 2 and Table 3 show the financial analysis by SAM program; this analysis is achieved by using the default of electricity cost and selected commercial PPA (Power Purchases Agreement) as financial model (SAM projects are usually greater than 0.5 MW, though SAM doesn't limit system size). This analysis compares between three locations in Egypt to select the best location under different cooling types (dry and wet cooling).

As mentioned previously sensitivity parameters are used for financial analysis SM, CF and storage capacity.

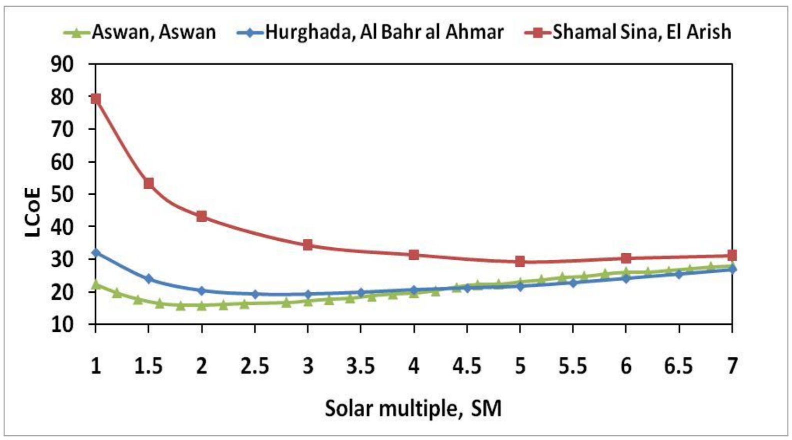

Fig. 3. Solar multiple Vs Levelized Cost of Energy.

Table 2
Cost analysis for dry cooling.

Parameters / Location	Aswan Aswan	Al Bahr al Ahmar Hurghada	El Arish Shamal Sina
Location Information, Lat. /Long, deg	23.97° N, 32.78° E	27.15° N, 33.72° E	31.08° N, 33.82° E
Irradiation at Design, W/m^2	600	600	600
Annual Irradiance, KWh/m^2	2916	2308	1487
Aperture Area, m^2	5846760	9093870	16235550
Solar Multiple, SM	1.8	2.8	5
Annual Water Usage, m^3	491,505	640,409	941,185
Hours of thermal Storage, hr	16	16	16
Annual Energy, GWh	2974	3142	2951
PPA price, $/kWh	14.38	16.98	25.87
LCOE Nominal, $/kWh	15.47	18.27	27.83
LCOE Real, $/kWh	12.5	14.76	22.49
Capacity factor, %	67.9	71.1	67.4
Total Land Area, feddan	5276.42	8206.78	14651.81

➢ Wet cooling analysis

Table 3 shows the effect of SM, CF and Storage hour on electrical annual energy, LCoE Nominal, LCoE Real, PPA price and total land area required for solar collectors (generation and storage) for wet cooling (condenser cooling). It is clear that Aswan city is also the smallest value of electricity price 13.42 $/kWh with CF 73 %, and the largest price of value of electricity price 24.68 $/kWh with CF 70.7 % for EL Arish city and the average value of electricity price 16.08 $/kWh with CF 75.9 % for Al Bahr al Ahmer city.

Table 3
Cost analysis for wet cooling.

Parameters / Location	Aswan Aswan	Al Bahr al Ahmar Hurghada	El Arish Shamal Sina
Location Information, Lat. /Long, deg	23.97° N, 32.78° E	27.15° N, 33.72° E	31.08° N, 33.82° E
Irradiation at Design, W/m^2	600	600	600
Annual Irradiance, KWh/m^2	2916	2308	1487
Aperture Area, m^2	5846760	9093870	16235550
Solar Multiple, SM	1.8	2.8	5
Annual Water Usage, m^3	9,171,856	9,626,086	9,453,749
Hours of thermal Storage, hr	16	16	16
Annual Energy, GWh	3196	3322	3096
PPA price, $/kWh	13.42	16.08	24.68
LCOE Nominal, $/kWh	14.43	17.30	26.55
LCOE Real, $/kWh	11.66	13.98	21.45
Capacity factor, %	73	75.9	70.7
Total Land Area, feddan	5276.42	8206.78	14651.81

The dry cost analyses are presented by some of bar charts in figures 4, 5 and 6. Moreover, a comparison between dry and wet cooling is introduced in figures 7, 8 and 9.

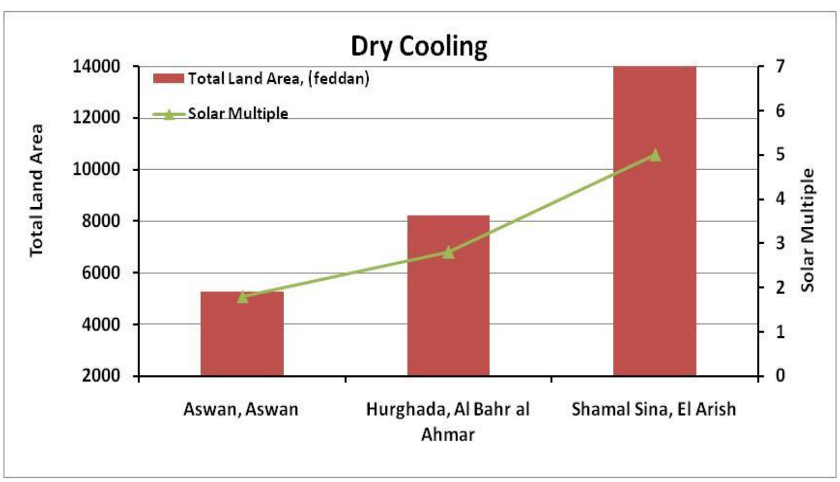

Fig. 4. Total land area required for three cities with SM.

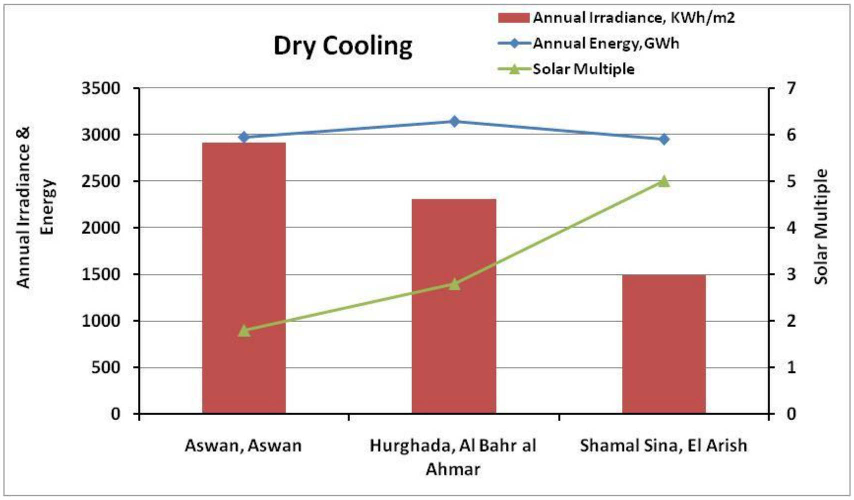

Fig. 5. Annual energy and annual irradiance with SM and locations.

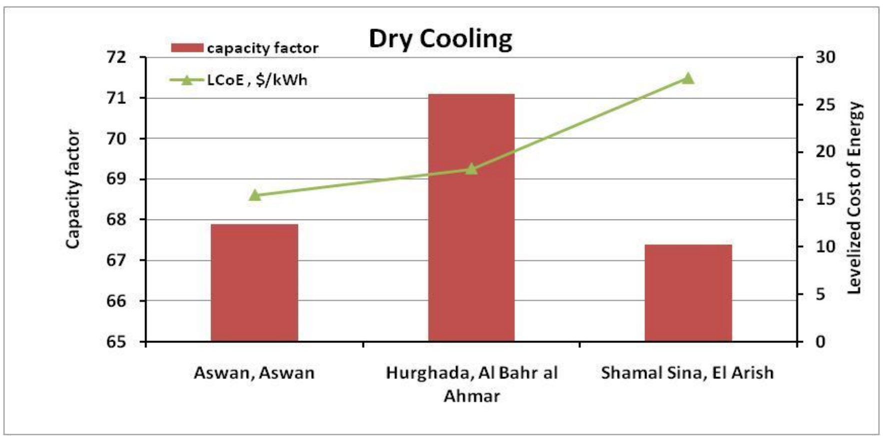

Fig. 6. Capacity factor and LCoE with location (wet cooling).

Figure 4 presents an effect of the SM, solar multiple, and the total land area with solar plant location for dry cooling. It is clear that low SM has small land area and vice versa. That means Aswan city has minimum land area, however, El Arish city has maximum land area. Figure 5 shows the effect of the solar multiple, SM, electrical annual energy and annual irradiation on solar plant location for dry cooling. It is clear that low SM has minimum electrical annual energy with maximum annual irradiation. That means Aswan city has maximum annual irradiation, however, Al Bahr al Ahmer has maximum electrical annual energy at annual irradiation less than form Aswan. El Arish city has minimum annual irradiation; this requires increasing SM to cover the demand energy. Figure 6 shows the influence of capacity factors and levelized cost of energy in different location of dry cooling.

Figure 7 shows the influence the cooling type on electrical annual energy for different locations. It is clear that the annual energy output from power block for wet cooling is the higher than the dry cooling for all locations. And also, the fig. 8 shows the influence capacity factors for different locations. The capacity factor for wet cooling is the higher than the dry cooling for all locations. Figure 9 shows levelized energy of cost on the location. It is noted that, the LCoE for wet cooling is the smaller than the dry cooling for all locations. Finally, it is concluded that the selection of the cooling type is restricted by the available location and demand requirement of cooling water.

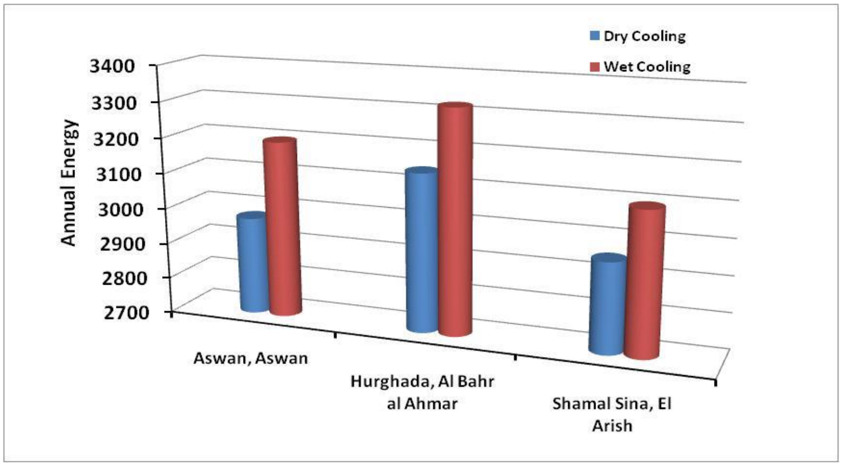

Fig. 7. Annual energy (electrical) for dry and wet cooling.

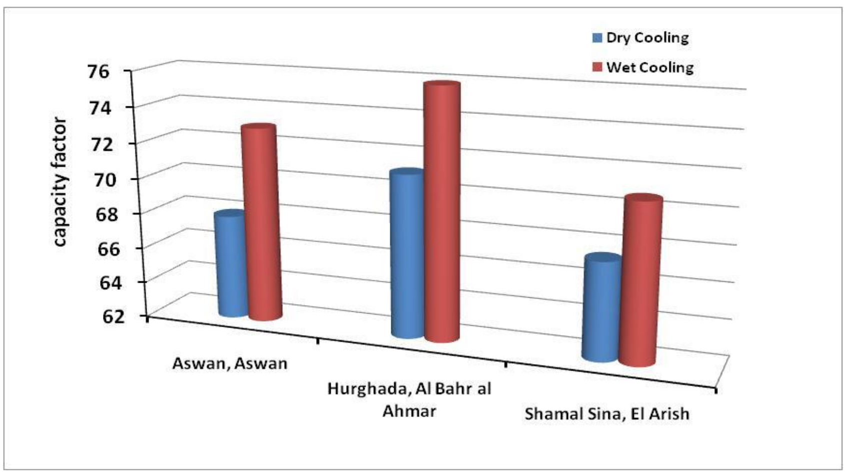

Fig. 8. Capacity factor for dry and wet cooling.

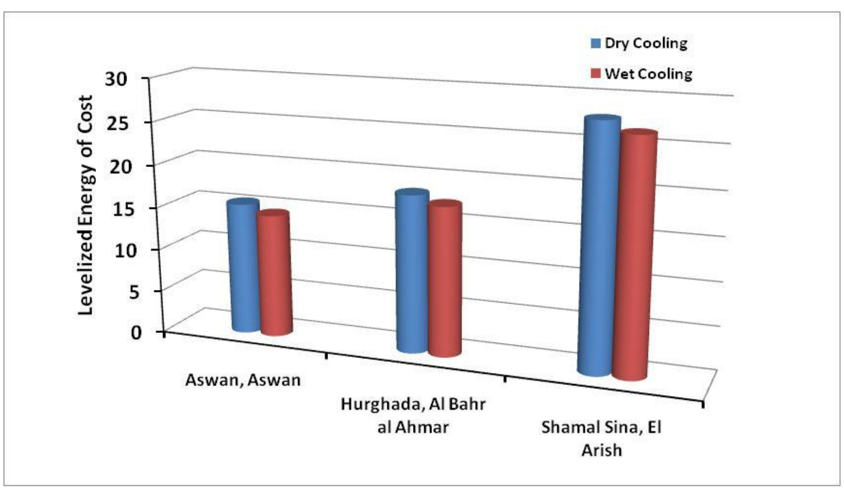

Fig. 9. LCoE for dry and wet cooling.

4.2. Storage tank analysis

Figure 10 shows the elevation diagram for hot salt tank which includes the dimensions for manufacture and installation. Figure 11 introduces all information and dimensions to construct the plates and shell for hot tank.

➢ **Preliminary value for tank cost**:

The initial cost is estimated (row materials) of the thermal storage tank which will include the following:

1. Foundation cost
2. Tank structure cost
3. Internal insulation cost
4. External insulation cost

The hot tank needs more provision design about cold tank, so that we will make the hot tank as cost reference, where the initial cost for hot tank greater than cold tank. Due to the thermal concerns upon the hot tank, the design of hot tank takes a deep consideration than the cold tank. Therefore, this study considers the cost of the hot tank as a cost reference because the cost analysis of the hot tank is more important and valuable than the cold tank.

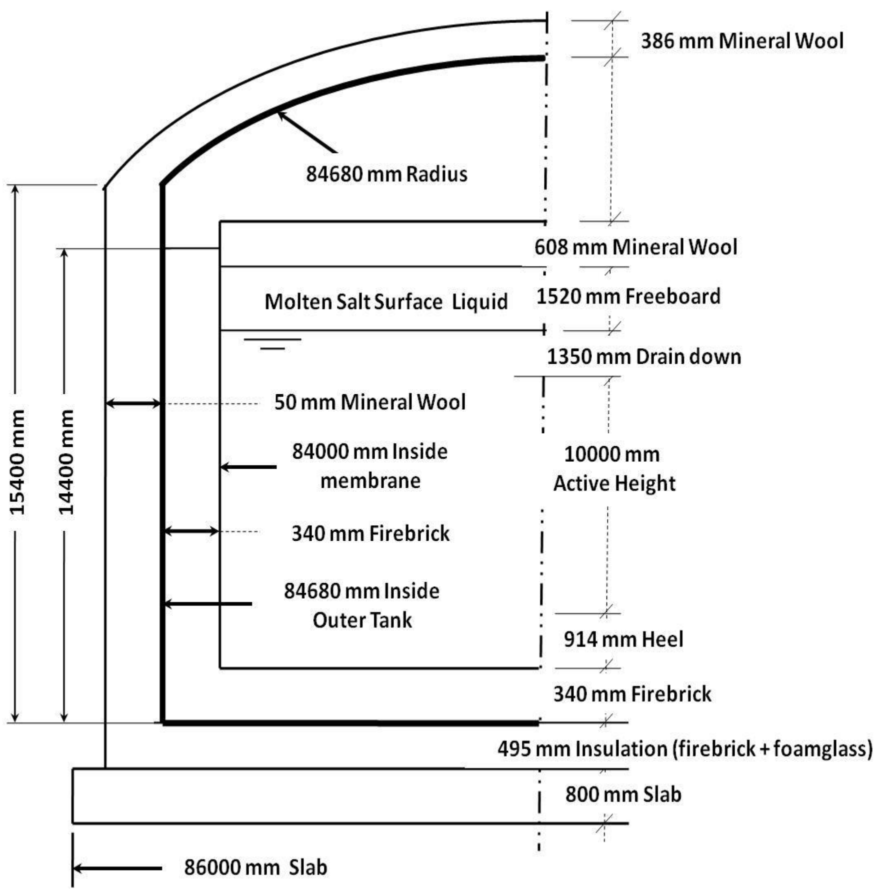

Fig. 10. Hot salt tank elevation diagram.

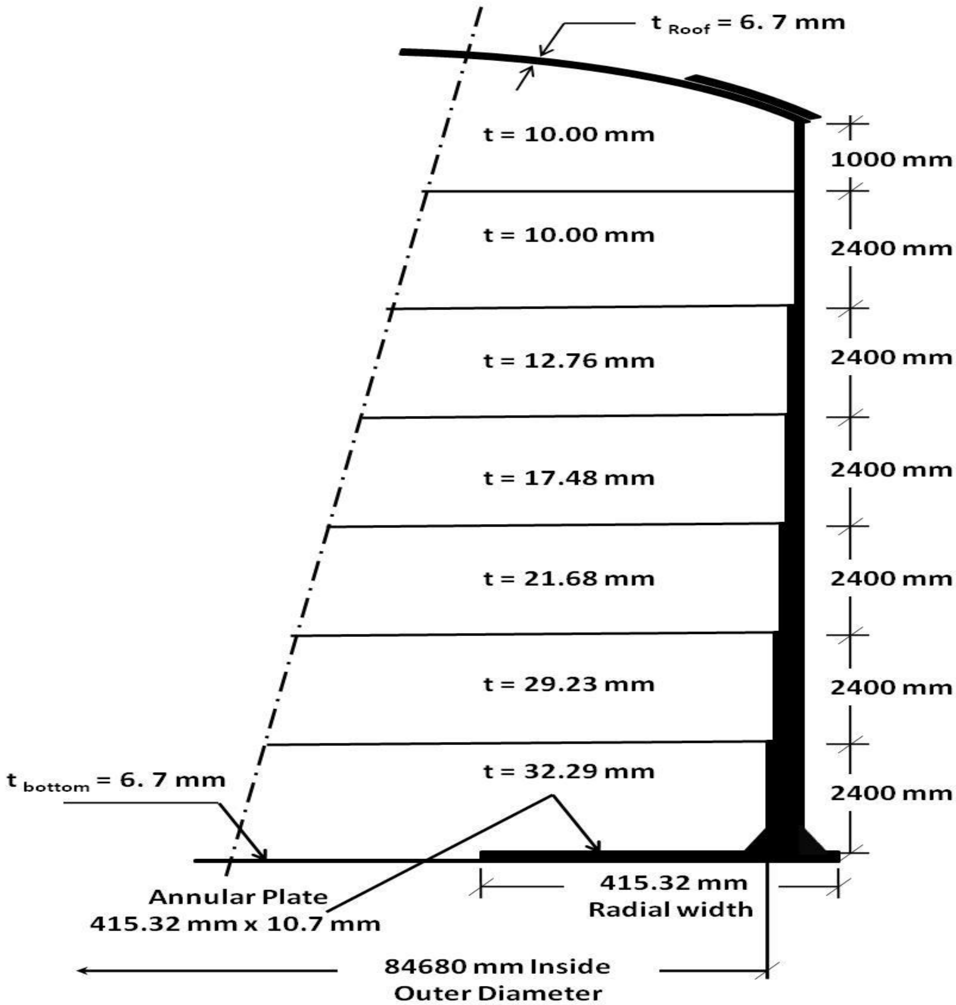

Fig. 11. Shell structure for hot tank.

Table 4
Price for hot tank row materials.

Items	Thermal conductivity (W/ m.K)	Price
Reinforced foundations	1.7	US $ 157.8 / m^3
ASTM A240 Gr 321 Density 8030 kg/m^3	19	FOB* US $ 1200/ Ton
Refractory brick SK-38 Bulk Density 2400 kg/m^3	0.68	FOB* US $ 100/ Ton
Firebrick Bulk Density 800 kg/m^3	0.13	FOB* US $ 135/ Ton
Foamglass	0.045	FOB* US $ 260/ m^3
Mineral wool	0.17	FOB* US $ 40/ m^3

Table 4 shows the list price for all row materials required to tank installation. Now, we calculate the preliminary cost according to list price as shown in Table 5.

Table 5
Hot salt tank cost estimate.

Item	Quantity	Price, US $
Foundations		
Slab concrete	5916.8 m^3	933,671.04
Refractory brick (Ring wall)	132.183 m^3 317.238 Tons	31,723.8
Foamglass	2336.559 m^3	607,505.34
Firebrick	18.692 m^3 14.954 Tons	2,018.74
Tank structure		
Floor	1.176 m^3 (t_b=10.7 mm) 36.997 m^3 (t_b=6.7 mm) 306.529 Tons	367,834.8
Shell	711 Tons	853,200
Roof	36.215 m^3 290.81 Tons	348,972
Internal Insulation		
Firebrick (floor)	1914.831 m^3 1531.865 Tons	206,801.75
Mineral wool (shell)	4636.02 m^3	185,440.8
External Insulation		
Mineral wool for tank side	204.964 m^3	8,198.56
Mineral wool for roof	2329.84 m^3	93,193.6

The amount of the tank cost as follows:

Reinforced concrete cost	= 933,671.04 US $
Tank structure cost	= 1,570,006.8 US $
Refractory brick cost	= 31,723.8 US $
Firebrick cost	= 206,820.49 US $
Foamglass cost	= 607,505.34 US $
Mineral wool cost	= 286,832.96 US $
Total initial cost	**= 3,683,560.43 US $**

Table 6 introduces a comparison between the three locations taking in the consideration the total volume of TES, the storage tank number and total initial cost for tanks. The SM=1 is taken a reference for this analysis. The tank initial cost for Aswan city has the smallest value while El Arish city has the higher value as shown in Table 6. The full load hours and tank dimensions have been taken the gray line as same element for three locations.

Table 6
Cost analysis for storage tank.

Items	Aswan Aswan	Al Bahr al Ahmar Hurghada	El Arish Shamal Sina
Solar Multiple, SM	1.8	2.8	5
Total volume of TES, m^3	197,889.2	307,983.2	549,970
Tank dimensions (diameter x height), m	84 × 10	84 × 10	84 × 10
TES Full-load hours; hr	16.00	16.00	16.00
Number of parallel tank pairs	4	6	10
Total initial cost, US $	24,683,560.43	36,683,560.43	60,683,560.43

5. Design outline

This work draws the road map for the designers which includes the thermal solar power plant location taking in the consideration the solar irradiation of every location. Additionally, the thermal storage methodology with full load hours equals 16 hrs. The designers should calculate the cost in details of the storage tanks and compare between the dry cooling and wet cooling for every location. The cost analysis should lead the designers to the best location which has the minimum SM and minimum LCoE. The thermal storage tank cost analysis should include the details of foundation cost, tank structure cost, internal insulation cost and external insulation cost.

6. Conclusion

Several of considerable findings are obtained from the molding of parabolic trough concentrators with using molten salts for HTF and TES simulations on SAM (Cost analysis) and thermal storage analysis:

- Cost analysis shows that SM of Aswan is smaller value and it equals 1.8 due to high annual irradiation 2916 kW.hr/m^2 .
- Aswan city has a smallest electricity price 14.38 $/kWh with CF 67.9 %. However, the largest price of value of electricity price 15.87 $/kWh with CF 67.4 % is for EL Arish city. Moreover, the average value of electricity price 16.98 $/kWh with CF 71.1 % for Al Bahr al Ahmer city.
- Aswan has the minimum SM and minimum LCoE. However, the Al Bahr al Ahmar has the highest value of SM and LCoE.
- Cost analysis is accomplished for dry and wet cooling analysis; the results indicated that the best cooling type is the wet cooling type for capacity factor and annual energy. While the analysis of LCoE indicated that the best cooling type is the dry type. The selection of cooling method to use depends on water resource of the location.
- Pair of thanks can be utilized due to the large volume of the storage tanks; every tank should have a 10 m height and 84 m diameter.

- The tank initial cost for Aswan city has the smallest value while El Arish city has the highest value.

References

[1] Ruegamer T, Kamp H, Kuckelkorn T, Schiel W, Weinrebe G, Nava P, et al. Molten Salt for Parabolic Trough Applications: System Simulation and Scale Effects. Energy Procedia 2014;49:1523–32. doi:10.1016/j.egypro.2014.03.161.

[2] Trieb F. Concentrating solar power for the Mediterranean region 2005.

[3] Trieb F. Trans-Mediterranean interconnection for concentrating solar power", Technical Report, German Aerospace Center (DLR), Institute of Technical Thermodynamics, Section Systems Analysis and Technology, Assessment 2006.

[4] Poullikkas A. Economic analysis of power generation from parabolic trough solar thermal plants for the Mediterranean region—A case study for the island of Cyprus. Renew Sustain Energy Rev 2009;13:2474–84. doi:10.1016/j.rser.2009.03.014.

[5] Fthenakis V, Mason JE, Zweibel K. The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. Energy Policy 2009;37:387–99. doi:10.1016/j.enpol.2008.08.011.

[6] Izquierdo S, Montañés C, Dopazo C, Fueyo N. Analysis of CSP plants for the definition of energy policies: The influence on electricity cost of solar multiples, capacity factors and energy storage. Energy Policy 2010;38:6215–21. doi:10.1016/j.enpol.2010.06.009.

[7] Sargent, Lundy. Assessment of parabolic trough and power tower solar technology costs and performance forecasts, NREL 2003.

[8] Ho CK, Kolb GJ. Incorporating Uncertainty into Probabilistic Performance Models of Concentrating Solar Power Plants. J Sol Energy Eng 2010;132. doi:10.1115/1.4001468.

[9] Krishnamurthy P, Mishra S, Banerjee R. An analysis of costs of parabolic trough technology in India. Energy Policy 2012;48:407–19. doi:10.1016/j.enpol.2012.05.041.

[10] Kearney D, Herrmann U, Nava P, Kelly B, Mahoney R, Pacheco J, et al. Assessment of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field. J Sol Energy Eng 2003;125:170–6. doi:10.1115/1.1565087.

[11] Gil A, Medrano M, Martorell I, Lázaro A, Dolado P, Zalba B, et al. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization. Renew Sustain Energy Rev 2010;14:31–55. doi:10.1016/j.rser.2009.07.035.

[12] Medrano M, Gil A, Martorell I, Potau X, Cabeza LF. State of the art on high-temperature thermal energy storage for power generation. Part 2—Case studies. Renew Sustain Energy Rev 2010;14:56–72. doi:10.1016/j.rser.2009.07.036.

[13] Esen M, Ayhan T. Development of a model compatible with solar assisted cylindrical energy storage tank and variation of stored energy with time for different phase change materials. Energy Convers Manag 1996;37:1775–85. doi:10.1016/0196-8904(96)00035-0.

[14] Laing D, Steinmann W-D, Tamme R, Richter C. Solid media thermal storage for parabolic trough power plants. Sol Energy 2006;80:1283–9. doi:10.1016/j.solener.2006.06.003.

[15] Lovegrove K, Luzzi A, Soldiani I, Kreetz H. Developing ammonia based thermochemical energy storage for dish power plants. Sol Energy 2004;76:331–7. doi:10.1016/j.solener.2003.07.020.

[16] Michels H, Pitz-Paal R. Cascaded latent heat storage for parabolic trough solar power plants. Sol Energy 2007;81:829–37. doi:10.1016/j.solener.2006.09.008.

[17] Luzzi A, Lovegrove K, Filippi E, Fricker H, Schmitz-goeb M, Chandapillai M, et al. Techno-Economic Analysis of a 10 Mwe Solar Thermal Power Plant Using Ammonia-Based Thermochemical Energy Storage. Sol Energy 1999;66:91–101. doi:10.1016/S0038-092X(98)00108-X.

[18] Yang Z, Garimella S V. Thermal analysis of solar thermal energy storage in a molten-salt thermocline. Sol Energy 2010;84:974–85. doi:10.1016/j.solener.2010.03.007.

[19] Bradshaw RW, Siegel NP. Molten Nitrate Salt Development for Thermal Energy Storage in Parabolic Trough Solar Power Systems. ASME 2008 2nd Int. Conf. Energy Sustain. Vol. 2, ASMEDC; 2008, p. 631–7. doi:10.1115/ES2008-54174.

[20] Kearney D, Kelly B, Herrmann U, Cable R, Pacheco J, Mahoney R, et al. Engineering aspects of a molten salt heat transfer fluid in a trough solar field. Energy 2004;29:861–70. doi:10.1016/S0360-5442(03)00191-9.

[21] Fernandes D, Pitié F, Cáceres G, Baeyens J. Thermal energy storage: "How previous findings determine current research priorities." Energy 2012;39:246–57. doi:10.1016/j.energy.2012.01.024.

[22] Mohamed MH, El-Sayed AZ, Megalla KF, Elattar HF. Modeling and performance study of a parabolic trough solar power plant using molten salt storage tank in Egypt: effects of plant site location. Energy Syst 2019;10:1043–70. doi:10.1007/s12667-018-0298-4.

[23] Yuanjing W, Cheng Z, Yanping Z, Xiaohong H. Performance analysis of an improved 30 MW parabolic trough solar thermal power plant. Energy 2020;213:118862. doi:10.1016/j.energy.2020.118862.

[24] Khajepour S, Ameri M. Techno-economic analysis of using three Fresnel solar fields coupled to a thermal power plant for different cost of natural gas. Renew Energy 2020;146:2243–54. doi:10.1016/j.renene.2019.08.075.

[25] Mostafavi Tehrani SS, Taylor RA, Nithyanandam K, Shafiei Ghazani A. Annual comparative performance and cost analysis of high temperature, sensible thermal energy storage systems integrated with a concentrated solar power plant. Sol Energy 2017;153:153–72. doi:10.1016/j.solener.2017.05.044.

[26] Herrmann U, Kelly B, Price H. Two-tank molten salt storage for parabolic trough solar power plants. Energy 2004;29:883–93. doi:10.1016/S0360-5442(03)00193-2.

[27] Ferri R, Cammi A, Mazzei D. Molten salt mixture properties in RELAP5 code for thermodynamic solar applications. Int J Therm Sci 2008;47:1676–87. doi:10.1016/j.ijthermalsci.2008.01.007.