# Analytical Study of a Modified PS10 in Aswan

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**Abstract**— According to the Egyptians' need to a renewable energy source for electric power generation, it is proposed to install a similar power plant as PS10 with a modified thermal energy storage system in Aswan. This study is a theoretical analysis of installing PS10 plant with the modified storage system to determine the performance of its operation in Aswan. In this study, a comparative storage capacity is developed between the existing PS10 in Sanlúcar la Mayor- Spain, and a modified storage one of similar specifications operated in Aswan, Egypt. The modified storage system has two tanks of suitable molten salts. The study includes cyclic operation of the two tanks during plant operation. It is expected to increase the storage capacity of the excising PS10 plant. Such solution is found very promising to accommodate the life in arid zones in Aswan.

**Index Terms—** Solar Power Tower System; CSP; Thermal Energy Storage; Modified Thermal Energy Storage; Modified System; SPT; Innovated SPT; PS10..

## 1 Introduction

Thermal Energy Storage works to make concentrated solar tower (CST) a more flexible and valuable technology for electricity generation [Duffe S, 5]. Thermal Energy Storage makes CST possible to meet electricity peak demand not only by extending the operation time when there is no solar irradiation but also by overcoming weather fluctuations [Y Tian, 4 - Tinton D, 3]. PS10 is a concentrating solar thermal power plant of 11MW output power. It is based on tower technology for grid-connected electricity generation [M. A. Mustafa, 2]. PS10 plant is located in the town of Sanlúcar la Mayor (37.2o Latitude - 6olongitude), 25 km west from the city of Seville [Final PS10 report, 10]. PS10 has the best available information in concentrating solar thermal power plants. Furthermore, it has a lower levelized cost of operation than any concentrating solar thermal power plant that produces electricity. PS10 plant is working with Direct Saturated steam Generation (DSG) concept, at considerably low operating condition (250ºC, 40bar) [Final PS10 report, 10]. Figure 1 shows the schematic diagram of PS10 plant.

In this plant, water was converted to steam in the receiver and used directly to power a conventional Rankine-cycle steam turbine. The heliostat field consisted of 624 heliostats of 121 m2 reflective area each.

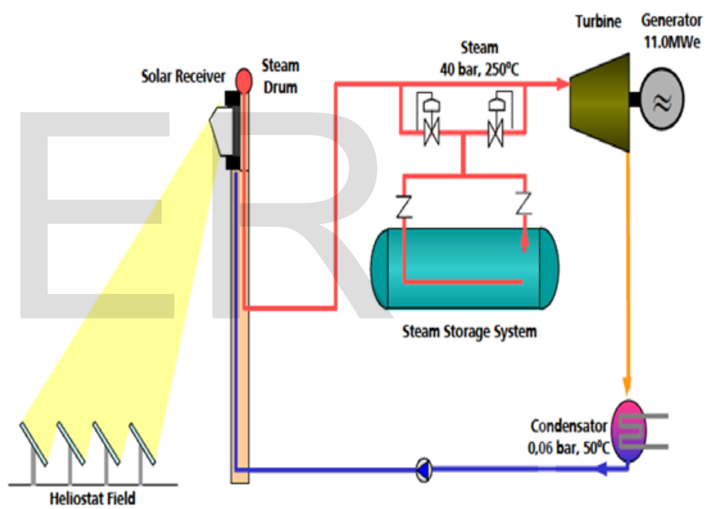


Figure 1 PS10 plant in Sanlúcar la Mayor, Spain

Thermal storage system is composed by four tanks that are sequentially operated in relation to their charge status [M. A. Mustafa, 2 - Final PS10 report, 10]. During full load operation of the plant, part of steam produced by receiver will be employed to load the thermal storage system. When energy is needed to cover a transient period, energy from saturated water in the tanks will be recovered. The annual energy generation amounts for PS10 about 23GWh [Solucar, 14]. Table 1 shows the technical descriptions of PS10 plant [Final PS10 report, 10].

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| Table 1 General description of PS10 plant | |
|---|---|
| Emplacement | Lat 37.2º, Log 6.23º |
| Nominal power | 11 MW |
| Tower height | 100 m |
| Technology | Saturated steam |
| Heliostat | 624 @ 121 $m^2$ |
| Area | 60 Has |
| Thermal storage technology | Water / steam |
| Thermal storage capacity | 50 min@ 50% Rate |
| Steam cycle | 40 bar, 250ºc |
| Annual electricity production | 23 GWh |
| Plant cost | $47M |

Unfortunately, the storage system was complex and thermodynamically inefficient. While PS10 successfully demonstrated power tower technology, it also revealed the disadvantages of a water/steam system, such as the intermittent operation of the turbine due to cloud transience and lack of effective thermal storage.

To encourage the development of CST, we should seek to redesign the storage system for PS10 plant to include molten salts as a heat transfer fluid (HTF) for increasing storage capacity and using steam only for power generation in simple Rankine cycle [Flueckiger S M, 7]. The molten salt was chosen because its high stability which reaches around 600°C [Angela M Patnode, 6] and that is suitable for working at high solar density in Aswan (23.5o Latitude - 33o longitude), [M. A. Mustafa, 2]. In particular, these nitrate salts have low corrosion rates with common piping materials and are relatively inexpensive [IREA, 15]. The goals of the redesigned plant are to validate nitrate salt technology, to reduce the technical and economic risk of power towers, to increase the storage capacity, and to stimulate the commercialization of power tower technology.

In this study, a comparative analysis is developed between the storage capacity of PS10 in Sanlúcar la Mayor- Spain, and the storage capacity of using two tanks molten salt storage system for PS10, in Aswan- Egypt. It describes the effect of the modification to increase the storage energy. This analysis, that will presented, is developed with MATLAB© software and excel spread sheet programs. The study takes many steps in order to make the proposed comparison. In section 2, the modification of tower receiver, storage system, and steam generator are described as the input parameters to the modified plant. In section 3, the analysis of MPS10 is discussed. Tower receiver, hot and cold storage tanks, MPS10 performance are the main elements for result analysis.

## 2 MODEL DESCRIPTION

The modified PS10 mentioned, is a PS10 with molten salt thermal energy storage. It required a new molten-salt heat transfer systems (including the receiver, thermal storage, piping, and a steam generator) and a new control system. The heliostat field, the tower, and the turbine/generator required only minimal modifications and the main modification will apply to the storage system. Figure 2 Show the modified storage system for PS10 plant.

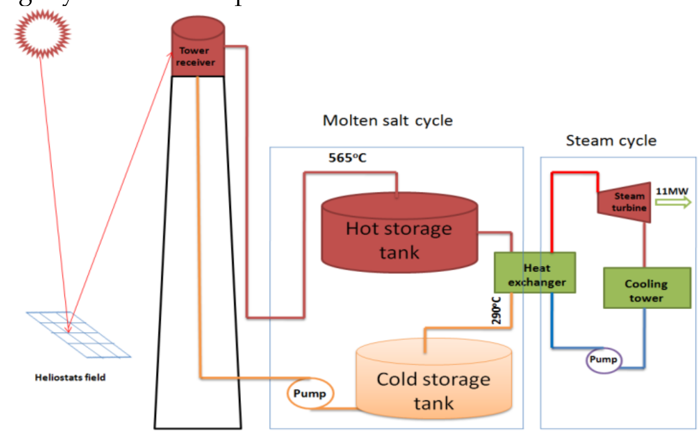



Figure 2 Modified storage systems for PS10 (MPS10) plant

Properties of molten salts used in MPS10 plant are listed in Table 2 [S D. Kearney, 1- Sohal M.S, 13]. These values will be considered constant during the calculations for different operating temperatures. Because thermal storage is an important issue for a solar power tower SPT system, the cost effectiveness of nitrate salts in a MPS10 plant was initially evaluated in terms of cost per unit thermal energy stored [Herrmann U, 19].

| Table 2 Properties of Molten salts used in MPS10 plant | |
|---|---|
| Composition, % | 60%$NaNO_3$, 40%$KNO_3$ |
| Freezing Point oC | 220 |
| Upper Temperature oC | 600 |
| Density at (400 oC) kg/$m^3$ | 1870 |
| Heat capacity at (400 oC) J/kg·k | 2660 |
| Cost $/kg | 0.49 |
| Storage Cost $/KWh | 5.8 |

In MPS10 plant, liquid salt at 290ºC (minimum operating temperature) is pumped from a cold storage tank through the receiver where it is heated to 565ºC [Lukas Heller, 11] (maximum operating temperature) and then on to a hot tank for storage [Robert M, 12]. When power is needed from the plant, hot salt is pumped to a steam generating system that produces superheated steam for a conventional Rankine cycle turbine/generator system. From the steam generator, the salt is returned to the cold tank where it is stored and eventually reheated in the receiver [Franclim R C, 8- Martin S, 18].

## 2.1 Receiver Modification

The receiver used for receiving sunlight from the heliostat field to raise the temperature of the HTF to the desired temperature. The receiver has been developed to fits the molten salt and also fits its temperature which go up to 565Oc instead of steam temperature, which wasn't exceed 250Oc. The receiver design has been optimized to absorb a maximum amount of solar energy while reducing the heat losses due to convection and radiation. The formula which describes the tower receiver operation can be expressed in Equation 1.

$$\acute{\eta}_{receiver} = \frac{Q^{\cdot}_{tr}}{Q^{\cdot}_{field}} = \frac{m^{\cdot}_{tr} * Cp * (T_{tr,out} - T_{tr,in})}{Q^{\cdot}_{field}} \quad (1)$$

The mass flow rate of the molten salt to the tower receiver varies to remain the outlet tower temperature constant at 565Oc by using a control on the pumping system of the tower. The heliostat reflected power is calculated according to BIRD model, based on the hourly performance, with clear sky conditions, Appendix. This calculation is out scope of this work as the study focus on the modified storage effect.

The receiver comprises a series of panels (each made of 32 thin-walled, stainless steel tubes) through which the molten salt flows in a serpentine path. The panels form a cylindrical shell surrounding piping, structural supports, and control equipment. The external surfaces of the tubes are coated with a black paint that is robust, resistant to high temperatures and thermal cycling, and absorbs 92% of the incident sunlight. It includes consideration of new steel alloys for the receiver tubes and ease of manufacture for the entire receiver subsystem. The design of that receiver allows it to rapidly change temperature without being damaged. It can safely change the molten salts temperature from 290Oc to 565Oc [Dylan Grogan, 16].

## 2.2 Storage Modification

The storage system is an important consideration in this study. It has been modified to a different system contains various control to ensure the validity of the HTF. The four steam tanks have been changed with two heat reservoirs which are called hot and cold storage tanks, as shown in the previous figure. They are externally insulated and constructed of stainless steel and carbon steel for the hot and cold tank, respectively.

The design of the storage system is done by using dynamic differential equation for the heat transfer between the HTF and each tank, with energy balances on each tank. The followed criteria to design the storage system are based on the autonomy of the CST plants, where the goal is to achieve many hours of electrical power production per day without solar radiation [Pacheco J E, 17]. It's assumed that the system doesn't have any losses (U=0.0; adiabatic operation). Equation 2 describes the calculation of the temperatures reached during the operation of the MPS10 plant in the hot and cold tanks [Franclim R C, 8].

$$M\,Cp\,\frac{dT}{dt} = m^{\cdot}\,\rho\,Cp\,(T_1 - T_0) + U\,A\,(T_2 - T_0) \quad (2)$$

Each tank accumulated with a specific amount of molten salts. Equations 3, 4, and 5 show the mass balance and describe the energy balance for any tank.

$$\frac{dM}{dt} = m^{\cdot}_{in} - m^{\cdot}_{out} \quad (3)$$

$$\frac{dE}{dt} = m^{\cdot}_{in}\,Cp\,T_{in} - m^{\cdot}_{out}\,Cp\,T_{out} \quad (4)$$

$$\frac{dE}{dt} = (m^{\cdot}_{in} - m^{\cdot}_{out})\,Cp\,T_{out} + M\,Cp\,\frac{dT_{out}}{dt} \quad (5)$$

An important consideration in successfully implementing this technology is the identification of pumps, valves, valve packing, and gasket materials that will work with molten salts. All pipes, valves, and vessels for hot salts were constructed from stainless steel because of its corrosion resistance in the molten salts environment. The cold salts system is made from mild carbon steel. Accordingly, MPS10 is designed with a minimum number of gasket flanges and most instrument transducers, valves, and fittings are welded in place.

## 2.3 Steam Generator Modification

The steam production has not changed much. It has been remained the electric generation system, Rankine cycle, and the only change will be the steam generation process. Instead of generating the steam directly from the receiver as PS10, a heat exchanger between the molten salts and water constructed after the molten salts exit from the hot tank [Kopp Joseph E, 9]. Equation 6 describes the heat amount required in heat exchanger.

$$Q^{\cdot}_{sg} = m^{\cdot}_{hex} * Cp * (T_{hex,in} - T_{hex,out}) \quad (6)$$

The rate of change of heat in the heat exchanger is accomplished by three steps. They are preheater, steam generator, and super heater. Rankine cycle calculation also is out scope of this work, the study focus on the modified storage effect; only the steam conditions in the steam generator are discussed. The steam generator, consist of a shell-and-tube heat exchanger. In this system, Stainless steel cantilever pump transport salt from the hot storage tank through the steam generator and back to the cold storage tank. Figure 3 shows the heat transfer in the steam generation process.

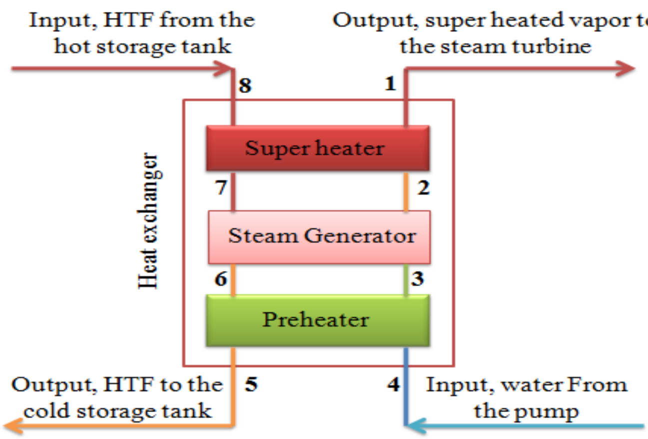



Figure 3 heat exchanging process for steam generations in MPS10 plant

The hot storage tank receives molten salts from the tower receiver and delivered it to a heat exchanger steam generator. Also the cold storage tank receives molten salt from the heat exchanger steam generator and delivers it to the tower receiver. It is worth mentioning that steam generator receives a fixed amount of molten salt.

## 3 MODEL RESULTS ANALYSIS

This section describes the theoretical results of the MPS10. These results are a simulation of MPS10 in Aswan. In this analysis, we take 21th March as a reference day for plant operation.

### 3.1 Tower Receiver

In Figure 4, the temperature of the molten salts at the tower receiver outlet reached its desired temperature (565Oc), during the day light. This achieved by the control system on the flow rate of molten salts to the receiver, Appendix. Figure 5, the control system allow the flow rate of the molten salts to increases when the receiver temperature became more than 565Oc and decreases when the receiver temperature became smaller than 565Oc. The control system make temperature at receiver inlet stays at 290Oc and temperature at receiver outlet stays at 565Oc during the plant operation.

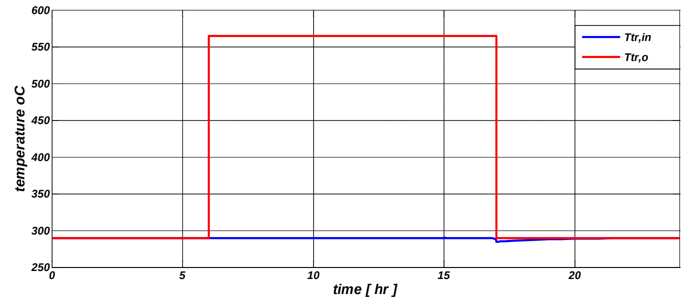



Figure 4 Simulation of MPS10, inlet and outlet temperature of the receiver

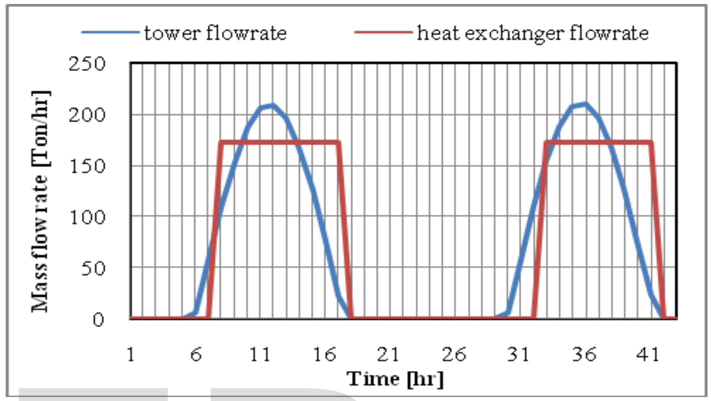



Figure 5 Simulation of MPS10, tower and heat exchanger mass flow rate, (21,22th March)

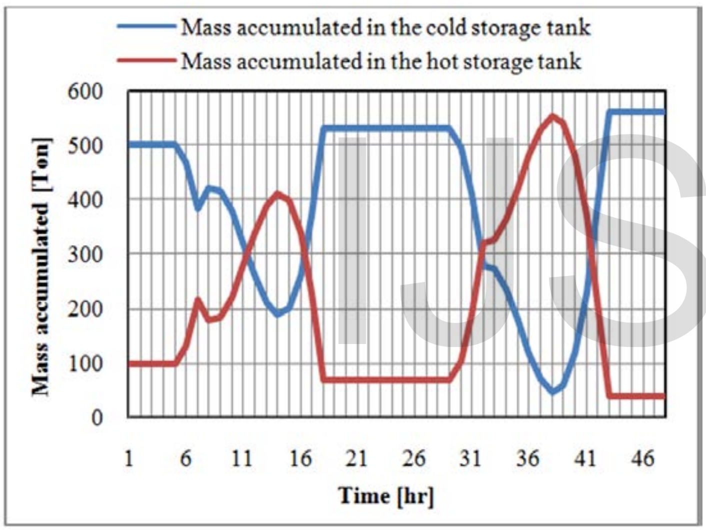
### 3.2 Hot and cold storage tanks

The thermal performance of the hot and cold storage tanks is the evidence on the extent of the thermal storage for the MPS10 plant. At the beginning of operation, hot storage tank is filling to the middle and raise its temperature by auxiliary heaters to 565Oc. The cold storage tank also is filled to the middle, but its temperature is raised to 290Oc. All of that is achieved in order to provide the operating conditions of the MPS10 for easy work.

The MPS10 begins to work with the emergence of the first solar light in Aswan. Molten Salt begins to move from the cold storage tank to the tower receiver; its temperature rises to 565Oc, and stored in the hot storage tank. Molten salt isn't transmitted from the hot storage tank to the heat exchanger steam generator until the quantity of molten salts is able to generate the amount of steam required for working the turbine.

With Sunset, molten salt stops transmission to the receiver while the transition to heat exchanger steam generator remains continues until the hot storage tank is empty. Each tank of MPS10 designed to accommodate about 600 tons of molten salts which mean store of about 320m3 of molten salts, (600 ton/1870 kg/m3). Figure 6 Show the cyclic operation of the two tanks in the first two operation days (21,22th March). Figure 7 Show the operation of the two tanks during 21,22th June.

| Table 4 Performance of PS10 and MPS10 | | |
|---|---|---|
| Item | PS10 in Spain | MPS10 in Aswan |
| Steam generator outlet conditions | saturated | superheated |
| Temperature at steam generator outlet $^0$C | 250 | 280 |
| Thermal Power MW | 35.8 | 37.9 |
| Output power MW | 11 | 14.2 |
| Thermal Power to Electric Power Efficiency % | 30.75 | 37.4 |
| Annual energy production GWh | 23 | 35.9 |



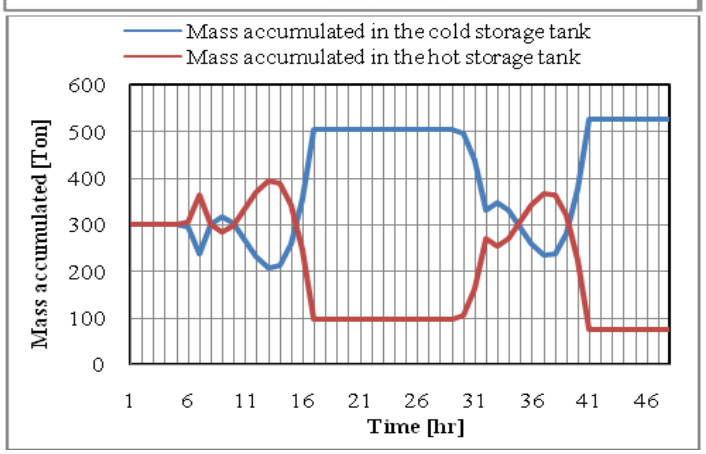
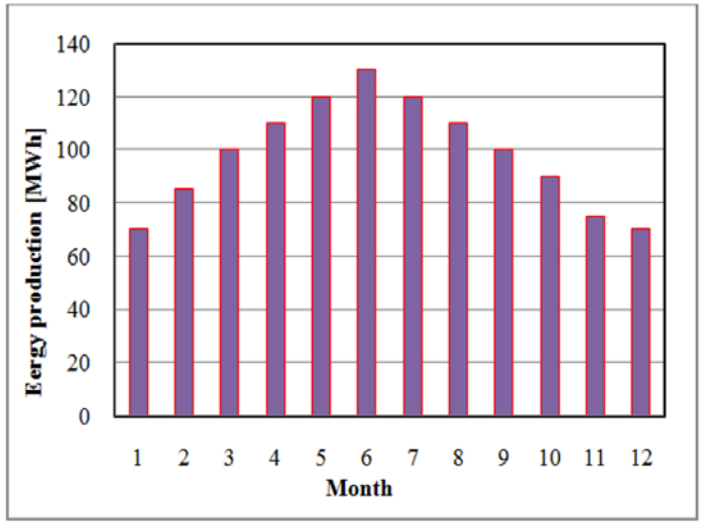




Figure 6 Simulation of MPS10, cyclic operation of the hot and cold storage tanks, (21th-22th March).

Figure 7 Simulation of MPS10, cyclic operation of the hot and cold storage tanks, (21th-22th June).

### 3.3 Plant performance

The modification of PS10 to molten salts storage system is




applied in order to increase the storage capacity of the plant when working in Aswan. PS10 produces about 23 GWh yearly. MPS10 increasing this value to about 35.9 GWh yearly. The increasing in the energy production value due to operating conditions of the plant varies from Spain to Egypt where high solar density in southern Egypt. Figure 8, illustrates the average energy production of the MPS10 plant during the year of operation.

Figure 8 Simulation of MPS10, monthly energy productions of MPS10 plant in Aswan.

The analysis of heat exchanger, Figure 3, listed in Table 3. These values are calculated using simple heat exchanger equations.

| Table 3 analysis of MPS10 steam production | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| salt flow rate [kg/s] | steam flow rate [kg/s] | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 |
| 60 | 18.4 | 28 | 25 | 25 | 50 | 29 | 38 | 55 | 565 |

Final presentation of the performance of MPS10 plant is listed in Table 4. It is noted that, the plant output power increased as the superheated conditions at turbine inlet, and so increase the plant thermal efficiency.

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## 4 FESABILITY STUDY OF MPS10

PS10 was built in December 2005 and opened in March 2007. The total Cost is ($47M), the specific cost is about 4200$/kWgross. In order to calculate the capital cost of the PS10 in 2014, the inflation rates are taken from 2007 to 2013, figure 9.

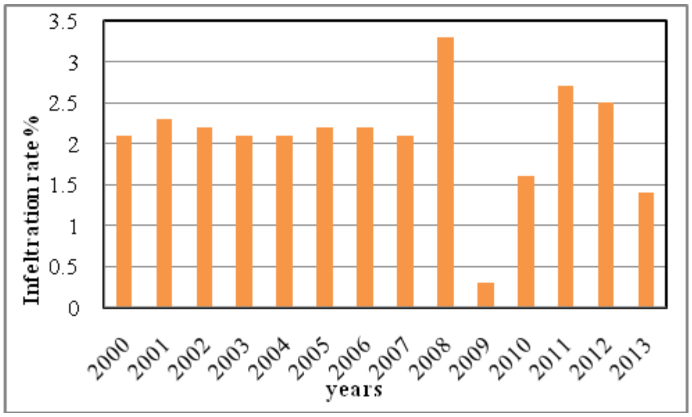


Figure 9 Annual Euro Inflation Rates Chart (2000-2013).

The total calculated cost of the PS10 in 2014 is ($52.8M), the specific cost is about 4800$/kWgross. The capital cost analysis of PS10 and MPS10 is illustrated in table 5. MPS10 involved in most of these cost analysis with the addition of the cost of modification parts that took place. Modified parts increase the capital cost to ($55.78M), the specific cost is about 5070$/kWgross.



Table 5 Capital cost analysis in ($M), 2014.

| Item | PS10 in Spain | MPS10 in Aswan |
|---|---|---|
| Storage cost [$M] | 2.024 | 2.584 |
| Solar field cost [$M] | 19.734 | 19.734 |
| Receiver cost [$M] | 6.578 | 8.398 |
| Tower cost [$M] | 2.53 | 2.53 |
| Power block cost [$M] | 10.12 | 12.92 |
| Land cost [$M] | 1.012 | 1.012 |
| Indirect cost [$M] | 8.602 | 8.602 |
| **Capital cost [$M]** | **52.8** | **55.78** |

The modification that applied to PS10 to be MPS10 has increased the cost of some parts, that's lead to increase the capital cost of the MPS10. The storage system cost increase as a result of installing two thermal storage tanks as well as the price of HTF. Increasing the receiver cost came to fit the materials that have been constructed, to bear its high temperature. Finally, the power block cost increased corresponding to installing a heat exchanger for steam generation.

In fact, this cost of MPS10 will fall in Aswan for several reasons. The most important reason that the landing cost of the MPS10 ($1M) is ignored in Aswan due to the governmental support for encourages national energy project on desert lands. In other hand, the indirect cost which depends on labour ($8.6M) also is reduced in Aswan due to the relatively low cost of labour and transportation (the Egyptian labour cost is lower than in Europe by about 75%). This means that the capital cost of MPS10 reduced to about ($48.33M), the specific cost is about 4393$/kWgross. This is expected to reduce the costing of produced electricity in Egypt.

## 5 CONCLUSIONS

This study is a theoretical analysis of constructed a solar power tower in Aswan. The PS10 plant in Spain is used as a demonstrative model. This plant is modified by using two tanks with molten salts storage system. The modification comes to fit the development in solar power tower plants. The MPS10 plant produces about 35.9 GWh yearly which equivalent to 150% of what was produced by PS10 with steam storage system. MPS10 power output is higher than PS10 by 3.2 MW. The modification increases the plant thermal to electrical efficiency by 21%. The feasibility study shows that installing MPS10 in Aswan saving about ($7.45M) labour and indirect cost. That means the capital cost of the MPS10 plant in Aswan will be less than in any other place in the world. This is a first step towards moving the Egyptian government to the exploitation of solar energy in southern Egypt.

## NOMENCLATURE

CST: Concentrated Solar Tower
PS10: A solar power tower plant in Spain
DSG: Direct Saturated steam Generation
HTF: Heat Transfer Fluid (molten salts)
SPT: Solar Power Tower
MPS10: Modified PS10 plant
NaNo3: Sodium Nitrate [60%]
KNo3: Potassium Nitrate [40%]
$\eta_{receiver}$: Receiver efficiency [92%]
$\dot{Q}_{tr}$: Tower received power [Kw]
$\dot{Q}_{field}$: Heliostat reflected power [Kw]
$\dot{m}_{tr}$: Mass flow rate in the receiver [Kg/s]
Cp: Specific Heat [2660 J/Kg·k at 400Oc]
$T_{tr.out}$: Temperature of receiver outlet [565OC]
$T_{tr.in}$: Temperature of receiver inlet [290OC]
M : Accumulated mass in each tank [kg]
dT/dt : Rate of temperature change [oC/s]

$\dot{m}$: Mass flow rate in each tank [Kg/s]
$\rho$ : Molten salts density [kg/m3]
$T_i$ : Tank inlet temperature [OC]
$T_o$: Tank outlet temperature [OC]
U : Overall heat transfer coefficient [w/m2.k]
A : Tank total area [m2]
$T_a$ : Tank ambient temperature [OC]
dM/dt : Rate of accumulated mass change [kg/s]
$\dot{m}_{in}$: Inlet mass flow rate to the tank [kg/s]
$\dot{m}_{out}$: Outlet mass flow rate from the tank [kg/s]
dE/dt : Rate of accumulated energy change [J/s]
$T_{in}$ : Tank inlet temperature [OC]
$T_{out}$ : Tank outlet temperature [OC]
$dT_{out}/dt$ : Rate of tank outlet temperature change [OC/s]
$\dot{Q}_{sg}$: Steam generations heat exchange [KW]
$\dot{m}_{hex}$: Heat exchanger mass flow rate [60Kg/s]
$T_{hex.in}$ : Heat exchanger inlet temperature [565OC]
$T_{hex.out}$ : Heat exchanger outlet temperature [290OC]
$M: American Million dollars

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## APPENDIX

- BIRD model calculations:

$$I_T = (I_d - I_{as}) / (1 - r_g r_s) \quad \text{(I)}$$

$$I_d = 0.9662\, I_o\, CosZ\, T_R\, T_o\, T_{um}\, T_w\, T_A \quad \text{(II)}$$

$$I_{as} = 0.79\, I_o\, CosZ\, T_{AA}\, T_o\, T_{um}\, T_w \left[(0.5\,(1 - T_R)) + (B_a(1 - T_{As}))\right] / \left[1 - M + M^{1.02}\right] \quad \text{(III)}$$



- Tower control