

Investigation of 50KW Parabolic Trough in SAM

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KEYWORDS

*HITEC solar
Physical
Empirical
SAM
NREL
CSP parabolic
trough*

ABSTRACT

The purpose of concentrated solar power plant to convert solar field into thermal energy with the help of parabolic trough collectors and receiver. Through extensive literature review studied that KSA has large solar potential due to large solar irradiations, rainless area, and as well as utilized solar sources to greater extend. The main objective of this research to simulate CSP parabolic trough (physical and empirical) of capacity 50kW with three thermal storage HTF fluid (HITEC solar salt, Terminal VP-1, Terminal 66). The HTF fluid is used to store thermal energy during overcast conditions or bad weather. A parabolic trough system contains linear reflectors that transmit light onto receiver tube (filled with working fluid). The SAM software widely used for the analysis for concentrated power plants that was developed by NREL. The net power generation data (kWh) are obtained on monthly basis, after running simulation using SAM. The value of total electric power to grid enhanced during summer season or decreased during the overcast condition. The total net electric power to grid was increased by using HITEC solar salt fluid because of its high specific heat value compared to other thermal storage fluids. While empirical CSP parabolic trough plant can produce high precision (accuracy) over wide range of parameters, and such empirical model can't provide predictive information outside these ranges. The proposed design of CSP parabolic trough plant encourages future development and innovations in sustainable energy.

1. Introduction

Through extensive literature review studied that the conventional fuels (fossil fuels) dominated the economy of Gulf countries from last few years. In 2018, the total electric power consumption was 296.44 TWh, that amount to 93% of total electricity generation. As Gulf countries faces acute level of environmental pollution due to dependence on fossil fuels. The recent expansions show that they plan to enhance sustainable energy share during the electricity production. The electricity consumption enhanced 7.6% annually due to increasing population or energy demands as well. In future KSA plans to overcome energy demands and enhance efficiency by dependence on concentrated power plant. As high solar potential in Saudi Arabia, now the total focus towards concentrated power plant. The worldwide installed capacity of concentrated solar thermal power plant up to 5500 MW during 2018. The power generation expansion in Saudi Arabia is too much essential in order to overcome energy demands. Simulated 100 MW parabolic trough plant with six hour of thermal energy storage has been investigated in terms of thermal performance and design, based on SAM [1-2]. The HITEC solar salt selected (HTF) due to its exceptional thermodynamics properties. The result portion showed that the selected CSP plant can produce

annual electricity of 285,288,353 kWh with plant efficiency of 21%. 8277 designed 100MW CSP parabolic trough plant using SAM software for electricity generation purpose. The SAM software is used to evaluate plant's economic and exegetic parameters such as annual energy production, monthly production, and cost of energy respectively. Simulated 50kW CSP parabolic trough type plant located in Louisiana [3-4]. The predictive model was developed using SAM software, which investigated plant performance and characterized CSP plant as well. The analysis results showed that by operating CSP plant and hours of storage, we can accomplish more than 70% reduction in electricity cost. Designed CSP parabolic trough plant with capacity of 100.0 MW and six hours' thermal storage [5-6]. The SAM software is employed for plant sizing, defining investment return, and measuring short sighted and straight forward control strategy.

CSP Parabolic trough plant:

The main objective of CSP (concentrated solar power) plant is to transform solar field directly into thermal energy and further convert it into useful mechanical work. The heat energy used to generate steam for industrial processes or to drive steam turbine (electricity generation). In general, the CSP is used to generate electricity by converting solar energy into thermal energy and then expand steam in turbine to generate mechanical power. The CSP integrates solar energy system and generates electric power during cloudy periods for hours before sunrise or after sunset. The CSP consists of mainly two parts: first one to collect solar energy (solar field) and convert into heat energy and second one converts this thermal energy to produce electricity [7-8]. The CSP plants used fundamental thermal energy storage fluid to produce electricity during both sunset and cloudy periods. This tendency to store solar energy makes CSP plant more dispatch able and flexible source of sustainable energy. Now a day, three different types of CSP plant are used to convert solar energy directly into heat energy. The specific technologies of CSP plants are parabolic trough, solar tower, and linear Fresnel. See Fig.1.

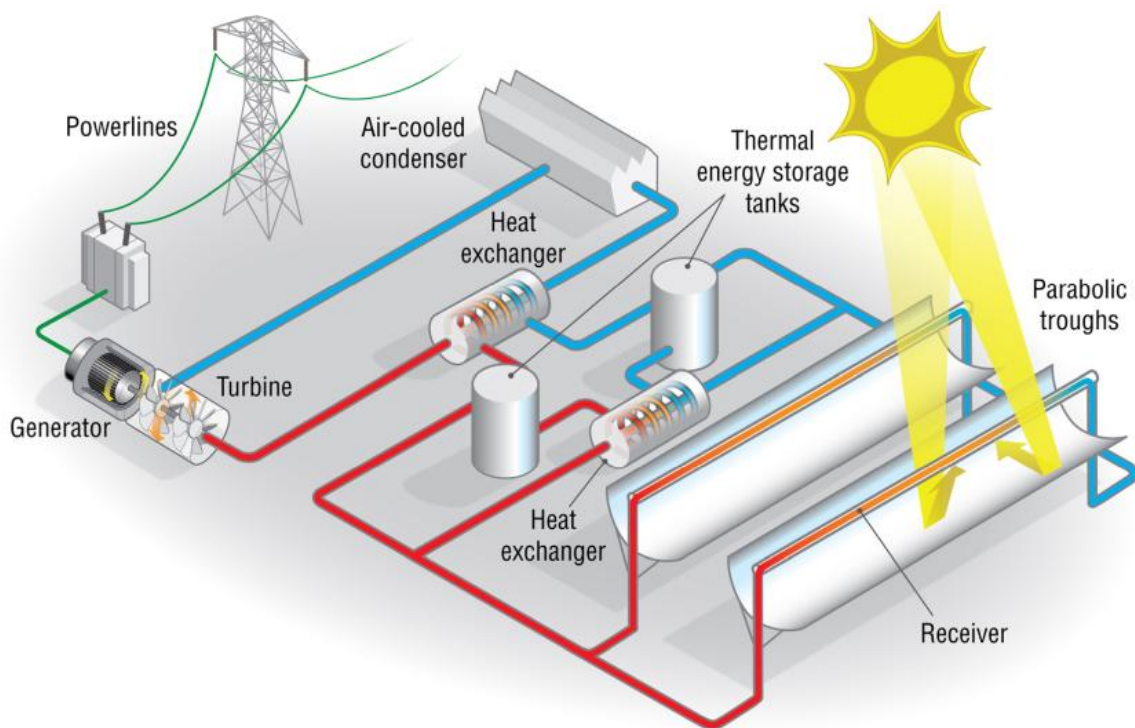


Figure.1. CSP Parabolic trough image

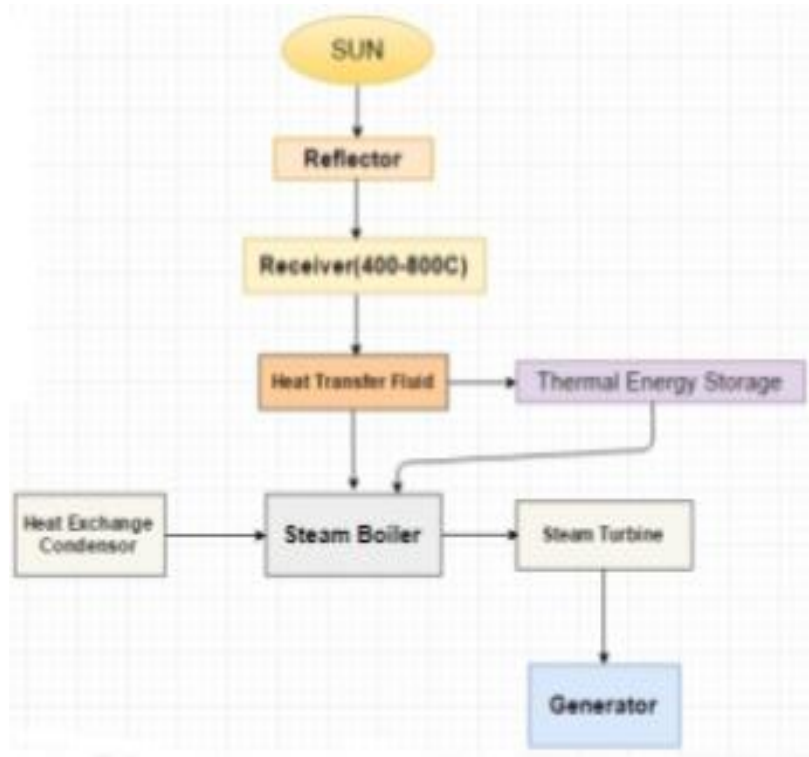


Figure.2. Block diagram of CSP Parabolic trough plant

A parabolic trough system contains linear reflectors that transmit light onto receiver tube (filled with working fluid). The receiver is directly above the parabolic trough mirror that tracking solar energy by rotating along single axis. A molten salt is used as a heat source for electric power generation purpose. The molten salt is used to store thermal energy during overcast conditions or bad weather. The molten salt contains composition of sodium nitrate and potassium nitrate. In parabolic trough system, the molten salt is heated up to 294°C - 394°C that further used for power generation system [9-10]. The temperature of the working fluid increased and stored thermal energy used is further used to generate electric power in a thermal steam turbine plant [11-12]. A solar trough system has overall efficiency (tendency to convert solar energy into electric work) is near about 25%. The CSP parabolic trough plant used receiver system to allows for higher efficiencies and greater operating temperatures. See Fig.2.

The key objectives of this research project are:

To determine optimum CSP power plant design (empirical and physical) in the most satisfactory site of KSA.

To simulate 50kW CSP parabolic trough plant with different thermal storage fluid, using SAM software.

To analyze annual performance and thermodynamic aspects of hypothetical CSP parabolic trough plant using SAM software.

2. Research Methodology

This section presents detailed methodology employed in developing CSP parabolic trough plant of capacity 50kW. The SAM is a free access software that can analyze various renewable energy systems. The methodology section consists with following the following basic steps as: configure collector and receiver components, define operating temperature and HTF, determine operation limits, loop configuration, specify design point of power cycle, identify

thermal storage parameters, update financial and cost, update uncertainties, and update TES capacity and solar multiple.

SAM (System Advisor Module) Software:

The objective of this research to develop model by using SAM software and characterize the performance of parabolic trough power plant [see fig.3](#). The SAM software developed by NREL funded by US Energy Department to evaluate performance of sustainable energy system. In CSP parabolic plant the SAM software used to evaluate initial or capital cost, PC input energy and total electricity to the grid. The SAM software also used to predict cost estimation and performance prediction for grid connected power plants based on system design and operating cost parameters. The transfer fluid contains some important properties like low viscosity, high density, good heat resounding capacity, and that can easily pass through number of tubes. The performance of parabolic trough largely depends on beam irradiance, diffuse irradiance, plane of array irradiance and global irradiance. As we know that beam irradiance is the key factor for any concentrating power plant due to its high variability as compared to global irradiance. The chances of uncertainty in beam irradiance data is larger and we measured all solar sources with great care. The diffuser irradiance is defined as amount of radiations received from sun per unit surface area. Through with the help of solar field optimization we can easily calculate receiver height, tower height, number of heliostats, and receiver page diameter. With the help of SAM software, we can investigate the power produced through solar field, thermal power in and out, and thermal power input to steam turbine. Though SAM software we can easily found out PC input energy, TES charge or discharge thermal power, and total electricity to the grid station. [See Fig.3](#).

This section presented extensive methodology while developing

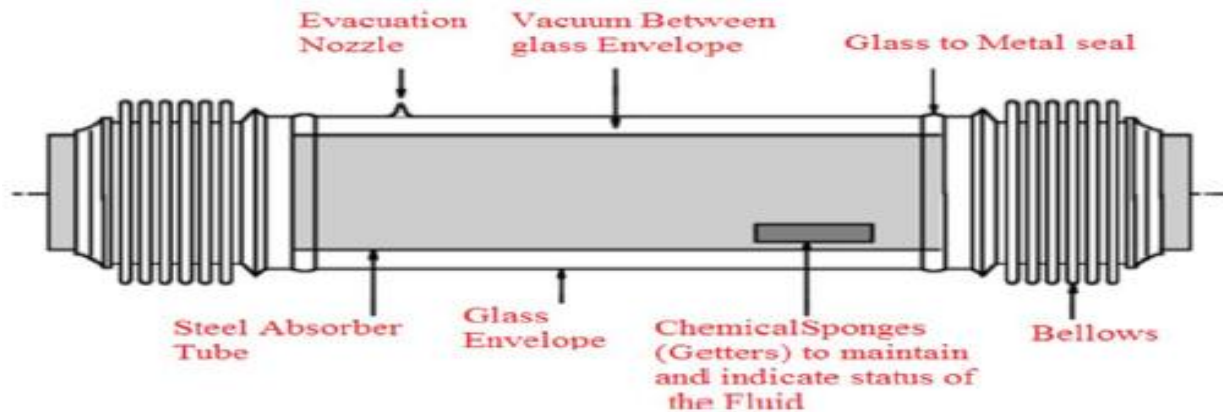


Figure.3. Parabolic trough receiver sectional view

Thermal Storage Fluid:

The thermal storage fluid is used to store thermal energy during overcast conditions or bad weather [4]. The temperature of the working fluid increased and stored thermal energy used is further used to generate electric power in a thermal steam turbine plant. In this research project, the HITEC solar salt, Therminol VP-1, and pressurized water was selected as HTF fluid. The Therminol VP-1 basically a synthetic HTF fluid that combines low viscosity, and thermal stability for efficient, dependable, and optimum performance in extensive temperature range of 12 °C to 398 °C. The Therminol 66 fluid is comparatively cheaper and easily available but its optimum (efficient) at low temperature range 10 to 220 °C. The HITEC solar salt HTF fluid gives good thermal efficiency for CSP parabolic trough plant, because of its high specific heat value compared to other fluids. The HITEC solar salt offers good heat carrying capability [13]. It is a low viscosity and high density fluid that can easily pass through receiver tubes with good thermal properties [13]. Furthermore, the HITEC fluid not easily contaminated and remains stable between 298 °C to 593 °C. [See Table.1 & Fig.4](#).

Table.1. HTF Fluid Properties [13-14]

Substance	Minimum Temperature (°C)	Maximum Temperature (°C)	Specific Heat (kJ/kg°C)	Density (kg/m ³)
Therminaol VP-1	12	400	1.532	765.461
Therminaol 66	0	345	1.538	
HITEC Solar Salt	238	593	1.561	1872.49

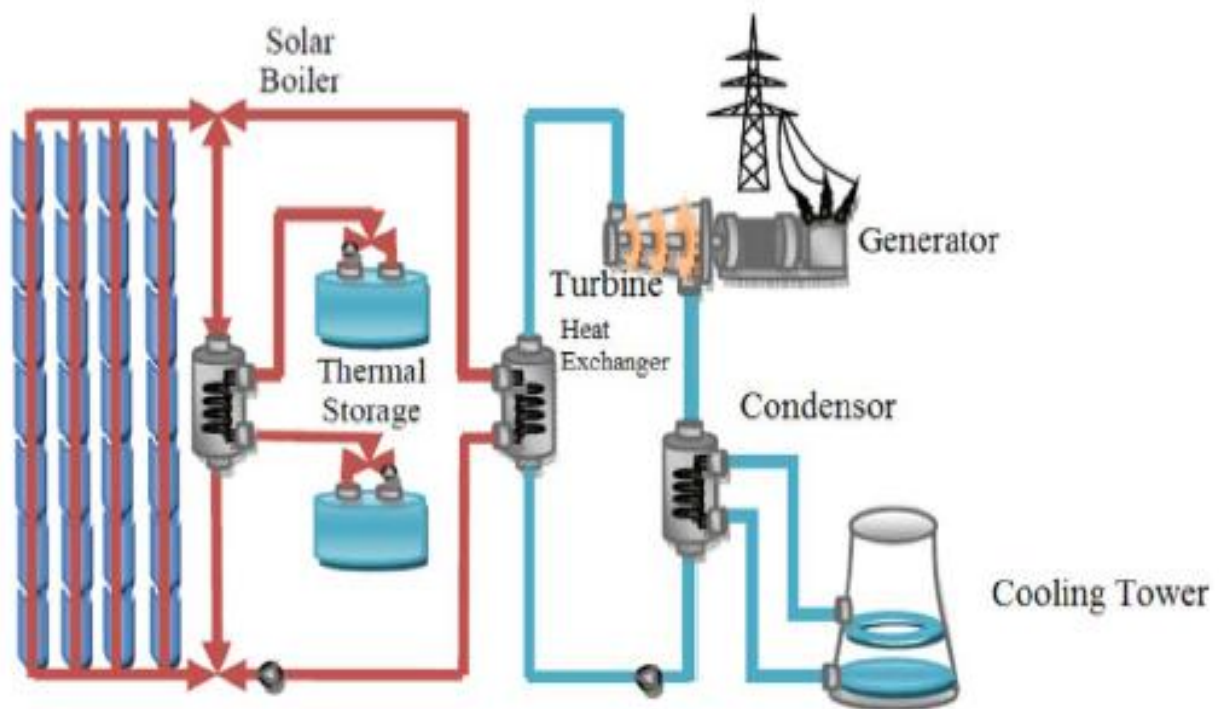


Figure.4. Schematic diagram of CSP Parabolic trough plant with HTF fluid

Characteristics of Proposed CSP Parabolic Trough:

Collectors & Field Optics:

The optical calculations and collector model used in both empirical and physical approach is mainly borrowed from SAM library. The collector is the main component solar field that directly reflects sun light onto receiver. This solar collector is totally different from receiver, which equipped with tube receiver and evacuated glass envelop respectively [5]. Furthermore, the receiver model contains numerous relationships between heat loss, substance properties, and surface temperature. The parabolic trough system includes both a collector to reflect solar field and receiver pipe to transport and absorb heat. See Fig.5. & Table.2-3.

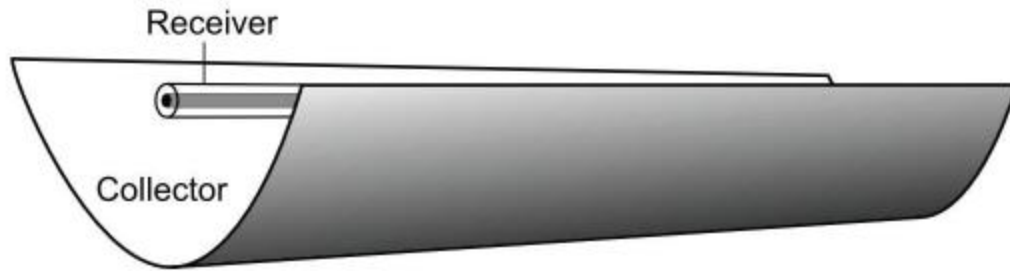


Figure.5. Collector and receiver assembly

Table.2. Collector geometrical parameters

Parameter	Metric value
Loops per assembly	8.0
Aperture area (reflective)	656 m ²
Aperture width	6.0 m
Collector assembly length	115.0 m
Distance between piping assemblies	1.0 m
Surface to focus path length [13]	2.15 m

Table.3. Optical Parameters

Parameter	Metric value
Optical error	0.958
Tracking error	0.975
Mirror reflectance	0.946
Geometry effects	0.920
Dirt on mirror	0.927

Mathematical Modelling:

The next step after site (location) selection is the determination of optimum design for CSP plant. The amount of useful heat gain is measured by the following relation [1]:

$$Q_u = F_R A_a \left[\frac{S - A_r}{A_a U_L (T_i - T_a)} \right] \quad (1)$$

F_R = Collector heat removal factor

A_r = Receiver area

A_a = Concentrator aperture area

S = Absorbed solar radiations

T_i = Fluid inlet temperature

T_a = Ambient temperature

U_L = Heat loss coefficient

The output temperature of the collector is determined by using the following equation: [13]

$$T_o = T_i + \frac{Q_u}{m \cdot C_p} \quad (2)$$

T_o = Outlet collector temperature

T_i = Inlet temperature (293°C in our case)

m = Mass flowrate of HTF fluid ($12 \frac{\text{kg}}{\text{s}}$)

C_p = Specific heat capacity of HTF fluid & desired outlet temperature is 525 °C)

The number of loops equipped is measured by the following relation:

$$\text{No. of loops required} = \frac{\left(\frac{P_{th}}{\text{Power collector output}} \right)}{\text{Number of collectors per loop}} \quad (3)$$

The solar field is the area where solar collecting devices like absorber, collector etc. have to be mounted [13]. The solar field is the most important parameter while designing any CSP plant.

The solar multiple (SM) is defined the aperture area expressed as a multiple of aperture area required to activate power cycle. The SM (solar multiple) is determined by using the following mathematical relation:

$$SM = \frac{\text{Power cycle capacity}}{\text{Solar field capacity}} \quad (4)$$

The SM (solar multiple) is selected as 2 for modelling and simulation of CSP parabolic trough plant. The solar field output basically defines the thermal energy production by solar field under design condition. The solar field output is measured at the boundary of power block and receiver as the function of SM (solar multiple).

$$Q_{sf,des} = \frac{W_{pb,des}}{\eta_{des}} \times SM \quad (5)$$

The estimated net power is the product between conversion factor and gross output power.

$$\text{Net output (MWe)} = \text{Gross output} \times \text{gross conversion factor (0.9)} \quad (6)$$

3. Result and discussion

The main objective of this research project to simulate CSP parabolic trough (physical and empirical) of capacity 50kW with three thermal storage HTF fluid (HITEC solar salt, Terminaol VP-1, Terminaol 66).

CSP Parabolic System Design:

The system design parameters consist with DNI, number of loops, power cycle and thermal energy storage. The DNI basically defines the amount of radiation received per unit field aperture area that always held normal to solar field. The field thermal power directly depends upon DNI or number of loops. As the value of DNI increased then field thermal power directly increased with same number of loops. See Fig.6.

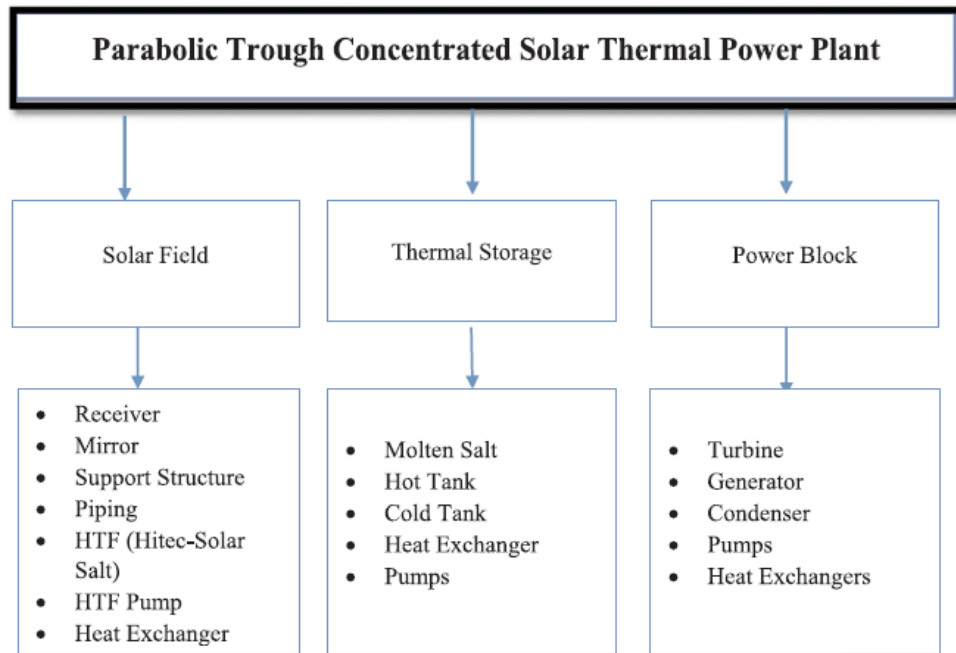


Figure.6. Parabolic trough showing system design parameters

However, both empirical and physical trough models are included in SAM library to allow for comparisons between the empirical and physical modelling approaches. The physical modelling technique accomplishes some other objectives: transient effects related to capacity, plant balance, headers, allow for flexible component specification, and multiple collectors and receiver types within single fluid. See Table.4-5.

Table.4. System design parameters of CSP parabolic trough (physical)

Parameters	Value
Gross output power	50 kW
Conversion factor (gross to net)	0.9
Net output	45 kW
Thermal efficiency	0.356
HTF cold temperature	291 °C

HTF hot temperature	393 °C
Condenser type	Air cooled
Receiver type	Schott PTR80
Absorber tube diameter (inner)	0.076 m
Hours of storage at design point	6

Table.5. System design parameters of CSP parabolic trough (physical)

Parameters	Value
Gross output power	50 kWe
Solar field area	940.6 m ²
Design point parasitic	15.63 kWe
Reflective Area	941 m ²
Solar Field area	887875 m ²
Equivalent full load hours	6
Conversion factor (gross to net)	0.9
Net output	45 kW

Monthly Net Electric Power (kWh):

CSP Parabolic Trough – Physical:

Table.6. Annual net power output (Physical) using HTF fluids

Annual Net Electricity Production (kWh)	Annual Net Electricity Production (kWh)	Annual Net Electricity Production (kWh)
HITEC Solar Salt	Terminol VP-1	Therminol 66
159801	116260.3	132865.4

Table.7. Annual net power output (Physical) using HTF fluids

Time stamp	Monthly energy (kWh)	Monthly energy (kWh)	Monthly energy (kWh)
	HITEC Solar Salt	Terminol VP-1	Therminol 66
Jan	12830.4	14442.8	15689.5

Feb	11455	8998.5	10543.1
Mar	13679.5	9001.6	10987.4
Apr	14346.2	8321.1	9561.9
May	14749.4	7999.5	9119.2
Jun	13617.8	7356.8	8845
Jul	12776.9	6798	8123.6
Aug	13616.5	7467.9	8590.4
Sep	11686.7	7987.2	8923.9
Oct	12938.3	9113.6	9712.3
Nov	13720.7	12897	15668.6
Dec	14383.8	15876.3	17100.5

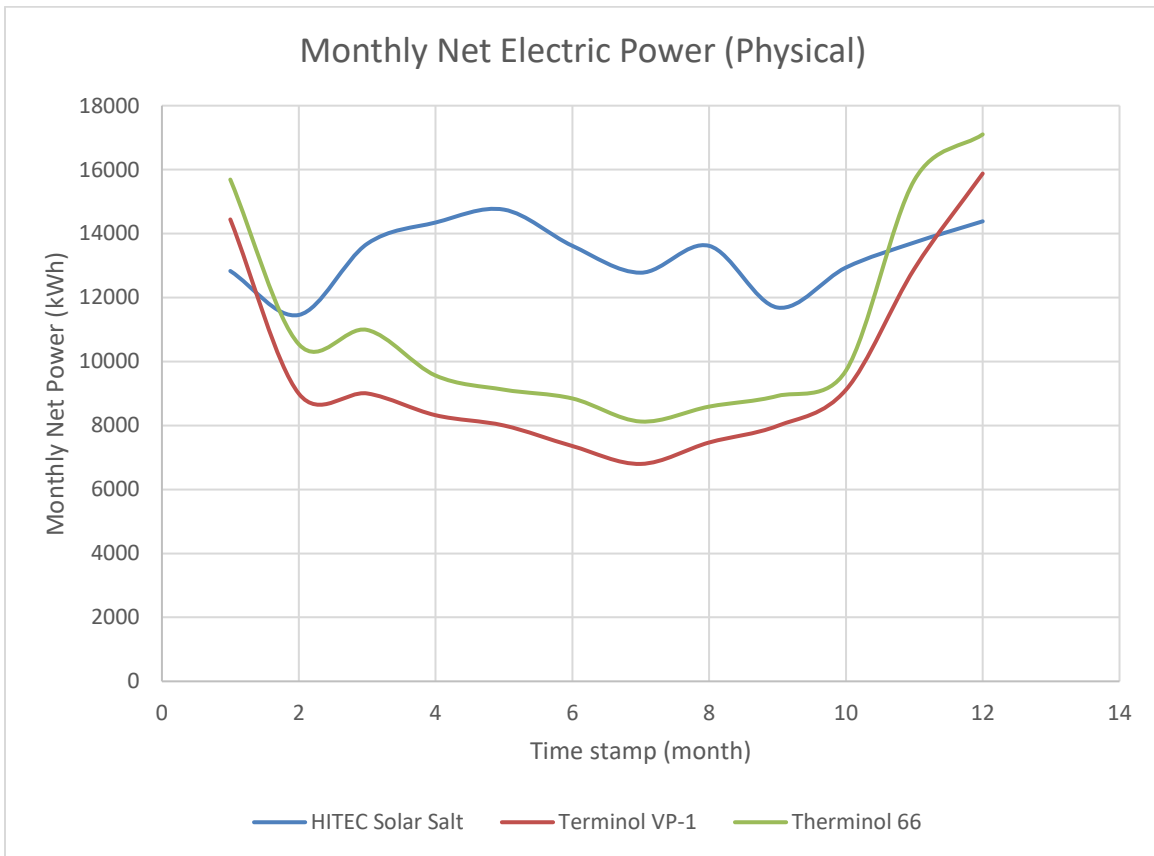


Figure.7. Graph between net electric power verses time stamp - Physical

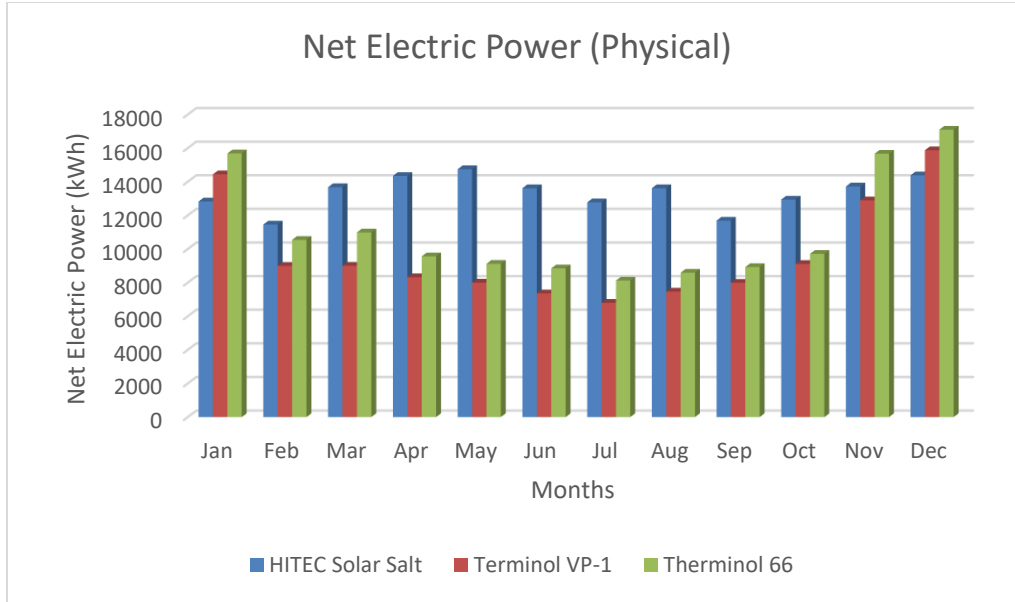


Figure.8. Monthly net electric power of CSP parabolic trough – Physical

CSP Parabolic Trough – Empirical:

The net output power is defined as the useful power that is transferred to electric grid for domestic and commercial users. The total electric power to grid was directly depends upon solar irradiation area. The monthly and annual net power was calculated by using SAM software. See Table.8-9 & Fig.9-10.

Table.8. Annual net power output (Empirical) using HTF fluids

Annual Net Electricity Production (kWh)	Annual Net Electricity Production (kWh)	Annual Net Electricity Production (kWh)
HITEC Solar Salt	Terminol VP-1	Therminol 66
82659.67	50648.02	59439.56

Table.9. Annual net power output (Empirical) using HTF fluids

Time stamp	Monthly energy (kWh)	Monthly energy (kWh)	Monthly energy (kWh)
	HITEC Solar Salt	Terminol VP-1	Therminol 66
Jan	4148.43	5698.98	6686.92
Feb	5090.72	4521.09	5417.04
Mar	7295.2	4541.9	4748.65
Apr	7667.64	3520.25	4314.51
May	8743.79	3123.24	4220.84
Jun	8920.8	3052.05	4062.55
Jul	9338.52	3040.98	3798.95
Aug	8960.04	3232.91	3650.57
Sep	7493.84	3161.95	3813.7
Oct	6452.51	4603.11	4811.21
Nov	4705.11	5264.33	6079.65

Dec	3843.07	6887.23	7834.97
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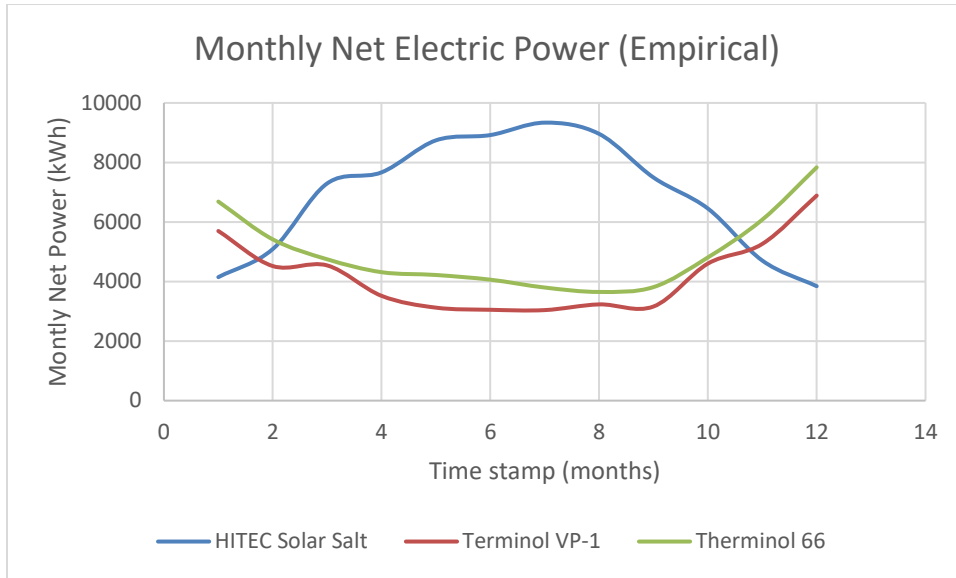


Figure.9. Graph between monthly net electric power (empirical) verses time stamp

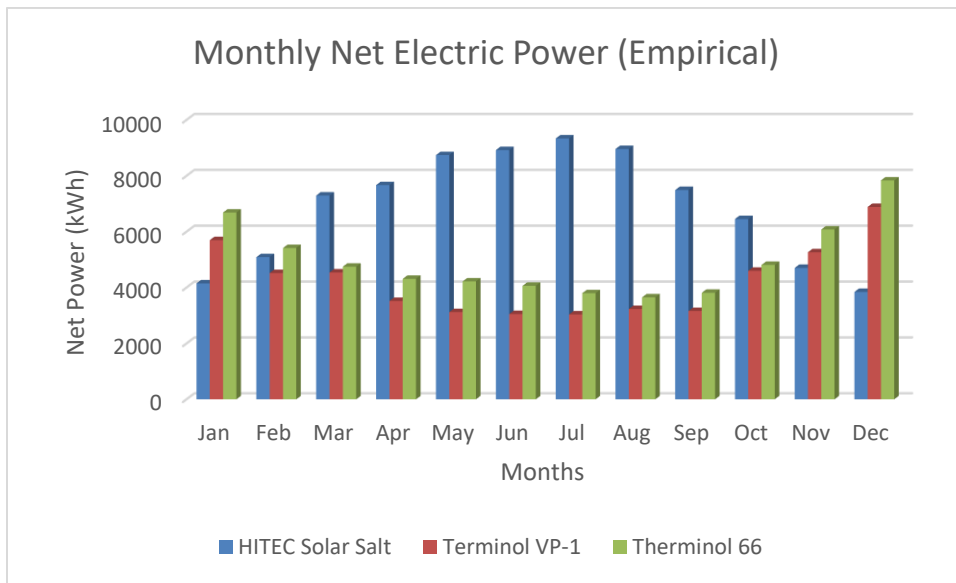


Figure.10. Monthly net electric power of CSP parabolic trough – Empirical

From above figure, the blue trend line represents the monthly net electric power using HITEC solar salt. Furthermore, grey trend line represents the monthly net electric power using Therminol 66, and orange line shows net electric power with therminol VP-1 HTF fluid. During summer season the solar irradiance are high that's why more solar field energy is transferred to electric power. The value of total electric power to grid enhanced during summer season or decreased during the overcast condition. Moreover, the total electric power to grid is mainly depends on HTF fluid. The total net electric power to grid was increased by using HITEC solar salt fluid because of its high specific heat value compared to other HTF fluids. The HITEC solar salt offers good heat carrying capability,

low viscosity and high density fluid that can easily pass through receiver tubes with good thermal properties. While empirical CSP parabolic trough plant can produce high precision (accuracy) over wide range of parameters, and such empirical model can't provide predictive information outside these ranges. The validation of result section is performed against an extensive range of data of one year from variety of days, and months with different weather profile, the results are extremely relevant for modelling large scale CSP parabolic trough plant.

4. Conclusion

Through extensive literature review concluded that KSA has large solar potential due to large solar irradiations, rainless area, and as well as utilized solar sources to greater extend. The objective of CSP (concentrated solar power) plant is to transform solar field directly into thermal energy and further convert it into useful mechanical work. A 50kW CSP parabolic trough plant is designed and simulated using SAM software. The huge potential of CSP parabolic plant in KSA due to favorable characteristics and high level of DNI. The value of total electric power to grid enhanced during summer season or decreased during the overcast condition. The total net electric power to grid was increased by using HITEC solar salt fluid because of its high specific heat value compared to other HTF fluids. The HITEC solar salt offers good heat carrying capability, low viscosity and high density fluid that can easily pass through receiver tubes with good thermal properties. While empirical CSP parabolic trough plant can produce high precision (accuracy) over wide range of parameters, and such empirical model can't provide predictive information outside these ranges. However, additional research required for measuring design parameters such as thermal capacity, heat transfer fluid, field configuration, collector loop, and efficiency. Furthermore, the sensitivity analysis and future studies are required to determine optimum situations for the practical and economic viability of CSP.

5. Acknowledgement

The research team extends their heartfelt gratitude and sincere appreciation to the Sustainable Energy Technologies Center for its invaluable support in conducting this research

6. References

1. Bishoyi, D. and Sudhakar, K. 'Modeling and performance simulation of 100 MW PTC based solar thermal power plant in Udaipur India', Case Studies in Thermal Engineering, pp. 216–226. doi: 10.1016/j.csite.2017.05.005. 2017
2. Casella, F., Casati, E. and Colonna, P. Optimal operation of solar tower plants with thermal storage for system design, IFAC Proceedings Volumes (IFAC-PapersOnline). IFAC. doi: 10.3182/20140824-6-za-1003.02622. 2014
3. Ezeanya, E. K. et al. 'System advisor model (SAM) simulation modelling of a concentrating solar thermal power plant with comparison to actual performance data', Cogent Engineering, 5(1), pp. 1–26. doi: 10.1080/23311916.2018.1524051. 2018
4. Rohani, S. et al. 'Modelling and simulation of parabolic trough plants based on real operating data', Solar Energy, 158(November), pp. 845–860. doi: 10.1016/j.solener.2017.10.023. 2017
5. Wagner, M. J.; Gilman, P. et al. 'A Detailed Physical Trough Model for NREL's Solar Advisor Model', NREL Publications, (October), p. 124. Available at: [http://nrelpubs.nrel.gov/Webtop/ws/nich/www/public/Record?rpp=25&upp=0&m=96&w=NATIVE\('LIBNOTE+ph+words+'NPL1106''\)&order=native\('author\(1\)'\),titl](http://nrelpubs.nrel.gov/Webtop/ws/nich/www/public/Record?rpp=25&upp=0&m=96&w=NATIVE('LIBNOTE+ph+words+'NPL1106'')&order=native('author(1)'),titl). 2011

6. Wind Energy Math Calculations: Calculating the Tip Speed Ratio of Your Wind Turbine <https://mmpa.org/wp-content/uploads/2015/09/Tip-Speed-Ratio-Provided-by-Kid-Wind-PDF.pdf>.
7. Salah- Ud-Din Khan, Shahab Ud-Din Khan, Sajjad Haider, Syed Mansoor Ali, Development of theoretical-computational model for radiation shielding. *Journal of Radiation Research and Applied Sciences*. Volume 13, Issue 1, 2020.
8. Salah Ud-Din Khan, Zeyad Ammar Almutairi, Omer Salah Al-Zaid, Shahab Ud-Din Khan. Development of low concentrated solar photovoltaic system with lead acid battery as storage device. *Current Applied Physics*. Vol 20. 4. pp 582-588. 2020.
9. Abdul Majid, Khuzaima Hussain, Salah Ud-Din Khan, Shahab Ud-Din Khan. First principles study of SiC as the anode in sodium ion batteries. *New Journal of Chemistry*. Vol 44(21), pages 8910-8921, 2020
10. Salah- Ud-Din Khan, Zeyad Almutairi, Meshari Alanazi, Shahab Ud-Din Khan, Safety analysis of pool-type double containment of system-integrated modular advanced reactor: A case study for Saudi Arabia. *International journal of energy research*. Vol 45, issue 8, pages 12047-12058, 2020.
11. Salah Ud-Din Khan, Shahab Ud-Din Khan, Sajjad Haider, Abdelrahman El-Leathy, Usman Ali Rana, Syed Noman Danish, Ramzan Ullah, "Development and Techno-Economic analysis of Small Modular Nuclear Reactor and Desalination System across Middle East region and North Africa region", *Desalination*, vol 406, pp 51-59, 2017.
12. Salah Ud-Din Khan, Shahab Ud-Din Khan, " Karachi Nuclear Power Plant (KANUPP) As case study for Techno-Economic Assessment of Nuclear power coupled with water Desalination", *Energy*, Vol 127, 15, Pg 372–380, 2017.
13. Deepak Bishoyi, K. Sudhakar. "Modeling and performance simulation of 100 MW PTC based solar thermal power plant in Udaipur India", *Case Studies in Thermal Engineering*, 2017
14. Asad Ullah, Mariam Mahmood, Sheeraz Iqbal, Muhammad Bilal Sajid et al. "Technoeconomic and GHG mitigation assessment of concentrated solar thermal and PV systems for different climate zones", *Energy Reports*, 2023