ENERGY PERFORMANCE SIMULATION OF THE 52MW MINOS SOLAR TOWER PROJECT

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Summary

MINOS Concentrated Solar Power (CSP) project in Crete island, is a strategic investment in Greece that receives continued and increasing government support and is at the focus of public attention. It is the first CSP plant in Greece, and it aims to cover 10% of the island of Crete power demand. The system's capacity is equal to 52MW and a molten salt thermal energy storage of 5 hours capacity is also included. This work attempts to estimate the total electricity production and the annual performance of the MINOS project, through the development of a dedicated model in System Advisor Model (SAM) software. The findings of this feasibility study provide valuable insights into the annual electricity production and the efficiency of this CSP project, facilitating informed decision-making for stakeholders and investors interested in the development of solar tower projects.

Keywords: CSP, Solar Tower, electricity production, solar energy, concentrated solar collectors

1. Introduction

Solar tower systems, or central solar receiver systems, are based on the conversion and transfer of direct incident solar radiation into thermal energy. This thermal energy is absorbed by high temperature fluid, used as a heat transfer medium, and it is then collected by a working fluid and employed to drive a steam engine cycle for electricity generation which is finally being supplied to the grid [1].

More specifically, the direct incident solar radiation that reaches the earth surface is reflected by the heliostats/mirrors and concentrated onto the solar receiver which is located on the top of the solar tower. Each mirror is installed on an individual tracking system, so that each of them be able to track the sun's orbit. After the solar radiation reaches the solar receiver and is concentrated on a particular surface of the tower, thermal energy it is transferred as heat to a fluid that flows through a heat exchanger located behind the surface of the receiver. The fluid is heated and vaporized either directly or indirectly. The steam produced feeds a steam turbine to produce mechanical work on its rotor, where it drives a generator to produce electricity. After the steam leaves the exhaust section of the turbine, it enters a condenser, where it is cooled (water-cooled or air-cooled) and becomes saturated water. After that, the water is taken to the top of the tower to be heated and start another new cycle [2].

MINOS CSP solar tower is a CSP tower project with 5h storage and 52MW electricity capacity to be constructed in the island of Crete, Greece. The site is located on the island of Crete, in Sitia Municipality,

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in the southeastern coastal area of Atherinolakos. The site is adjacent to the industrial zone of the Atherinolakos conventional power station, owned by the Public Power Corporation, and rated at 200Mwe [5]. Due to its proximity, the project will be easily connected with the electricity grid.

MINOS solar tower uses concentrated solar thermal technology and consists of 19,514 of sun-tracking mirrors which reflect the sun to the top of the Tower. The required adjustments of the mirrors during the sun's course within a day is performed automatically. A molten salt mixture is heated by the concentrated solar radiation and is stored in a tank on the ground. The heated salt is used to transfer its heat to water to generate steam which activates a steam turbine with a turning motion to generate electricity.

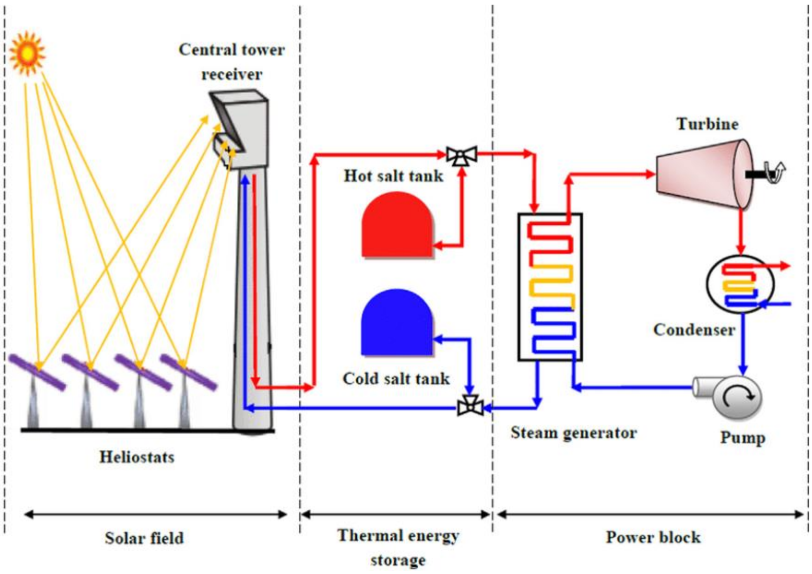


Figure 1 Schematic diagram of a solar tower power plant. (Source: https://www.researchgate.net/)

The plant is fully prepared for construction, and a 25-year Power Purchase Agreement (PPA) is set to be signed with a fixed tariff of €268/MWh. The project has been awarded a €42 million subsidy from the European Union through the NER300 program. Specifically, this subsidy offers an additional tariff of €115/MWh, which will be disbursed throughout the operational years until December 31, 2025.

Figure 2 Visualization of the MINOS CSP Solar Tower to be constructed in Crete, Greece (Source: https://www.nur-minos.com/)

2. Methodology

For the study of the concentrated solar power (CSP) system with thermal storage, meteorological data for the area were initially extracted from PVGIS in the form of a Typical Meteorological Year (TMY) file. Subsequently, key technical specifications of the system were collected, including those related to the solar tower, the heliostat field, the thermal storage, and the power cycle. The collected meteorological data and technical specifications were then entered the System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL). The purpose was to calculate the capacity factor, the performance of subsystems, the electrical energy production, and the energy consumption required for the operation of the system.

The fundamental equations used by SAM for calculating the results presented in this work, are as follows:

$$\text{Optical Efficiency (\%)} = \left(\frac{\text{Thermal energy Absorbed by receiver}}{\text{Incident Solar Energy on Heliostats}}\right) \times 100 \quad \text{(eq. 1)}$$

- Thermal Energy Absorbed by Receiver: The amount of heat absorbed by the tower's receiver.
- Incident Solar Energy on Heliostats: The total solar energy incident on the heliostats.

$$\text{Thermal efficiency (\%)} = \left(\frac{\text{Useful Thermal Energy output}}{\text{Thermal Energy Absorbed by Receiver}}\right) \times 100 \quad \text{(eq. 2)}$$

- Useful Thermal Energy Output: The heat utilized for energy production or storage.
- Thermal Energy Absorbed by Receiver: The amount of heat absorbed by the receiver.

$$\text{Power Cycle Efficiency (\%)} = \left(\frac{\text{Gross Electric Power Output}}{\text{Thermal Energy Input to Power Block}}\right) \times 100 \quad \text{(eq. 3)}$$

- Gross Electric Power Output: The electric power generated by the power cycle before subtracting parasitic consumptions.
- Thermal Energy Input to Power Block: The heat entering the power cycle for conversion into electrical energy.

$$\text{Capacity Factor (\%)} = \left(\frac{E_{\text{actual}}}{P_{\text{max}} \times T}\right) \times 100\% \quad \text{(eq. 4)}$$

- E_{actual} is the actual energy produced during the year in kilowatt-hours (kWh) or megawatt-hours (MWh).
- P_{max} is the maximum capacity of the solar power tower in kilowatts (kW) or megawatts (MW).
- T is the total number of hours in a year, representing the maximum time the plant could theoretically operate.

3. Solar radiation data

Atherinolakos is located in the southeast of Crete with a longitude/latitude of 26.14 E/35.014 N. With the use of PVGIS, a file (.tmy) of the annual solar radiation data of this area was created, with purpose of using it in the computational tool used for the simulation.

The solar irradiance data to be used takes into account the variability that occurs at short intervals, making the simulation results more accurate.

Based on PVGIS data, it is observed that for the month of June at 12 pm, the average value of direct solar radiation in the region is 819.66 W/m^2, while in the month of winter solstice the maximum value of direct incident radiation is 492.34 W/m^2 at 11:00 am. Also, the average value of daily direct radiation is 5.8

kWh/m^2 while the average value of diffuse radiation is 1.58 kWh/m^2. In addition, the average annual temperature of the area is 19.6 °C and the average wind speed during the year is 6.6 m/s [3].

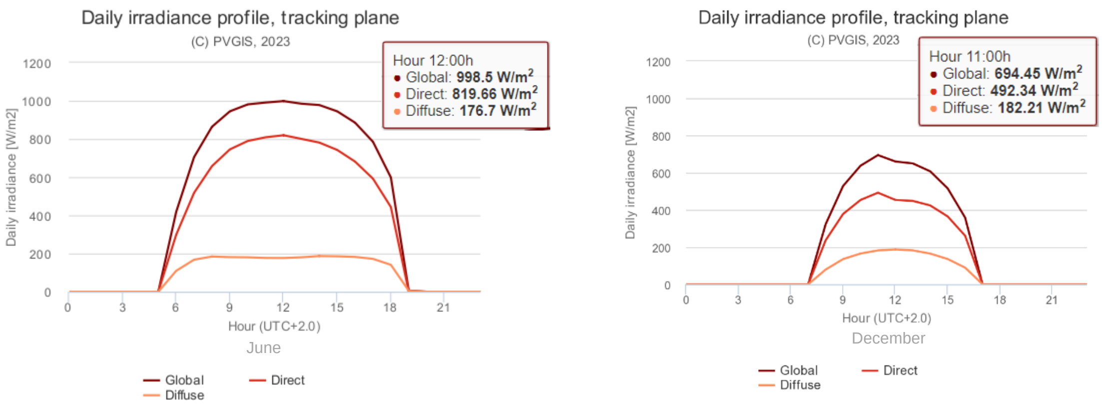


Figure 3 Average daily variation of solar radiation for the months of June and December (Source: https://re.jrc.ec.europa.eu/)

4. Technical Data

The basic technical characteristics of the MINOS project are provided by the company and are given in Table 1.

Table 1 Technical characteristics of MINOS project

Nominal power of the steam turbine	52 MW
Heliostats	19,514
Single heliostat area	20 m^2
Solar tower	
Tower height	200 m
Receiver height	16 m
Receiver diameter	8 m
Number of panels	20 m
Heat transfer fluid	molten salt
HTF hot temperature	565 C°
HTF cold temperature	265 C°
Storage system	
Storage type	2 tank
Tank height	12 h
Tank fluid minimum height	1 h
Tank diameter	17.7 m
Full load hours of storage	5 hours
Rankine cycle parameters	
Boiler operating pressure	120 bar
Condeser type	Air-cooled

The solar tower concentrating system with 5 hours thermal storage capacity, uses an external solar receiver to absorb heat and transfer it to the molten salts. The molten salts mixture is a composition of

60% NaNo3 and 40% KNO3 and it is used as heat transfer medium, flow through the hot salt tank to the heat exchanger and transfer the absorbed heat to the water (water boiler). The water state is changed to superheated steam at a constant pressure of 120 bar. During this process, the maximum temperature of the transferred fluid is 565 ºC and the minimum temperature is 265 ºC. The low temperature (cooled) salt is transferred, by the use of pumps, to the cold salt tank or to the inlet of the receiver for re-absorption of heat. Similarly, the saturated steam at the outlet of the steam turbine passes through the condenser and then it is transferred to the heat exchanger.

In order to produce power of 52 MWe at the steam turbine's (Rankine) outlet, the power of 124 MWt is required in the turbine's inlet given that the thermal efficiency of the cycle is 42%. Since the direct solar irradiance (DNI) in the area is known, the design point of the plant (Design Point) was set at 850 W/m^2. Considering the steam turbine's power requirements, the receiver's surface sized to be capable to absorb a thermal power up to 140 MWt, taking into account the heat losses occurring during the salt transportion.

The heliostatic field, which concentrates the solar radiation to the receiver, is consisted of 19,514 mirrors with the surface area of each mirror equals 20 m^2. Based on the zoning shown in Figure 44, the area covered by the heliostatic field is 390.28 acres, with the total land area required to install the system being 1,598.51 acres. In Fig.3 is shown the positioning of heliostats in the field, with the central solar tower as a reference point, taking into account the differences in altitude of the land.

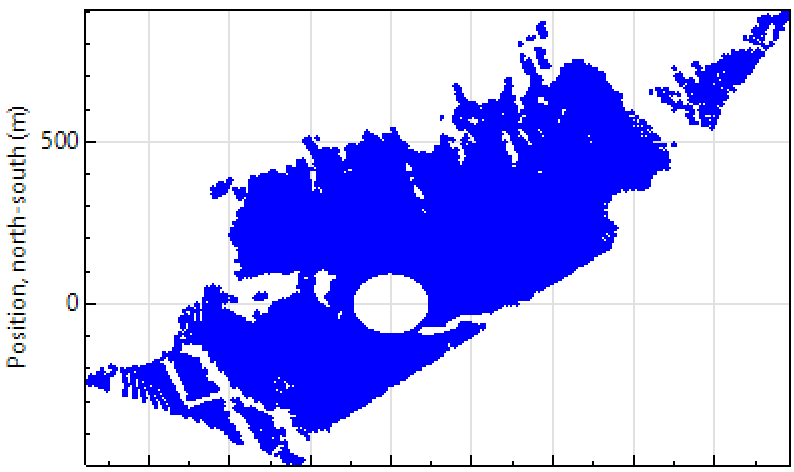
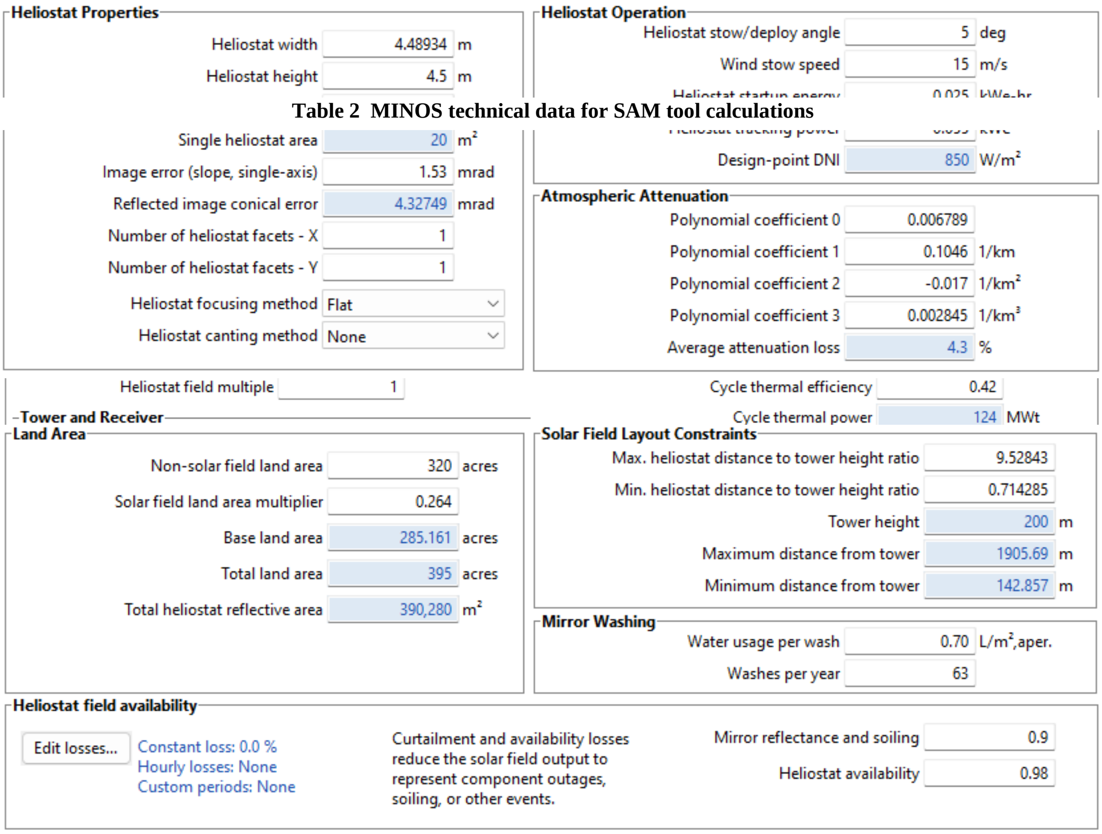


Figure 4 Positioning of heliostats in the MINOS field

Table 2 MINOS technical data for SAM tool calculations



Heliostat Properties

Heliostat width	4.48934	m
Heliostat height	4.5	m
Single heliostat area	20	m²
Image error (slope, single-axis)	1.53	mrad
Reflected image conical error	4.32749	mrad
Number of heliostat facets - X	1	
Number of heliostat facets - Y	1	
Heliostat focusing method	Flat	
Heliostat canting method	None	

Heliostat Operation

Heliostat stow/deploy angle	5	deg
Wind stow speed	15	m/s
Heliostat startup energy	0.025	kWe-hr
Design-point DNI	850	W/m²

Atmospheric Attenuation

Polynomial coefficient 0	0.006789	
Polynomial coefficient 1	0.1046	1/km
Polynomial coefficient 2	-0.017	1/km²
Polynomial coefficient 3	0.002845	1/km³
Average attenuation loss	4.3	%

Heliostat field multiple	1	
Cycle thermal efficiency	0.42	
Cycle thermal power	124	MWt

Tower and Receiver

Land Area

Non-solar field land area	320	acres
Solar field land area multiplier	0.264	
Base land area	285.161	acres
Total land area	395	acres
Total heliostat reflective area	390,280	m²

Solar Field Layout Constraints

Max. heliostat distance to tower height ratio	9.52843	
Min. heliostat distance to tower height ratio	0.714285	
Tower height	200	m
Maximum distance from tower	1905.69	m
Minimum distance from tower	142.857	m

Mirror Washing

Water usage per wash	0.70	L/m²,aper.
Washes per year	63	

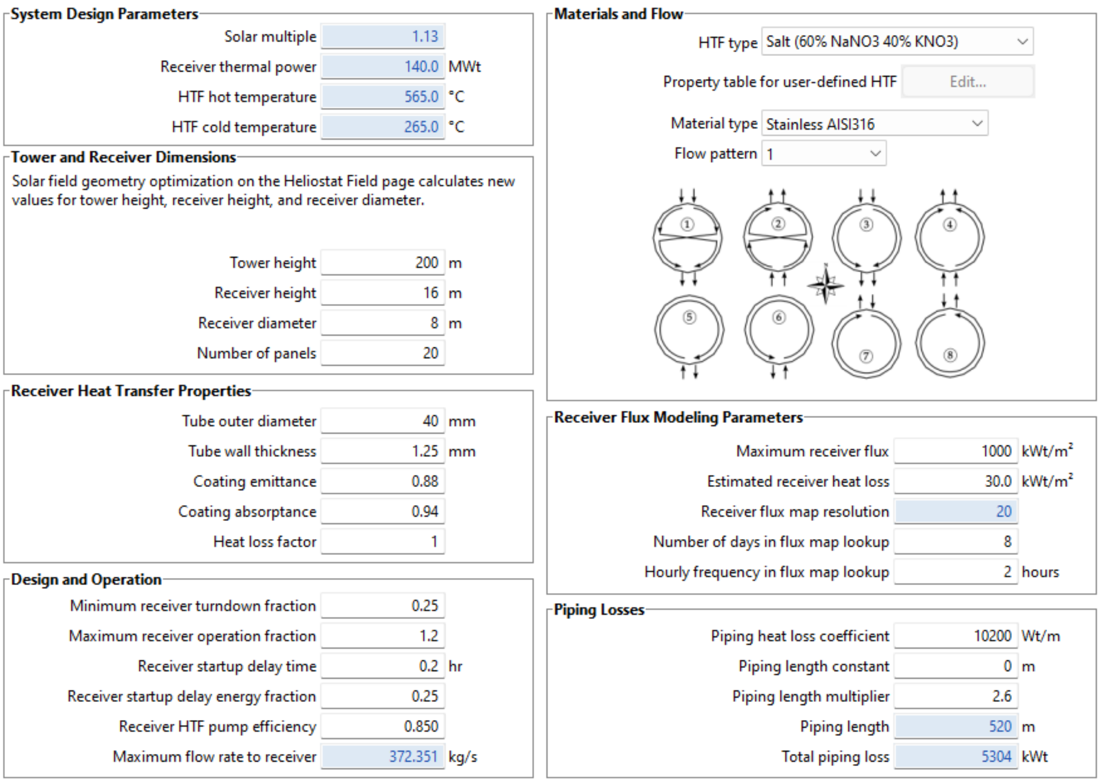
Heliostat field availability

Edit losses...
Constant loss: 0.0 %
Hourly losses: None
Custom periods: None

Curtailment and availability losses reduce the solar field output to represent component outages, soiling, or other events.

Mirror reflectance and soiling	0.9
Heliostat availability	0.98

Main technical parameters entered into SAM in order to simulate the system operation are presented in



System Design Parameters

Solar multiple	1.13	
Receiver thermal power	140.0	MWt
HTF hot temperature	565.0	°C
HTF cold temperature	265.0	°C

Tower and Receiver Dimensions

Solar field geometry optimization on the Heliostat Field page calculates new values for tower height, receiver height, and receiver diameter.

Tower height	200	m
Receiver height	16	m
Receiver diameter	8	m
Number of panels	20	

Receiver Heat Transfer Properties

Tube outer diameter	40	mm
Tube wall thickness	1.25	mm
Coating emittance	0.88	
Coating absorptance	0.94	
Heat loss factor	1	

Design and Operation

Minimum receiver turndown fraction	0.25	
Maximum receiver operation fraction	1.2	
Receiver startup delay time	0.2	hr
Receiver startup delay energy fraction	0.25	
Receiver HTF pump efficiency	0.850	
Maximum flow rate to receiver	372.351	kg/s

Materials and Flow

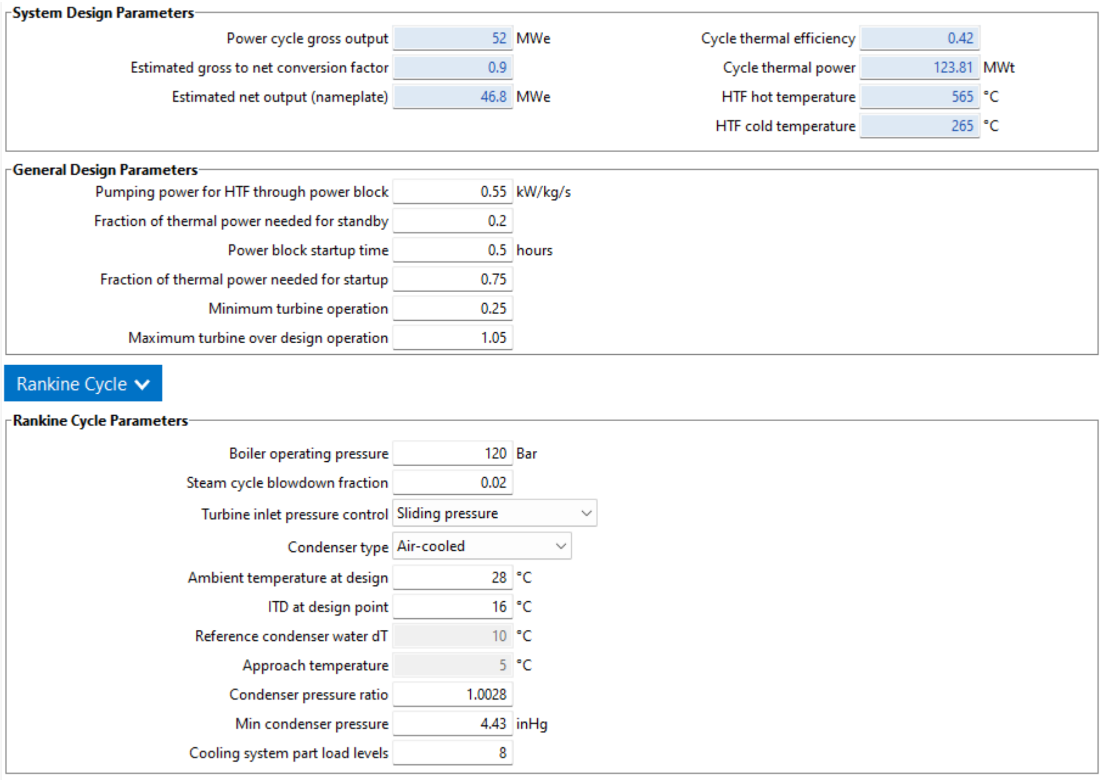
HTF type	Salt (60% NaNO3 40% KNO3)
Property table for user-defined HTF	Edit...
Material type	Stainless AISI316
Flow pattern	1

Receiver Flux Modeling Parameters

Maximum receiver flux	1000	kWt/m²
Estimated receiver heat loss	30.0	kWt/m²
Receiver flux map resolution	20	
Number of days in flux map lookup	8	
Hourly frequency in flux map lookup	2	hours

Piping Losses

Piping heat loss coefficient	10200	Wt/m
Piping length constant	0	m
Piping length multiplier	2.6	
Piping length	520	m
Total piping loss	5304	kWt



5. Results

The results selected to be presented after the SAM analysis, concern the system's Capacity Factor, the efficiency of the subsystems, the total electrical power of the system for electricity production and the consumptions required for its operation.

In a solar power tower system, the overall efficiency is influenced by three key factors. The optical efficiency pertains to the ability of the heliostats to collect and direct solar radiation towards the receiver. Proper alignment and reflectivity of the mirrors are critical for achieving high performance.

The thermal efficiency depends on how effectively the receiver converts the collected heat into usable thermal energy. Key factors include the design of the receiver and its ability to minimize thermal losses.

Finally, the power cycle efficiency depends on the system's ability to convert thermal energy into electrical energy.

In the chart below, the variation of the optical field efficiency, the power cycle efficiency and the thermal efficiency, during the year, are shown.

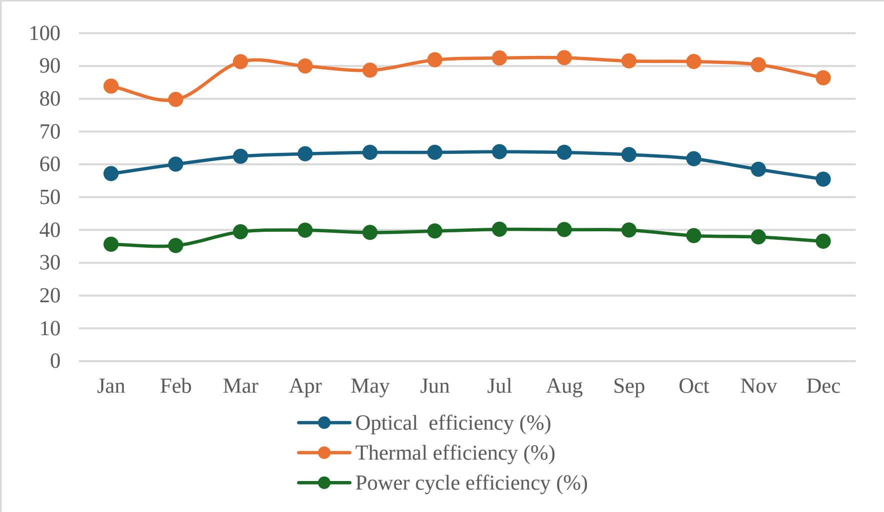


Figure 5 Monthly variation in optical efficiency, thermal efficiency, and power cycle efficiency

Table 3 System efficiency during the year

Month	Optical efficiency (%)	Thermal efficiency (%)	Power cycle efficiency (%)
Jan	57.14	83.83	35.62
Feb	60.03	79.76	35.23
Mar	62.44	91.27	39.43
Apr	63.2	89.95	39.92
May	63.62	88.68	39.21
Jun	63.65	91.84	39.66
Jul	63.84	92.42	40.17
Aug	63.63	92.5	40.08
Sep	62.96	91.5	39.93
Oct	61.68	91.33	38.25
Nov	58.45	90.37	37.84
Dec	55.47	86.37	36.53
Average	**61.34**	**89.15**	**38.49**

According to the analysis, the total energy produced and fed into the grid by the solar tower system with 5 hours of thermal storage is 109.26 GWh/y and the annual system capacity factor is 24.5%. Correspondingly, the annual consumption necessary for the operation of the system is 12 GWh/y.

Table 4 shows the monthly generated energy of the system as well as the electricity needed for the subsystems operation, necessary for the overall system’s operation.

Table 4 Capacity factor and electricity produced and consumed by the solar power tower.

Month	System energy consumption (MWh)	Solar tower energy produced (MWh)	Capacity factor (%)
Jan	500.8	3,472.2	9.3
Feb	555.1	4,209	11.3
Mar	938.7	8,299	22.3
Apr	1,101	9,977.8	26.8
May	1,083.4	9,781.4	26.3
Jun	1,473.9	14,385.7	38.7
Jul	1,514.6	15,025.8	40.4
Aug	1,499.5	14,979.1	40.3
Sep	1,195.1	11,249.4	30.3
Oct	905.8	8,057.9	21.7
Nov	710.1	5,932.6	16
Dec	517.5	3,890.8	10.5
Sum	**11,995.6**	**109,260.70**	

The diagram below shows the monthly energy produced and consumed by the system during the year, after data analysis in SAM and taking into account the efficiency of the systems and.

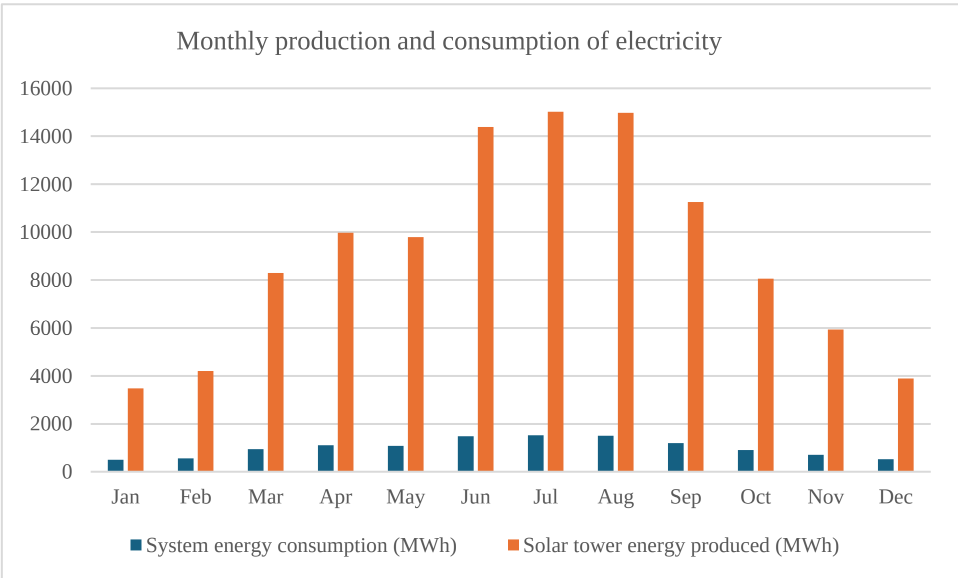


Figure 6 Electricity produced and consumed by the solar power tower.

Based on the electricity produced by the solar tower (values in Table 4), the variation of the capacity factor of the system during the year is presented in Fig7.

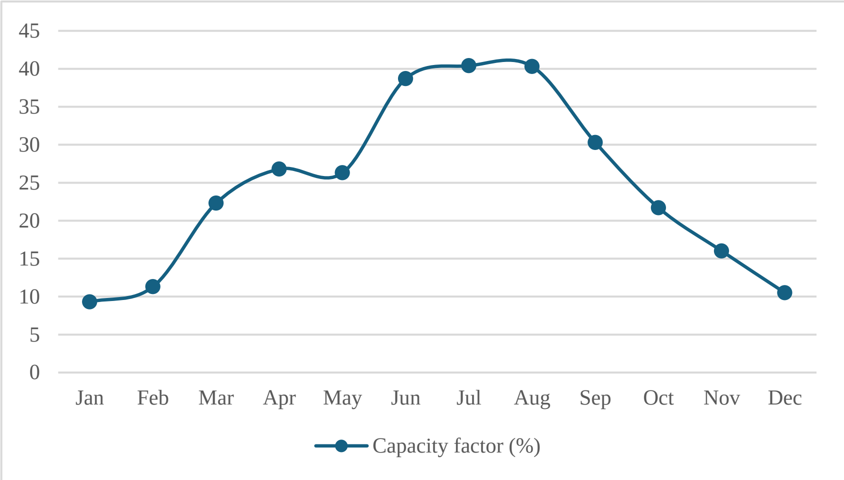


Figure 7 Monthly variation of the capacity factor

During the summer solstice period, where the amount of direct solar radiation is maximum, there is an increase in the system's capacity factor compared to the month of December when the winter solstice occurs. Particularly in July the capacity factor is increased from 10.50% to 40.4%. Regarding the generated electricity as a function of the system capacity factor, there is an increase in the summer months and a corresponding decrease in the winter months. This is also noticed by the energy consumed by the system during its operation in summer and winter period as well. In addition, it was found that the penetration rate of the system in electricity generated from RES and in total electricity production as well, for the island of Crete, peaks in the summer months. More specifically, the highest penetration of the system in electricity generated from renewable sources has occurred in the month of June with a percentage of 18.96%, while the system's contribution in total production (RES & conventional systems) is up to 8.62%.

According to a survey by ELSTAT in cooperation with CRES, each Greek household consumes 13,994 kWh per year [4]. The energy produced and fed into the grid by the solar tower system is sufficient to cover the demand of almost 7,800 households.

The electrical energy required for the solar tower's subsystems operation is up to 10.98%. A percentage of this amount of energy is generated from backup power plants and the rest of it from the system itself. It is worth mentioning that the energy required for the tower's subsystems operation, could cover the annual electricity demand of about 850 households. The energy needed for tower's subsystems operation could be mitigated using an independent renewable energy source whose operational needs would be negligible. Adopting solutions like this, would help to increase the amount of electricity fed into the grid from the solar tower system as well as to reduce the amount of energy needed to maintain the fluid's temperature over its critical lower value during the night.

6. Conclusions

In this paper, the simulation of the first ever designed concentrating solar-thermal system in Greece, with a capacity of 52MW, was presented. It is a pilot project while processes are underway to find a tenderer to construct and operate the project.

Through the simulation carried out for the solar tower power system, there were interesting outcomes regarding the system's contribution in meeting the energy needs for the island of Crete. The maximum performance of the system has occurred during the summer period where it is capable to feed the grid with an amount of energy equal to 15,025.8 MWh, while the system's capacity factor for the month of July is up to 40.4%. The electricity generated only from this system contributes significantly to the annual electricity demand, with the maximum contribution occurring in the month of July where the penetration of the system is up to 8.62%. The total electricity generated from the system (109.26 GWh/y) is capable to meet the annual energy needs of about 7,800 households.

The simulation results were compared to the project calculations by the company and it was shown that SAM software is a reliable tool for modeling various renewable energy systems and more specifically concentrating solar thermal systems as analyzed in this paper.

Further research is needed on the design and sizing of an individual RES system to cover the energy requirements for the operation of the concentrated solar tower, since the electrical energy requirements for running the concentrated solar tower subsystems cannot be considered negligible. Furthermore, a financial study could be carried out regarding the system's sustainability (construction costs, operating costs, maintenance costs, life cycle of the various sub-units of the system).

7. References

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