

# Optimization of a Heliostat Field by Multiobjective Particle Swarm Optimization (MOPSO) Algorithm Based on Energy, Exergy, and Economic Point of Views

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## Research Article

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1                   **Optimization of a heliostat field by multiobjective particle swarm optimization (MOPSO)**  
2                   **algorithm based on energy, exergy, and economic point of views**

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19                  **Abstract:** This research is devoted to the energy, exergy, and economic analyses and optimization of a  
20                  heliostat field. The model of the heliostat solar receiver includes detailed geometric factors related to the  
21                  optical and thermal losses and efficiencies throughout the year. The main parameters of the thermal  
22                  performance of this system consist of energy and exergy efficiencies, and economic parameters are  
23                  investigated. By computing the energy, exergy, and economic analysis tools, they are applied for the analysis  
24                  of performance, and viability of the system's operating in Tehran City, including the detailed information of  
25                  the environmental conditions of that location. For optimization purposes, 7 design variables related to  
26                  geometric specification of the heliostat field are selected and the related lower and upper bonds are selected.  
27                  Two target functions considered for the optimization are heliostat field exergy efficiency and payback period.  
28                  The economic feasibility results of this study reveal that the net present value is 58.84 million US\$, the  
29                  payback period is 6.76 years, and the internal rate of return is 0.16. By considering the MOPSO algorithm,  
30                  the annual mean exergy efficiency is increased from the 30.9% to 34.3% while the heliostat field payback  
31                  period in reduced from the 6.76 to 4.3 years.

32                  **Keywords:** Heliostat; Optimization; Energy; Exergy; Economic

33                  **1. Introduction**

34                  The concentrated solar power (CSP) called the solar tower, is one promising technology to utilize solar  
35                  energy. The CSP solar system is a set of mirrors with the tracking system in different lines; sometimes it is  
36                  called a heliostat field [1]. This device is the core element in solar technology. The system is based on a  
37                  set of mirrors rotating on two axes, reflecting and concentrating the sunlight at the top of a spot or tower.  
38                  There, the sunlight turns into heat with high-temperature, which can be used to produce steam or a hot  
39                  working fluid for electrical power generation[2, 3]. The thermodynamic and optical assessment of heliostat  
40                  fields has been extensively reported in the literature[4-6]. The solar collector performance is affected by  
41                  different types of the reflector and receiver and working fluid. In the application of this device, selecting the  
42                  proper types of the working fluid, storage systems, and thermal and optical performance of the solar

43 receiver are very important parameters [7]. In an experimental study done by Said et al.[5], the effect of the  
44 number of mirrors on the optical performance of Fresnel heliostat was investigated. Results of this research  
45 showed that by increasing the number of mirrors, the optical efficiency of this type of heliostat was increased  
46 too. Since by variation of the number of mirrors from 7 to 9 and 11, the optical performance of this system  
47 varied to 20.65%, 27.13%, and 29.13%, respectively. Moreover, the concentration ratio of this device varied  
48 from 6.74 to 9.77 due to changing the number of mirrors from 7 to 11.

49 Eddhibi et al. [8] studied a heliostat field, including different losses like shadowing losses, blocking and  
50 atmospheric attenuation, and cosine loss in modeling and simulation. This study's results revealed  
51 efficiencies associated with the cosine loss, atmospheric attenuation, and shadowing and blocking losses  
52 of 82.41%, 95%, and 92%, respectively. The same investigation was conducted by other research groups,  
53 with good results' agreement [9, 10]. The optimization of a heliostat field with specified geometry was done  
54 by Talebizadeh et al. [11] to find the best achievement of the heliostat field for the maximum heat absorption  
55 of the solar receiver. Results revealed that increasing the height of the tower by 7.7% and reducing the  
56 heliostat field by 19.5% lead to about a 4% increase and a 17% decrease of the heliostat field's total  
57 efficiency and total area, respectively. The economic optimization of a heliostat field was conducted by Li  
58 et al. [12] to obtain the maximum absorbed solar energy per unit cost of the specific heliostat field (Lhasa).  
59 In this study, the unit cost of collected energy was evaluated for different parameters including radius of the  
60 field, optical parameters of the mirrors, the height of the tower, and the heliostat mirror cost. Results of this  
61 optimization showed that increasing the radial distance by 6% leads to an increase of the unit cost of  
62 collected energy from 12.49 to 12.98  $\text{MJ}/\text{\$}$ . In the optimization of a hybrid combined power cycle and the  
63 solar dish made by Saghafifar [13], the layout configuration of the heliostat was analyzed for two  
64 arrangements. Also, different economic parameters such as net present value (NPV), payback period (PP),  
65 levelised cost of electricity (LCoE), and life cycle saving, Knopf objective function were investigated for  
66 these two configurations. Results of heliostat field optimization showed that the weighted efficiency was  
67 58.6% for the radial –staggered layout and 58.4% for the spiral layout. This study showed that the LCoE  
68 for both layouts is close to 34  $\text{\$/MW}_h$ .

69 A new method was applied by Zi and Zhifeng [14] for the PS 10 location in China. In this research, the  
70 optical effects of the heliostat were investigated considering a solar tracking system in the field layout.  
71 Heliostat field different parameters including mean optical efficiency, cosine efficiency, blocking and  
72 shadowing effects, and atmospheric transmission were evaluated annually. A good agreement was  
73 obtained when comparing the results of this study with those of the existing heliostat layout. The exergy  
74 and thermo-economic study of a solar power plant with a central receiver were conducted by Toro et al.  
75 [15]. A thermodynamic and economic evaluation and optimization of this solar power plant were conducted  
76 to obtain the best exergy and economic efficiencies of the systems, reducing the exergy destruction and  
77 the exergoeconomic cost of the produced power. In other studies [16, 17], different layouts heliostat fields

78 including the staggered, spiral, and combinations of these two arrangements were investigated and  
79 compared. The obtained results from this research showed that the optical efficiency of the spiral layout  
80 was better than that of the staggered layout and that even the combined layout has better performance  
81 than the staggered arrangement. The energy and exergy evaluation of a system composed of a solar tower  
82 for power generation with molten salt as the working fluid was carried out for different operating and design  
83 parameters such as the type of power cycle , the direct normal irradiation (DNI), and the concentration ratio  
84 [18]. The conclusion of this research revealed that the major exergy destruction happens in the receiver  
85 system. Moreover, the results showed thermodynamics efficiency of the receiver and the whole system  
86 increased by increasing the concentration ratio and the DNI. It was also concluded that the system thermal  
87 efficiency increased if advanced power cycles were used such as reheat and supercritical Rankine cycles  
88 [18, 19]. The combination of a solar tower with an energy storage system using molten salt as the operating  
89 fluid in Chile was studied by Gallardo et al. [20]. The conclusion of this research revealed the optimal solar  
90 power plant in terms of size and configuration operating in Chile. The result was the suggestion of CSP and  
91 TES configuration. Results of this combination showed that the specific exergy cost for this system was  
92 65.6 US\$/MWh in 2018 and that this cost was estimated as 48.1 US\$/MWh in 2030 [20]. The hybrid  
93 combination of CSP and TES systems was studied in several similar types of research [21]. Different  
94 parameters such as energy efficiency (ENE), exergy efficiency (EXE), and some important economic  
95 parameters such as the LCoE for different solar systems and storage units were investigated [22, 23]. Other  
96 similar researches have been carried out for the application of different operating fluids such as molten salt,  
97 thermal oil, and supercritical carbon dioxide, and inclusion of phase change materials (PCM) to increase  
98 the energy storage of the system [23, 24].

## 99 **2.1. Research gap and innovation**

100 From the previous researches, it can be concluded that although several types of research have been  
101 done about the heliostat solar receiver and integration with other systems to produce electricity, heating,  
102 and cooling,

103 No research in literature includes three 3E including energy, exergy, and economic analyzes in the field  
104 of solar heliostat alone and optimization with multi-objective particle swarm optimization MOPSO algorithm  
105 that considered exergy and economic aspects of this field.

106 Because the only energy and exergy analyses are not enough to evaluate a system and a  
107 comprehensive economic study gives a better view of choosing a system. Also, by configuration  
108 optimization of the heliostat field with the MOPSO algorithm, the system can operate with better  
109 performance with low expenses. Since no additional sub-systems are added to the heliostat field and only  
110 the geometry is changed. For this target, the heliostat solar receiver is modeled considering all the factors  
111 related to the optic and thermal losses and efficiencies during 8760 hours a year. In this work, the energy,  
112 exergy, and economic analyses of a typical heliostat solar receiver system are conducted. The model is

113 validated by comparing it with results obtained from the literature. Various key performance parameters  
114 such as ENE and EXE, and economic parameters such as PP, NPV, and IRR are evaluated for the system  
115 operating in Tehran City. Furthermore, by choosing two target functions (EXE and payback period), the  
116 configuration of the heliostat field is optimized.

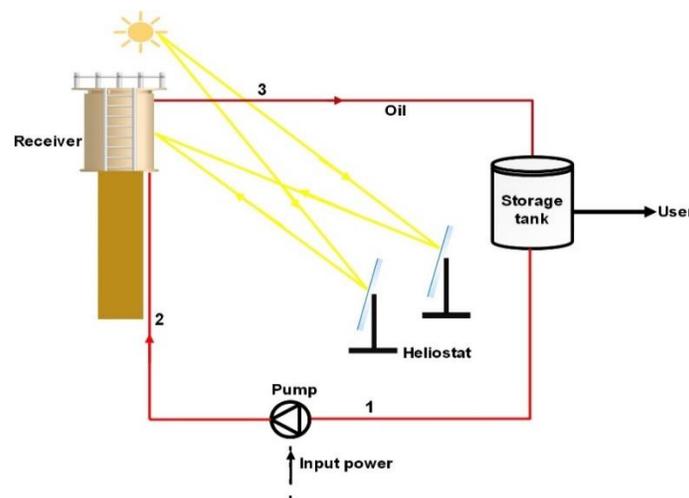
117 The main innovative aspects of this study can be summarized as:

- 118 • Thermodynamic and economic analyses of a heliostat solar receiver.
- 119 • Evaluation of the exergy lost rate for each component of this typical solar receiver.
- 120 • Optimization of heliostat field by MOPSO algorithm
- 121 • Evaluation and investigation of the key parameters related to the energy and exergy  
122 performance, and economic feasibility of this system in Tehran City.

## 123 2. Methodology and model

### 124 2.1. System and process description

125 The schematics of the system and process under analysis are illustrated in Figure 1. Schematics of the  
126 system and process under analysis The heliostat layout is radially staggered. The circulation pump moves  
127 the working fluid (Therminol-VP1) into the system. After absorbing heat in the receiver, the working fluid is  
128 transferred to the thermal energy storage tank, the stored thermal energy being ready to be used for any  
129 useful purpose. The operating fluid conveys the thermal energy from the solar receiver to the storage tank  
130 and the storage tank providing a heat source for useful purposes.

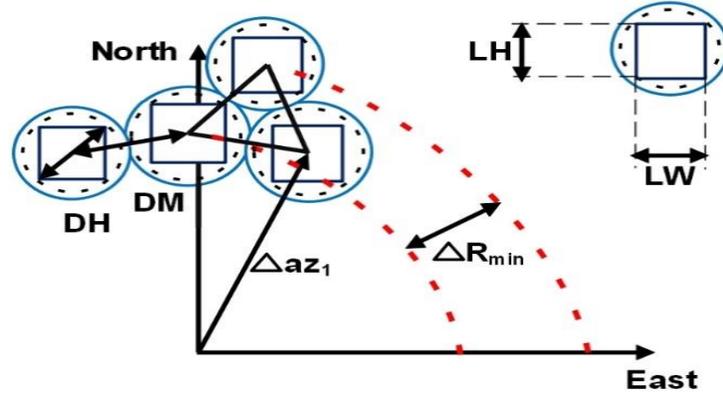


131

132 Figure 1. Schematics of the system and process under analysis

133 **2.2. Heliostat optic modeling**

134 The solar radiation modeling is described in Appendix A. Figure 2. The layout of heliostat field  
 135 fundamentals shows the heliostat field layout's characteristics. A lot of geometrical information is required  
 136 for the evaluation of how the incident solar radiation in every single heliostat reaches the receiver at the top  
 137 of the tower.



138

139 Figure 2. The layout of heliostat field fundamentals [25]

140 The distance between adjacent heliostats centers is the characteristic diameter that can be expressed as  
 141 [26]:

$$DM = \sqrt{L_H^2 + L_W^2} + desp \quad (1)$$

142 where desp denotes the extra separation between adjacent heliostats, and  $L_W$  and  $L_H$  are the width and  
 143 the height of the heliostat, respectively. In the first zone, the minimum radial increase of the field ( $\Delta R_{min}$ ) is  
 144 obtained as [26]:

$$\Delta R_{min} = DM \cos(30^\circ) \quad (2)$$

145 For the heliostat field first zone, the azimuth angular spacing ( $\Delta az_1$ ) is obtained as [26]:

$$\Delta az_1 = 2 \sin^{-1} \frac{DM}{R_1} \quad (3)$$

146 Where  $R_1$  is the radial distance the first row of heliostats from the tower, obtained as [26]:

$$R_1 = N_{hel_1} \frac{DM}{2\pi} \quad (4)$$

147  $N_{hel_1}$  is the number of heliostats in the first row.

148 The distance between two adjacent mirrors is a function of the radial length from the tower as the layout  
149 is radially staggered. Therefore, the farther from the tower the more space between mirrors. If this space is  
150 higher than DM, installing an additional heliostat would be possible. When all these spaces have been filled  
151 with additional heliostats, the field is settled. For the  $i^{th}$  field, the azimuth angular spacing is obtained as  
152 [26]:

$$\Delta az_i = \left( \frac{\Delta az_1}{2^{i-1}} \right) \quad (5)$$

153 The radial distance between the first row of  $i^{th}$  field and the tower ( $R_i$ ) can be obtained as [26]:

$$R_i = 2^{i-1} \left( \frac{DM}{\Delta az_1} \right) \quad (6)$$

154 and for every line of  $i^{th}$  field, the number of heliostats is expressed as [26]:

$$N_{hel_i} = \left( \frac{2\pi}{\Delta az_i} \right) \quad (7)$$

155 For the  $i^{th}$  field, the number of heliostats rows can be obtained [26]:

$$N_{row_i} = \left( \frac{R_{i+1} - R_i}{\Delta R_{min}} \right) \quad (8)$$

156 The heliostat optic performance is obtained as [27, 28]:

$$\eta_{opt} = \rho \times \eta_{s\&b} \times \eta_{cos} \times \eta_{spillage} \times \eta_{at} \quad (9)$$

157 where  $\eta$  denotes efficiency, and subscripts s&b, cos, ref, at, and spillage are respectively shadowing and  
158 blocking, cosine, spillage, and atmospheric attenuation.  $\rho$  denotes mirror reflectivity efficiency is considered  
159 to be 95% [29].

160 The cosine efficiency can be obtained by [27, 28]:

$$\eta_{cos} = \cos \left[ \arccos \frac{1}{2} (\vec{S} \cdot \vec{R}) \right] \quad (10)$$

161  $\vec{S}$  and  $\vec{R}$  are the unit vector of incident and reflected lights.

162 The shadowing and blocking efficiency can be considered by the following relation [27, 28]:

$$\eta_{s\&b} = 1 - \frac{A_{SH}}{A_{HSR}} \quad (11)$$

163 Subscripts SH means shaded. The method of calculation of  $\eta_{s\&b}$  is explained in Ref. [27].

164 The atmospheric attenuation efficiency can be expressed as [29]:

$$\eta_{at} = 0.99321 - 0.0001176d + 1.97 \times 10^{-8}d^2 \quad d < 1000 \text{ m} \quad (12)$$

$$\eta_{at} = \exp(-0.0001106d) \quad d > 1000 \text{ m}$$

165 Spillage efficiency can be evaluated as [30]:

$$\eta_{spillage} = \int_{-r_{ap}}^{r_{ap}} f_1 \times d \quad (13)$$

166 where  $f_1$  is obtained as [30]:

$$f_1 = \frac{1}{\sigma_1 \sqrt{2\pi}} \cdot \exp\left(-\frac{R^2}{2\sigma^2}\right) \quad (14)$$

167 where R is the space between the base of the tower and each heliostat, and  $\sigma_1$  can be evaluated as [30]:

$$\sigma_1 = \frac{d}{3} \sqrt{(\tan(\delta_s))^2 + (\tan(\epsilon_{surf}))^2 + (\tan(\epsilon_{track}))^2} \quad (15)$$

168 where  $\epsilon_{track}$  and  $\epsilon_{surf}$  are the errors caused by tracking and angular deviation due to surface defects, which  
 169 are considered to be equal to 1° and 2°, respectively [30].  $\delta_s$  denotes solar declination, evaluated in  
 170 Appendix A.

171 In Eq. (13)  $r_{ap}$  is the effective size of the receiver opening, which can be obtained as [30]:

$$r_{ap} = \sqrt{\frac{A_{ap}}{\pi}} \times \cos(\theta_R) \quad (16)$$

172 where  $\theta_R$  denotes the angle between the vertical direction and the reflected irradiation,  $A_{ap}$  means total  
 173 aperture area,  $\cos(\theta_R)$  being obtained as [30]:

$$\cos(\theta_R) = \cos(\alpha_s) \times \cos(\varphi) \quad (17)$$

174 where  $\varphi$  is latitude and  $\alpha_s$  is the angle of solar altitude given in Appendix A.

### 175 **2.3. Energy analysis**

176 The focus of the present study is not on the energy storage subsystem, but on the heliostat and receiver  
177 tower system, the steady-state analysis allowing the most relevant searched results. The energy and mass  
178 balance equations for each component of the system can be expressed as:

$$0 = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + \dot{Q}_{net} \quad (18)$$

$$0 = \dot{m}_{in} - \dot{m}_{out} = 0 \quad (19)$$

179 where  $h$  is the specific enthalpy, subscripts in and out are inlet and outlet streams of the control volume,  
180 respectively, and  $\dot{Q}_{net}$  is the heat power received by the control volume, which is evaluated as:

$$\dot{Q}_{net} = \dot{Q}_S - \dot{Q}_{loss} \quad (20)$$

181 In the heliostat field, the solar energy input can be evaluated as [31]:

$$\dot{Q}_S = \eta_{opt}\alpha A_{ap}G_b \quad (21)$$

182 where  $A_{ap}$  is the total aperture area,  $G_b$  is the solar direct beam irradiation, and  $\alpha$  is the absorption factor of  
183 the solar receiver. The thermal power losses of the system are evaluated as [32]:

$$\dot{Q}_{loss} = \dot{Q}_{loss,conv} + \dot{Q}_{loss,rad} \quad (22)$$

184 where subscripts conv and rad mean convection and radiation heat transfer from the solar receiver to the  
185 environment. The radiative thermal power loss can be obtained as [32]:

$$\dot{Q}_{loss,rad} = \sigma \cdot \epsilon_{re} \cdot A_{re} (T_{re}^4 - T_{amb}^4) \quad (23)$$

186 where  $\sigma$  is the Stefan-Boltzman constant,  $\epsilon$  is the receiver surface emissivity,  $A_{re}$  is the surface area of the  
187 solar receiver, and  $T$  is its absolute temperature. Subscript amb means ambient. The convective thermal  
188 power loss can be evaluated as [32]:

$$\dot{Q}_{loss,conv} = h_{forced} \cdot A_{re} (T_{re} - T_{amb}) \quad (24)$$

189 A denotes the surface area of the receiver, and T its temperature.  $h_{\text{forced}}$  is the forced convection heat  
 190 transfer coefficient can be obtained as [32]:

$$h_{\text{forced}} = \frac{k_m \cdot Nu_{\text{forced}}}{D_{\text{re}}} \quad (25)$$

191 where  $k_m$  is the air thermal conductivity, and Nu and  $D_{\text{re}}$  are the Nusselt number and the solar receiver's  
 192 diameter, respectively. For forced convection due to the ambient wind flow over the receiver, the Nusselt  
 193 number is obtained as [32]:

$$Nu_{\text{force}} = 0.00239 \cdot Re^{0.98} + 0.000945 \cdot Re^{0.98} \quad (26)$$

194 the Reynolds number being evaluated as [32]:

$$Re = \frac{U_{\text{wind}} D_{\text{re}}}{\nu_m} \quad (27)$$

195  $U_{\text{wind}}$  and  $\nu_m$  mean wind speed and kinetic viscosity.

196 The overall ENE of the proposed system is expressed as:

$$\eta_{\text{energy}} = \frac{\dot{Q}_{\text{net}} - \dot{W}_p}{A_{\text{ap}} G_b} \quad (28)$$

197 where subscript p refers to the circulation pump, and  $\dot{Q}_{\text{net}}$  is the net thermal power received by the receiver  
 198 and  $\dot{W}$  is the mechanical power needed for the circulation pump operation, evaluated as

$$\dot{W}_p = \frac{\dot{m}_1 (h_{2s} - h_1)}{\eta_p} \quad (29)$$

199 where  $h_{2s}$  is the specific enthalpy of the stream leaving the pump if the pumping process is assumed to be  
 200 isentropic. The pump efficiency is considered 85%.

## 201 **2.4. Exergy analysis**

202 Exergy is defined as achievable mechanical work when a system reversibly evolves up to be in equilibrium  
 203 with the ambient contacting it [33, 34]. Exergy analysis can be used to identify and quantify irreversibilities,  
 204 and thus imperfections, in a system. For a stream, the total specific exergy is expressed as [33, 35]:

$$ex = (h - h_0) - T_0 (s - s_0) + T_0 \sum x_i R_i \ln y_i + \sum x_i ex_{\text{chi}} + \frac{V^2}{2} + gz \quad (30)$$

205 where  $T$  is the absolute temperature,  $h$  is the specific enthalpy, and  $s$  is the specific entropy.  $R_i$  is the  
 206 particular gas constant of chemical species  $i$  in the stream,  $ex_{chi}$  its specific chemical exergy,  $x_i$  its mass  
 207 fraction and  $y_i$  its molar fraction.  $g$ ,  $V$ , and  $z$  are gravitational acceleration, velocity, , and height,  
 208 respectively. Subscript 0 refers to the environmental (equilibrium) conditions. Table 1 summarizes the  
 209 exergy destruction rate (EDR) relations for the main components of the system under analysis.

210 Table 1. EDR relations for the system main components

No.	Component	Exergy destruction rate
1	Pump	$\dot{m}(ex_1 - ex_2) + \dot{W}_p$
2	Solar receiver	$\dot{m}(ex_2 - ex_3) + \dot{Q}_{loss} \left(1 - \frac{T_{amb}}{T_{re}}\right)$
3	Heliostats	$G_b A_{ap} \left[1 - \frac{4}{3} \left(\frac{T_{amb}}{T_{Sun}}\right) + \frac{4}{3} \left(\frac{T_{amb}}{T_{Sun}}\right)^4\right] - \frac{\dot{Q}_S}{\alpha} \left(1 - \frac{T_{amb}}{T_{hel}}\right)$

211 The symbols and subscripts in Table 3, are defined earlier. The EXE of the proposed system can be  
 212 calculated by:

$$\eta_{exergy} = \frac{\dot{Q}_{net} \left(1 - \frac{T_{amb}}{T_{re}}\right) - \dot{W}_p}{G_b A_{ap} \left[1 - \frac{4}{3} \left(\frac{T_{amb}}{T_{Sun}}\right) + \frac{4}{3} \left(\frac{T_{amb}}{T_{Sun}}\right)^4\right]} \quad (31)$$

213 where  $T_{Sun}$  is the Sun temperature (.

## 214 2.5. Economic analysis

215 Heliostat field, central tower, and receiver are the three main elements of the plant, which are analyzed  
 216 separately. In what follows, the Z factors are expressed in units of US dollars. The total capital investment  
 217 of the plant is evaluated as [30, 36, 37]

$$Z_{plant} = Z_{re} + Z_{tow} + Z_{piping} + Z_{heliostat\ field} \quad (32)$$

218 In Which, subscripts re, and tow denote receiver and tower. The investment cost of each system component  
 219 is depicted in Table 2 [13, 30, 38, 39].

220 Table 2. The investment cost of mirrors, land, wire, and other costs

No.	Description	Cost function	Ref
-----	-------------	---------------	-----

1	Heliostat	Mirror	$Z_{\text{mirror}} = 126N_{\text{hel}}A_{\text{hel}}$	[13, 30, 38, 39]
2		Wire	$Z_{\text{wire}} = \sum_{i=1}^{100} N_{\text{hel,cell},i} \left[ 0.031r_{\text{cell},i} + 24 \sqrt{\frac{A_{\text{hel}}}{\rho_{\text{cell},i}}} \right]$	[13, 30, 38, 39]
			$\rho_{\text{cell},i} = \frac{N_{\text{hel,cell},i}A_{\text{hel}}}{A_{\text{cell},i}}$	
3		Land	$Z_{\text{land}} = 0.62(1.5A_{\text{land}} + 1.8 \times 10^5)$	[13, 30, 38, 39]
4	Tower		$Z_{\text{tow}} = 1.09025 \times 10^6 \exp(0.00879H_{\text{tow}}) \quad H_{\text{tow}} < 120 \text{ m}$ $Z_{\text{tow}} = 0.78232 \times 10^6 \exp(0.01130H_{\text{tow}}) \quad H_{\text{tow}} > 120 \text{ m}$	[38, 40]
5	Piping		$Z_{\text{piping}} = \left[ 3600 \frac{D_{\text{outer}}}{1.31} + 420 \frac{D_{\text{int}}}{0.87} \right] H_{\text{tow}} + 90000 \frac{D_{\text{int}}}{0.87}$	[30, 36, 37]
6	Receiver		$Z_{\text{re}} = 23500A_{\text{re}}$	[30, 36, 37]

221 where  $Z$  is the capital investment,  $D_{\text{outer}}$  and  $D_{\text{int}}$  are the outer and inner diameters of concentric piping.  
222  $N_{\text{hel,cell},i}$  is the number of heliostats in cell  $i$ .  $r_{\text{cell},i}$  is the receiver - cell's center distance. Subscripts  $\text{hel}$  and  
223  $\text{land}$  refer to heliostat and land, respectively [41]. It should be noted that the cells closer to the receiver have  
224 more heliostats; however, shorter cables are required for these cells. Wiring cost evaluation starts  
225 considering that for the cells of the equal area the density of heliostats is obtained as [13, 17, 39, 41, 42].  
226 The cost of equipment installation is estimated as [43]

$$Z_{\text{ins}} = 0.2Z_{\text{plant}} \quad (33)$$

227 Plant's maintenance costs can be estimated as [30]

$$Z_{\text{om}} = 0.03Z_{\text{mirror}} + 0.04Z_{\text{tow}} \quad (34)$$

228 Moreover, during development and building phases, some indirect additional costs must be considered,  
229 which can be estimated as [30, 44, 45]

$$Z_{\text{if}} = 0.05Z_{\text{plant}} \quad (35)$$

230 Another cost related to unexpected technological/ regulatory issues is evaluated as [30, 44, 45]

$$Z_{\text{cont}} = 0.1Z_{\text{plant}} \quad (36)$$

231 At the end of the heliostat field lifetime, the costs of decommissioning can be estimated as [30]:

$$Z_{dec} = 0.05Z_{plant} \quad (37)$$

232 Concerning the plant operation, labor costs for 20 years of the lifetime of the project need to be  
 233 considered. The salaries of the labor and required staff are presented in Table 3.

234 Table 3. Annual salaries and required number of staff of the plant [30]

Employee	Annual salary (US\$)	Required number of staff
The operator of the control room	40000	$N_{opr}$
Technician of the solar field	40000	$N_{tec}$
Plant engineer	92000	1

235 In Table 3, subscripts opr and tec denote operator and technician, respectively. The number of operators  
 236 for the control room can be evaluated as [30]:

$$N_{opr} = 3 + 2 \left( \frac{A_{hel} N_{hel}}{100000} \right) \quad (38)$$

237 and the number of technicians for the solar field as [30]:

$$N_{tec} = 1 + 3 \left( \frac{A_{hel} N_{hel}}{100000} \right) \quad (39)$$

238 Hence, the total labor cost can be expressed as [30]:

$$Z_{lab} = 1.5 \sum_{staff} sal_{stf} N_{stf} N_{years} \quad (40)$$

239 where  $N_{stf}$  is the number of required employees as operators, technicians, and engineers mentioned  
 240 earlier.  $sal_{stf}$  is the annual salary of each employee as detailed in Table 3.  $N_{years}$  denotes the project lifetime  
 241 (20 years) [31, 46]. Therefore, the total cost of the heliostat plant is obtained as:

$$Z_0 = Z_{plant} + Z_{ins} + Z_{om} + Z_{if} + Z_{cont} + Z_{dec} + Z_{lab} \quad (41)$$

242 The simple payback period (SPP) [31, 46]:

$$SPP = \frac{Z_0}{Z_f} \quad (42)$$

243  $Z_0$  is one of the most significant indices for evaluation of a plant, where  $Z_f$  is the annual income. The annual  
 244 cash flow  $Z_f$  can be obtained as [31, 46]:

$$Z_f = Y_{\text{heating}} k_{\text{heating}} \quad (43)$$

245 where  $Y_{\text{heating}}$  is the capacity of heating production during a year, and  $k_{\text{heating}}$  denotes the specific cost of  
 246 that heating.

247 The inflation rate effect can be evaluated by[47]:

$$Z_n = Z_0(1 + i)^n \quad (44)$$

248 In which  $n$  is the number of years.  $i$  is the inflation rate which is equal to 3.11% [48]. The payback period  
 249 (PP) is evaluated as [31, 46]:

$$PP = \frac{\ln\left(\frac{Z_f}{Z_f - r \cdot Z_0}\right)}{\ln(1 + r)} \quad (45)$$

250 where  $r$  is the discount factor (considered 3% in this study). The total gain from the plant during its lifetime  
 251 is defined as the net present value, evaluated as [31, 46]:

$$NPV = Z_f \frac{(1 + r)^{N_{\text{years}}} - 1}{r(1 + r)^{N_{\text{years}}}} - Z_0 \quad (46)$$

252 Another significant economic factor is the internal rate of return, evaluated as [31, 46]:

$$IRR = \frac{Z_f}{Z_0} \left[ 1 - \frac{1}{(1 + IRR)^N} \right] \quad (47)$$

253

254

### 255 **3. MOPSO Algorithm**

256

257 The MOPSO algorithm is one kind of of the PSO algorithm to solve multi-objective optimization. The  
 258 MOPSO and PSO algorithms use an update of the particle location and velocity in the same manner. As it  
 259 is known in the PSO algorithm the update for the velocity and location of a particle can be found by  
 260 calculation of two parameters. These two parameters are the optimal solution that each particle is obtained  
 261 (individual best), and the optimal solution that the whole population is gained (global best). In the simple  
 262 version of the PSO algorithm, the position and speed updates can be evaluated by [49, 50]:

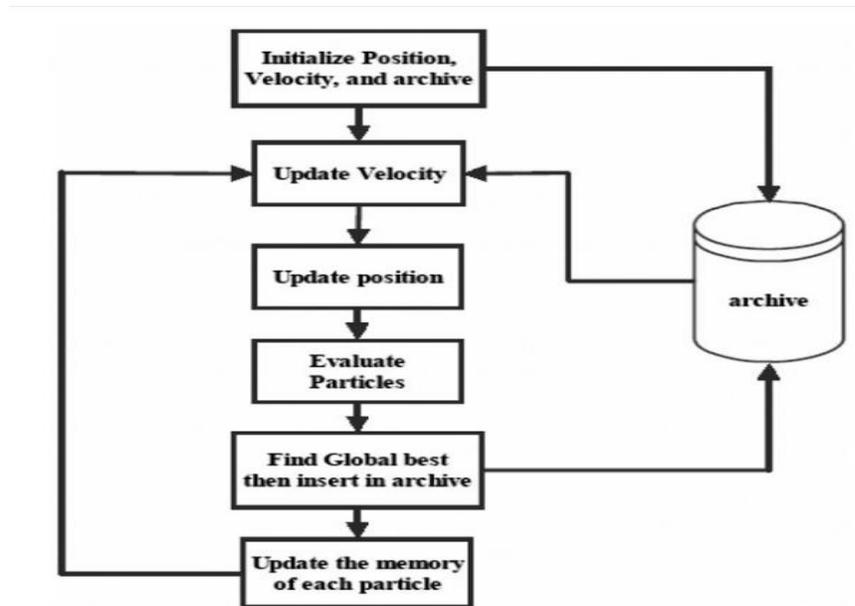
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$$v_{id}(t + 1) = wv_{id}(t) + r_1c_1(P_{id} - x_{id}(t)) + r_2c_2(g_d - x_{id}(t)) \quad (48)$$

$$x_{id}(t + 1) = x_{id}(t) + v_{id}(t + 1) \quad (49)$$

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In the above equations,  $a$  and  $d$  are dimensional search space,  $v_{id}(t)$ ,  $x_{id}(t)$ ,  $v_{id}(t + 1)$ ,  $x_{id}(t + 1)$ ,  $P_{id}$ ,  $g_{id}$ ,  $w$ ,  $c_1$  and  $c_2$ , and  $r_1$  and  $r_2$  are the existing particle velocity, existing particle location, newest particle velocity, newest particle location, the best result that the particle, the best result that the whole population has obtained thus far, inertia weight, acceleration coefficients, and random numbers within the interval  $[0, 1]$  [49, 50]. The MOPSO flowchart is represented in Figure 3.



271

Figure 3. The flowchart of the MOPSO algorithm [51]

272

273 Two selected objective functions for the optimization are as follows:

$$\text{Objective I} = \eta_{\text{exergy}} \quad (50)$$

$$\text{Objective II} = PP \quad (51)$$

274 The design variables and the range of them considered in this optimization are depicted in Table 4.

275

276

Table 4. The ranges of design variables

No.	Design variables	Unit	Lower bond	Upper bond
1	L	m	16	25
2	l	m	6	12
3	d	m	8	14
4	H <sub>t</sub>	m	100	140
5	$\beta$	m	5	30
6	R <sub>a</sub>	m	2	8
7	R <sub>H</sub>	m	8	14

#### 278 4. Results and discussion

279 The outcomes of the complete 3E analyses of a typical heliostat are presented in this section. It starts  
 280 with validation of the model (and of its implementation in a MATLAB code) and is followed by the relevant  
 281 description of the location where the system is operating (Tehran City), ending with the energy, exergy, and  
 282 economic results and analysis. For that purpose, it is assumed that all the thermal energy reaching the  
 283 storage tank in Fig. 1 is used daily. In the first step, the solar radiation in each hour is calculated through a  
 284 year. After it, the amount of solar radiation absorbed by the solar receiver is calculated. Then, considering  
 285 the energy analysis the outlet temperature of the storage tank is calculated. By calculating the  
 286 thermodynamic properties in each stream of the system, the exergy evaluation is done. By considering the  
 287 initial and installation cost and other indirect costs, the economic investigation is done. For the optimization,  
 288 the two target functions are considered and the Pareto-front figure is presented and the optimization point  
 289 is selected. For the parametric study, the results of the heliostat field are compared before and after  
 290 optimization. Input parameters of the heliostat field model are summarized in Table 5 [9, 13, 26, 41, 52-  
 291 54]. Properties of the working fluid(Therminol VP-1), are tabulated in Table 6 [55].

292

293

294

Table 5. Input parameters of the model

No.	Parameter	Unit	Value/definition
1	Working fluid	-	Therminol VP-I
2	L	m	20
3	H <sub>t</sub>	m	120
4	d	m	10
5	R <sub>a</sub>	m	4
6	R <sub>H</sub>	m	9
7	L <sub>H</sub>	m	12.3
8	L <sub>W</sub>	m	9.8
9	Field zones number	-	3
10	N <sub>hel</sub>	-	20
11	N <sub>tot</sub>	-	1460
12	φ	Degree	35.689 N
13	L <sub>loc</sub>	Degree	51.5 E
14	Field layout	-	Radial-staggered/spired
15	l	m	8
16	The additional separation distance between adjacent heliostats	m	0
17	ṁ	kg/s	4.5
18	β	Degree	10
19	Heliostat vertical distance from the ground	m	5
20	P <sub>1</sub>	kPa	101.3

Table 6. Properties of Therminol VP-1 [55]

No.	Parameter	Unit	Value/definition
1	Composition	-	Biphenyl/diphenyl oxide eutectic mixture

2	Density at 15°C	kg/m <sup>3</sup>	1069
3	Thermal conductivity at 15 °C	W/(mK)	0.1367
4	Specific heat at 15 °C	kJ/(kgK)	1.529
5	Viscosity at 15 °C	kg/(ms)	0.005051
6	Specific enthalpy at 15 °C	kJ/kg	4.7
7	Normal boiling point	°C	257
8	Crystallizing point	°C	12
9	Average molecular weight	kg/kmol	166
10	Maximum bulk temperature	°C	400
11	Flashpoint PMCC	°C	110
12	Flashpoint COC	°C	124

#### 298 4.1. Model validation

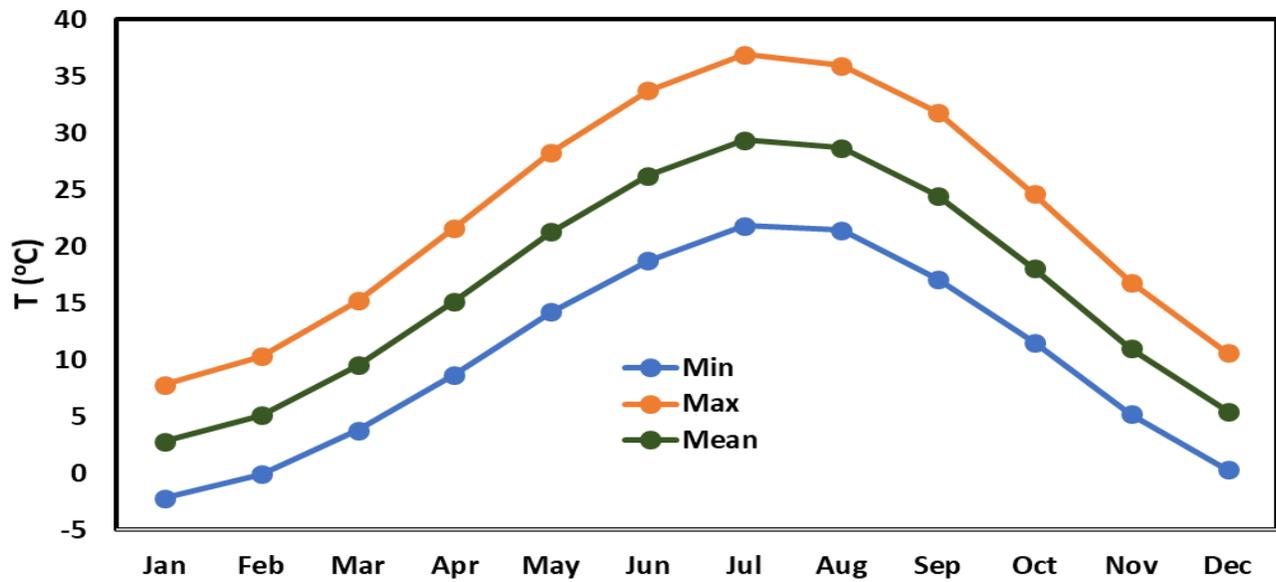
299 Results from Ref [39] were used for the model validation. The model was implemented in MATLAB, and  
300 the data summarized in Table 6 from Ref [39] inserted in the developed code. The comparison between  
301 the key parameters of the heliostat solar tower evaluated using the present model (and its implementation)  
302 with the data in Table 20 of Ref [39] is made in Table 7. For evaluation of the EXE of the heliostat system,  
303 the reference [56] is considered. In that reference, the solar radiation about 800 W/m<sup>2</sup> and heliostat and  
304 central receiver characteristics in Table 1 of that reference are considered. The heliostat field and central  
305 receiver EXE's are calculated about 75.0% and 55.8%, respectively in that reference. So, in general, the  
306 EXE of the total heliostat system is about 41% by multiplying these two exergy efficiencies. By inserting the  
307 solar radiation and heliostat and central receiver of the reference [56], the total EXE is calculated around  
308 38.9%. The deviation is around 5% which is acceptable in engineering calculation.

309 Table 7. Comparison of results of the present model and Ref [39]

No.	Parameter	Unit	Model	Ref [39]	Difference (%)
1	Annual thermal energy provided by the heliostat field	GWh	102.3	99.275	3
2	Heliostat field mean cosine efficiency	%	85.1	83.21	2.2
3	Heliostat field mean attenuation efficiency	%	94.1	95.23	1.2
4	Heliostat field averaged spillage efficiency	%	94	97.68	4

310 **4.2. Heliostat location**

311 The field is located in Tehran City, Iran, at 35.41° N latitude and 51.19° E longitude [57]. Tehran City is  
312 a semi-arid metropolis with very hot summers and cold winters, with eventual snowfall. Based on a yearly  
313 average, Tehran City has about 13 daylight hours and 11 hours of sunshine[58, 59][59, 60][59, 60. As can  
314 be seen from Figure 4, the city experiences the maximum and minimum temperatures in July and in  
315 January, respectively. The three months with the highest temperatures (by decreasing order) are July,  
316 August, and June, and the three months with the lowest temperatures (by increasing order) are January,  
317 February, and December. The mean temperature changes from 3.8 °C up to 21.8 °C. Generally, the highest  
318 temperature in the city is 36.9 °C, and the lowest temperature is 0.3 °C [60].

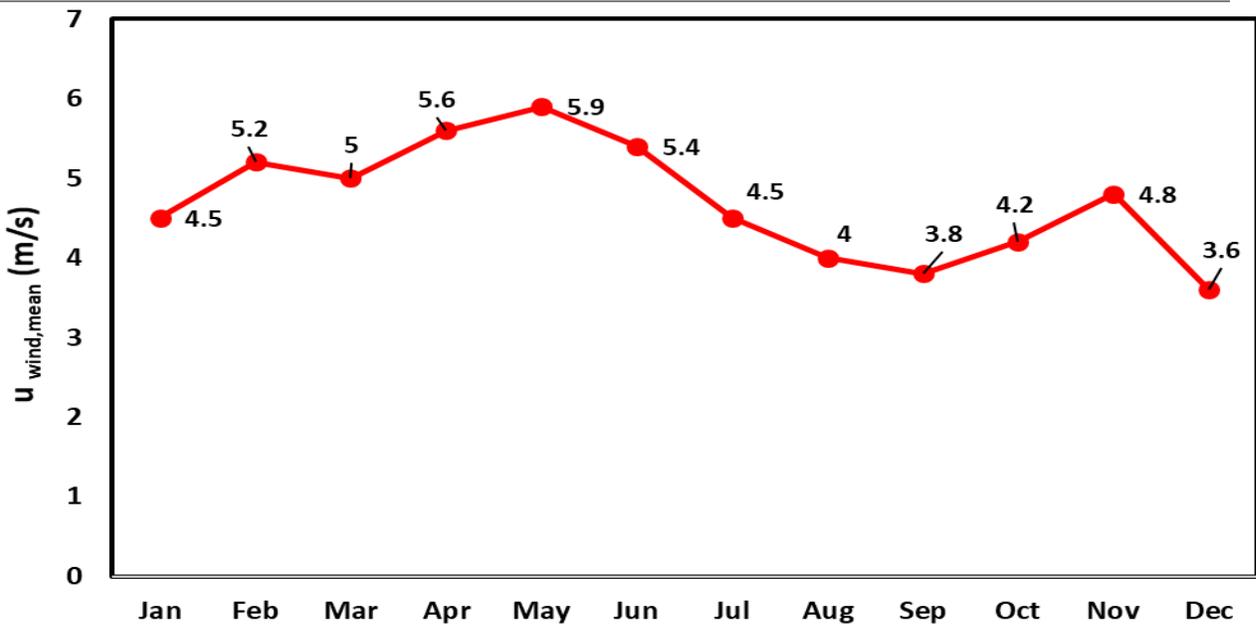


319  
320 Figure 4. The minimum, maximum, and mean temperatures of the Tehran City

321 Table 8 summarizes detailed information about annual wind speed in Tehran, categorized by different  
322 wind velocity ranges. The annual total amount of wind velocity for each range also can be found. This  
323 number means the total number of occurrences of wind flow within each of the wind velocity range along a  
324 year. Figure 5 reports the mean wind velocity of Tehran City during a year. As illustrated, the maximum  
325 mean wind velocity of about 5.9 m/s occurs in May, and December has the lowest mean wind velocity of  
326 about 3.6 m/s. The three months of April, May, and June have the highest mean wind velocities, and August,  
327 September, and December have the minimum mean wind velocities.

328 Table 8. The quantity of wind velocity in the particular ranges for each month in Tehran [61-63]

Wind velocity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
$1 \leq U_{wind}$	59	62	82	79	71	76	98	106	119	96	64	60	752
$4 \leq U_{wind}$	25	36	65	61	53	67	73	51	43	37	31	8	473
$7 \leq U_{wind}$	15	22	20	32	27	27	7	5	6	10	14	2	161
$11 \leq U_{wind}$	0	2	2	7	12	3	2	1	0	2	2	2	29
$U_{wind} > 16$	0	0	0	0	0	0	0	0	0	0	0	0	0

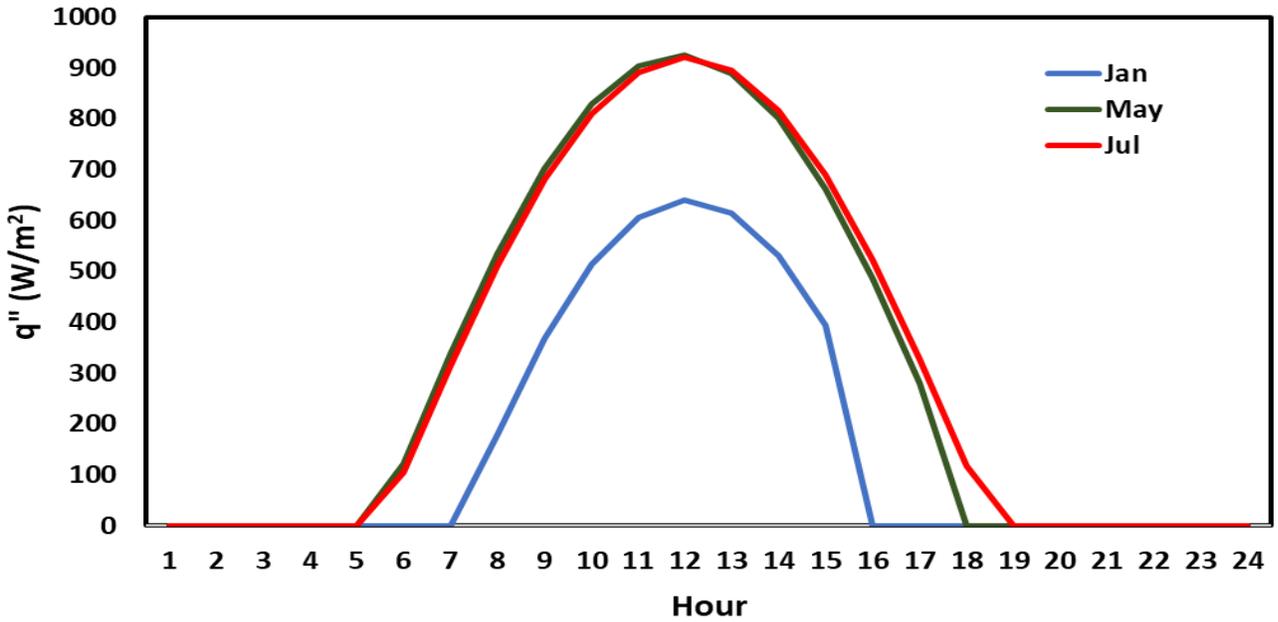


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330

Figure 5. Mean wind velocity in the Tehran City

331 Figure 6 presents the solar radiation during January, May, and July 15<sup>th</sup>. As can be seen, the solar  
 332 radiations for July and May are close, with a maximum close to 894 W/m<sup>2</sup>. The highest achievable solar  
 333 radiation in January is about 641 W/m<sup>2</sup>. Since January has a late sunrise and early sunset in comparison  
 334 to May and July, the solar radiation is significantly lower. A typical day of May and July has 13 and 14 hours  
 335 of solar radiation, respectively.



336

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Figure 6. Solar radiation during the January, May, and July 15<sup>th</sup>

338

#### 4.3. Daily energy analysis of the heliostat field

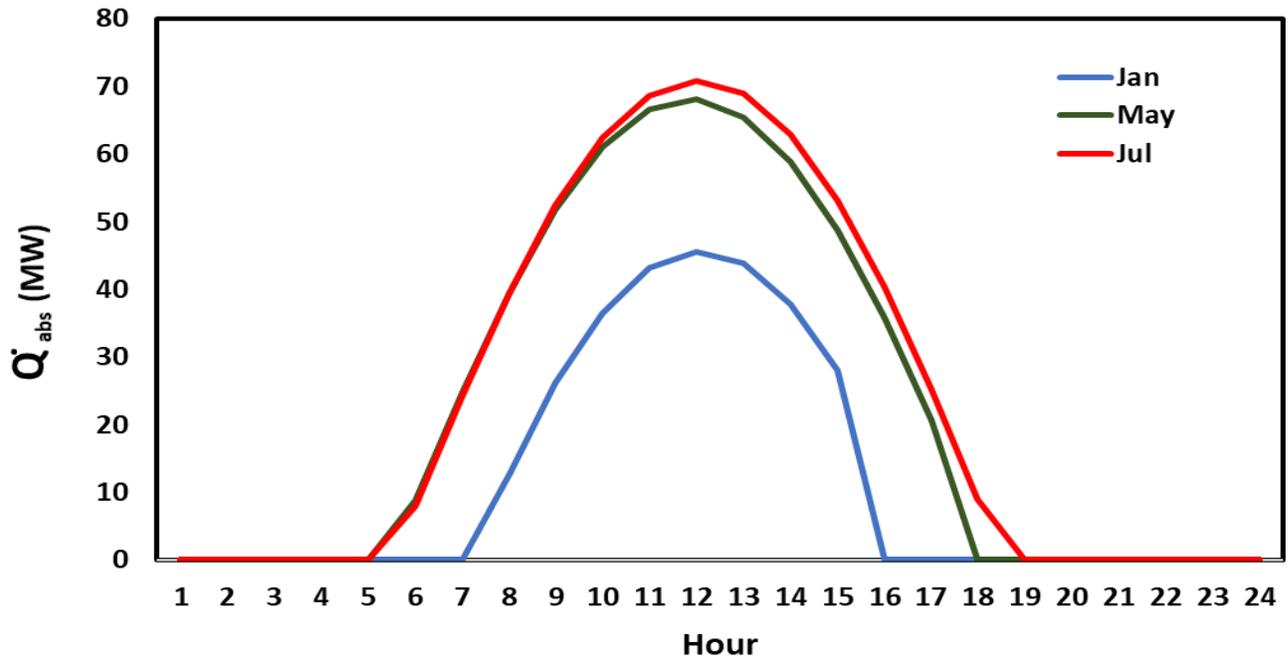
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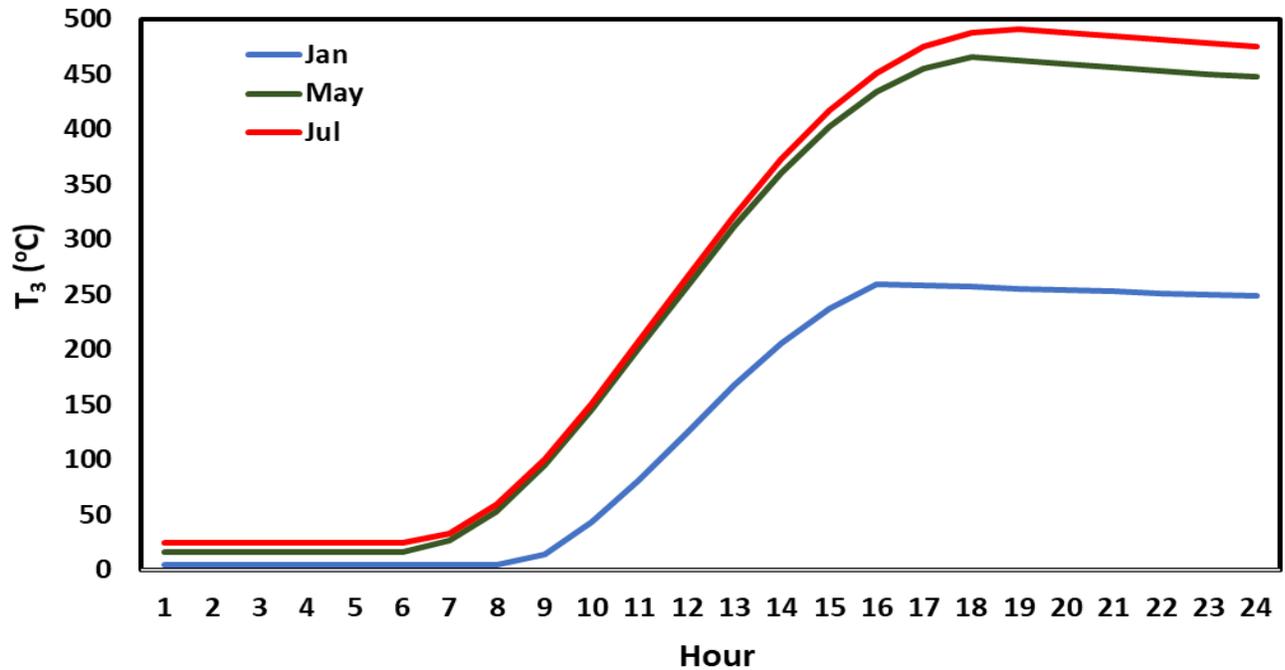
Figure 7 presents the absorbed solar power by the solar receiver,  $\dot{Q}_{abs}$  being the absorbed solar radiation from the heliostats to the solar dish. As depicted, the maximum absorbed solar power of about 70.9 MW belongs to July, followed by 68.1 MW maximum solar power absorbed in May. Similarly, to Figure 5, January has the lowest maximum absorbed solar power of about 45.6 MW.



343  
344

Figure 7. Absorbed solar power without any losses during January, May, and July 15<sup>th</sup>

345 Figure 8 presents the solar receiver outlet temperature for January, May, and July 15<sup>th</sup>. For all these  
 346 three months, this temperature increases when the sun rises, but with different behaviors for each month.  
 347 The decrease of this outlet temperature begins with the sunset, as no more solar radiation is available and  
 348 thermal energy losses from the solar receiver become dominant. Although May and July trends are close  
 349 to each other, the highest outlet temperature of about 490 °C occurs in July. The highest achievable solar  
 350 receiver outlet temperature for May is about 465 °C, the lowest outlet temperature of about 259 °C belonging  
 351 to January.



352

353

Figure 8. Outlet temperature from the solar receiver during January, May, and July 15<sup>th</sup>

354

#### 4.4. Optimization results

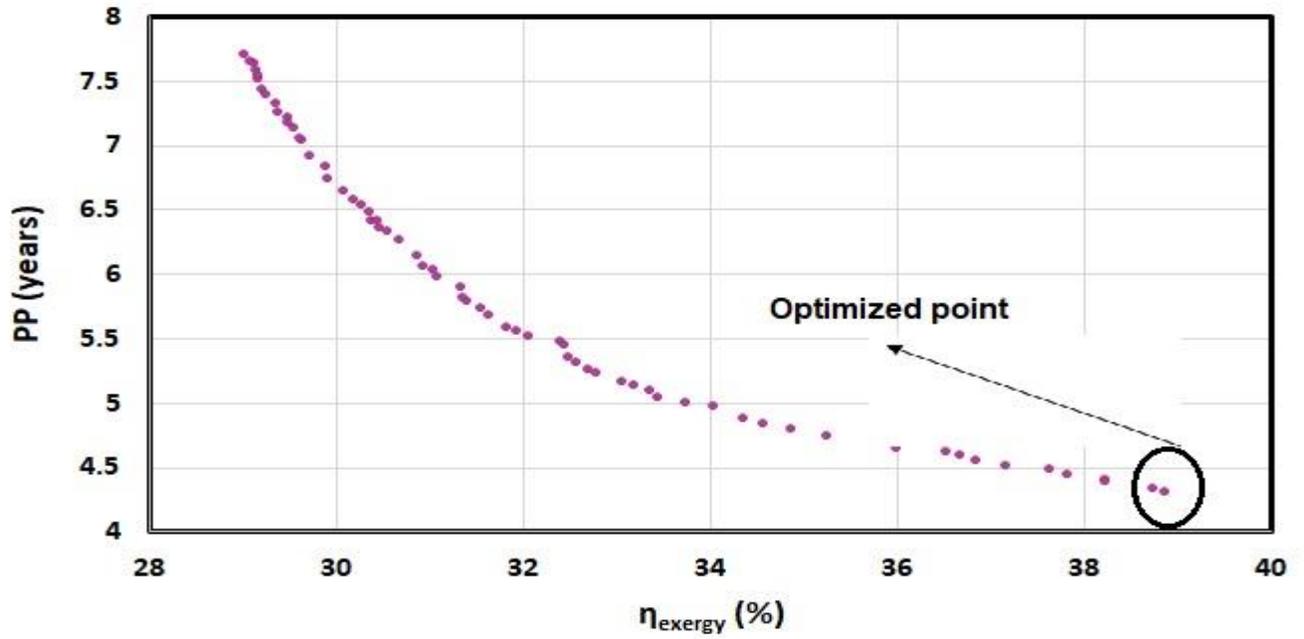
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Figure 9 shows the Pareto-front curve for variation of objective functions versus decision variables depicted in Table 4. In this figure, the effects of changing the decision variables on objective functions are presented. In the optimized point, the EXE reaches 38.9% and the PP is reduced to 4.3 years. Table 9 shows the optimized decision variables.



359

360

Figure 9. The Pareto-front curve

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Table 9. The optimized decision variables

No.	Design variables	Unit	Optimized value
1	L	m	17.1
2	l	m	6
3	d	m	8.1
4	H <sub>t</sub>	m	100.5
5	$\beta$	m	6
6	R <sub>a</sub>	m	2
7	R <sub>H</sub>	m	8

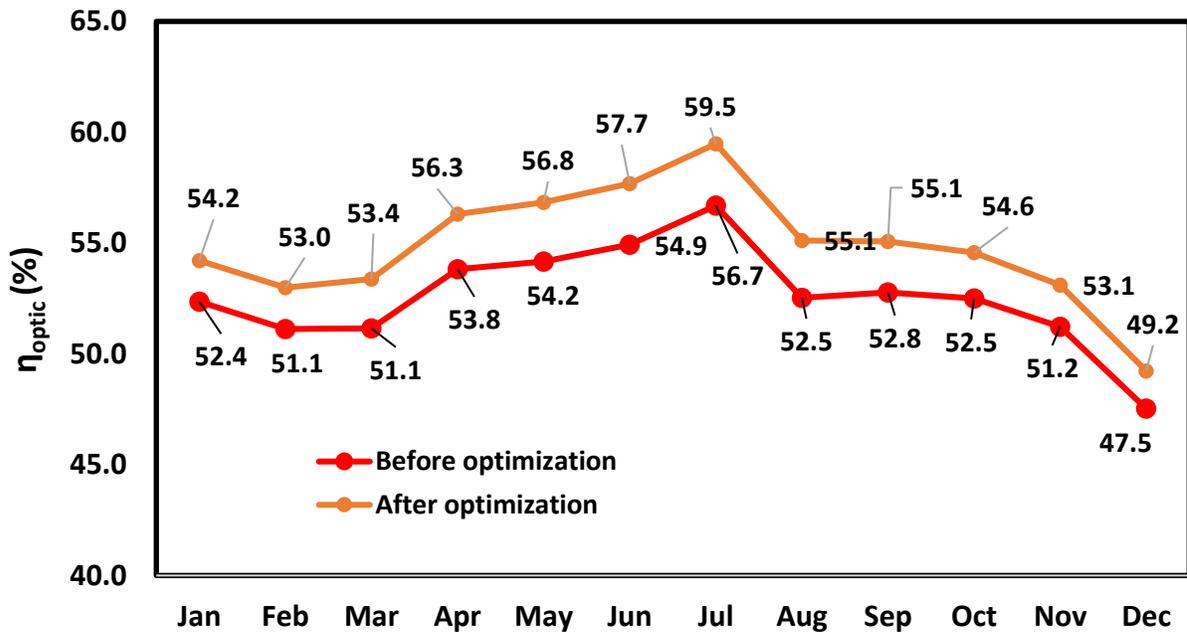
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364 **4.5. Parametric study**

365 Figure 10 displays the monthly average heliostat optic efficiency before and after optimization. The  
 366 maximum optic efficiency of about 56.7% belongs to July, December having the lowest heliostat optic  
 367 efficiency of about 47.5 %. While after optimization, these values reach 59.5% and 49.2%, respectively. It  
 368 is noticeable that the variation between the minimum and maximum achievable heliostat optic efficiency  
 369 over a year is not significant. Moreover, the highest heliostat optic efficiency can be obtained in the four  
 370 months of April, May, June, and July.

371



372

373 Figure 10. Monthly average of the heliostat optic efficiency before/after optimization

374 Figure 11 presents the monthly averaged absorbed solar energy for each month before/after  
 375 optimization. As mentioned before, the  $Q_{abs}$  defines solar energy absorbed without any loss. The highest  
 376 achievable absorbed solar power is about 2.6 TJ which occurs in July, December having the lowest of about  
 377 1.1 TJ. The three months of November, December, and January have a low potential for solar energy  
 378 absorption; on the opposite side, May, June, and July have the highest potential for solar energy absorption.  
 379 Several reasons can be invoked for lower absorbed solar power in December than in January, such as the  
 380 heliostat optic efficiency and angle of radiation. By doing optimization, the average solar energy absorbed  
 381 is improved. This increase is more considerable in hot months than cold ones.

382

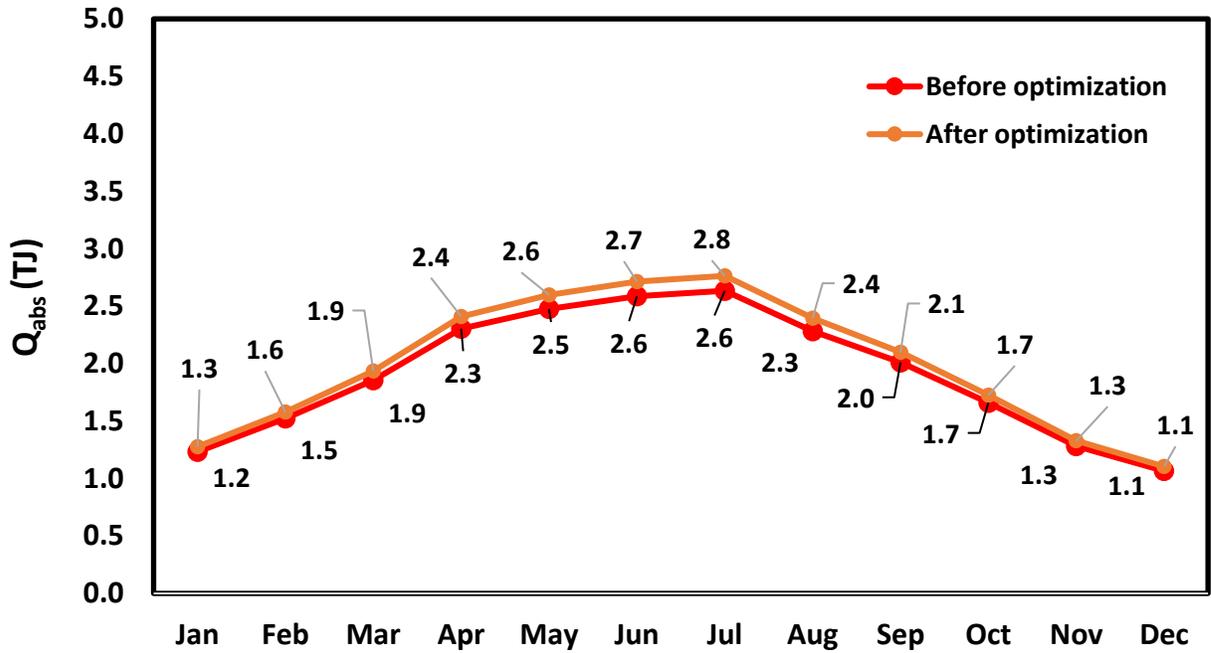


Figure 11. Monthly average absorbed solar energy

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Figure 12 exhibits the monthly averaged outlet temperature from the solar receiver for each month before/after optimization. As can be seen, this means temperature reaches a maximum of 274.9 °C in July and a minimum of about 123.6 °C in December before optimization. The highest mean working fluid temperatures occur in May, Jun, and July, November, December, and January having the lowest mean working fluid temperatures. Optimization of the heliostat field improves the outlet temperature of the working fluid. For example, in July the working temperature reaches 322.2 °C (around 17.2%).

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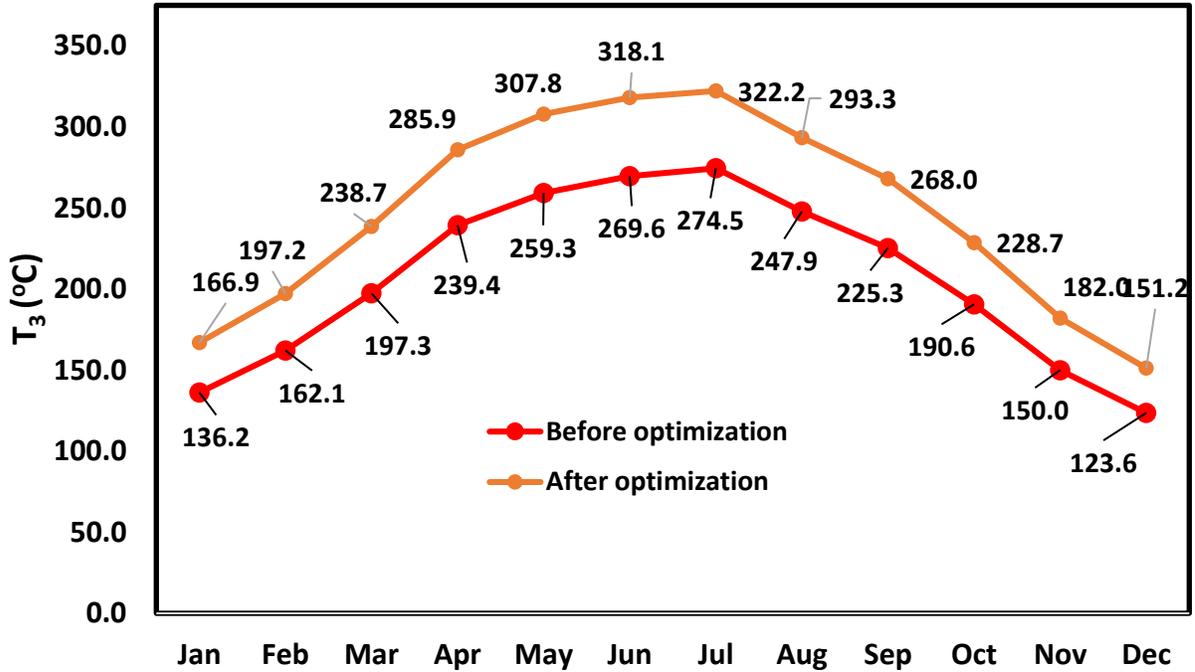
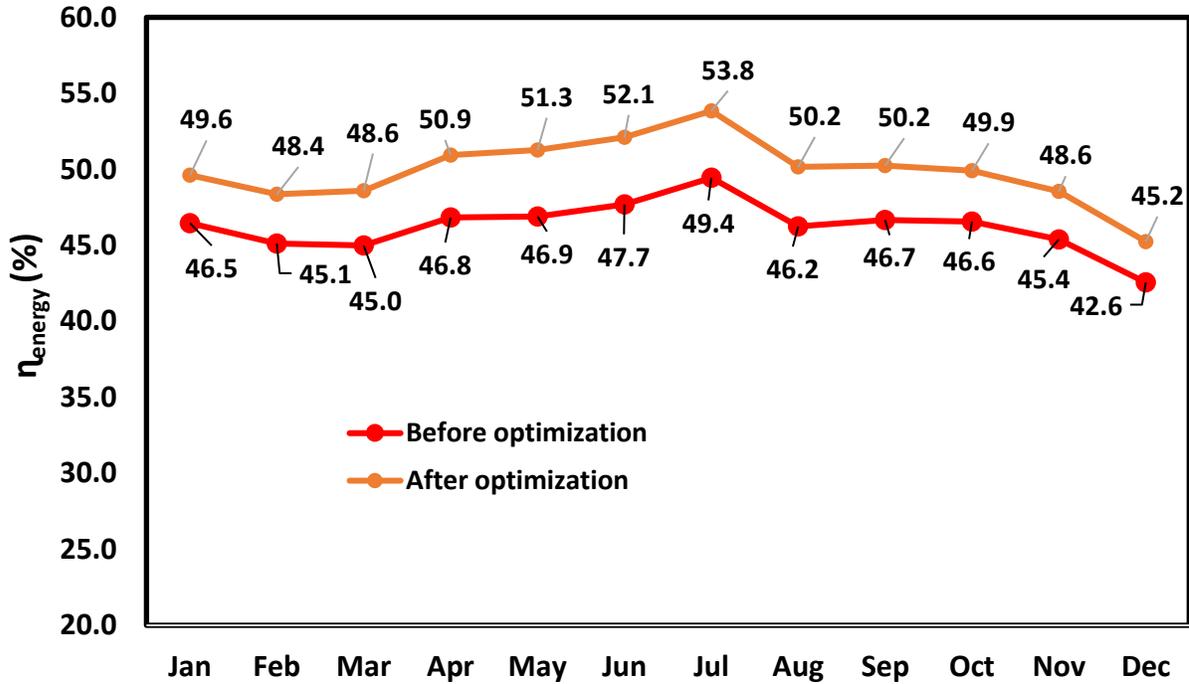


Figure 12. Monthly average outlet temperature from the solar receiver

Figure 13 illustrates the monthly average heliostat solar tower ENE before and after optimization. Similar to previously presented results, the maximum ENE of about 49.4% belongs to July, December having the lowest ENE of about 42.6%. Although there is a significant difference in the average net energy absorbed by the solar tower in the July and December months, as depicted in Figure 11, there is a comparatively slight difference of about 16% on the ENE's. This is due to the solar energy input in the denominator of Eq. (28). As the solar energy input for each month changes, and is at the lowest level in months such as December and January, the reduction of both the numerator and the denominator for these months decreases the corresponding ENE's difference. After optimization, the ENE is improved. For example, in July, the heliostat field ENE is improved from 49.4% to 53.8%.

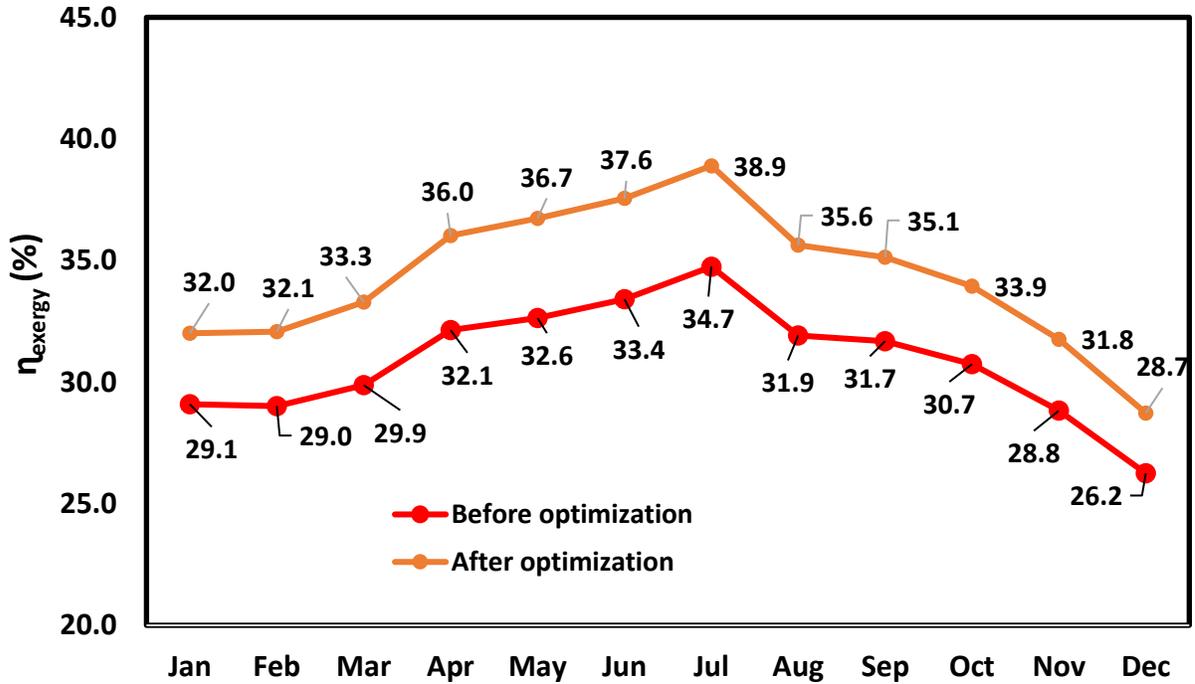


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Figure 13. Monthly average heliostat solar tower ENE

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Figure 14 shows the monthly averaged heliostat solar tower EXE. The trends in Figures 13 and 14 are similar. July has the highest EXE of about 34.7%, and December the lowest EXE of about 26.2%. The highest EXE is available in the three months of May, June, and July. Since both energy and EXE's follow the same pattern and only the numerator and denominator of EXE are multiplied with a ratio. Similar to the heliostat field ENE, the heliostat field EXE is promoted.



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Figure 14. Monthly averaged heliostat solar tower EXE during a year

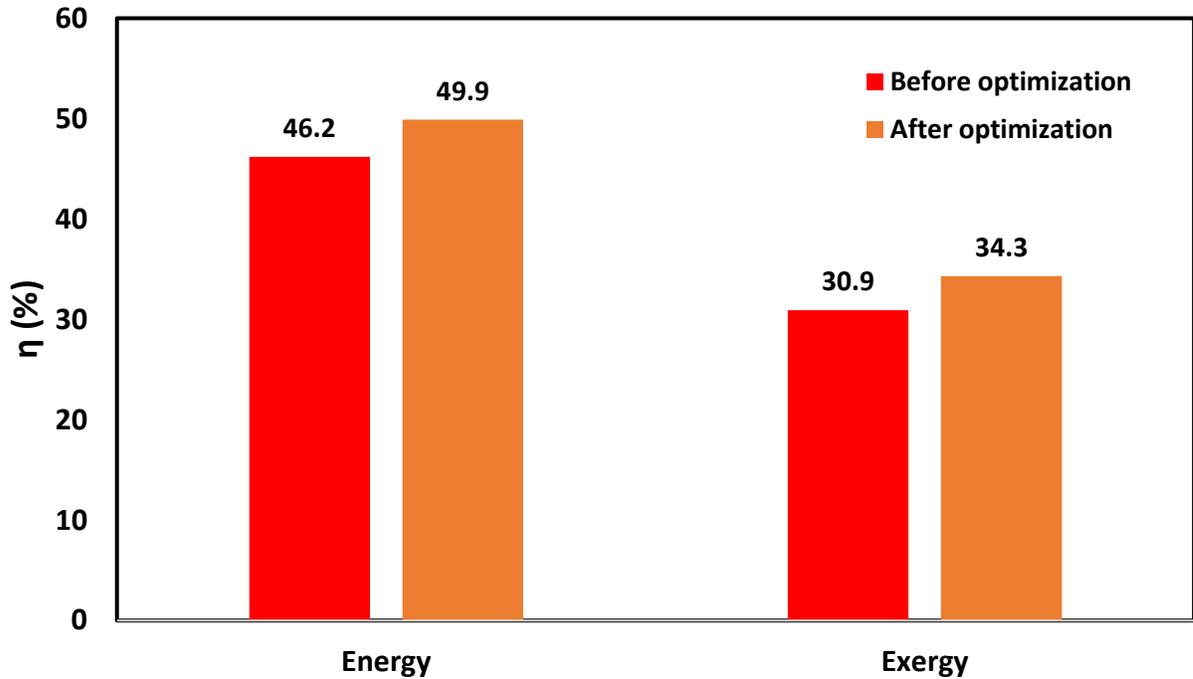
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Figure 15 shows the annual ENE and EXE of the heliostat solar field before and after optimization.,  
 423 These values before optimization are equal to 46.2% and 30.9%, respectively while the MOPSO  
 424 optimization algorithm improves these values to 49.9% and 34.4%, respectively.

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Figure 15. The annual ENE and EXE of heliostat solar tower

430 The results of the economic evaluation and annual ENE and EXE of the heliostat solar tower are  
431 summarized in Table 10.

432 Table 10. Economic results of the heliostat solar field

No.	Parameter	Unit	Value	Value
			(Before optimization)	(After optimization)
1	NPV	US\$	$58.84 \times 10^6$	$63.34 \times 10^6$
2	SPP	Year	6.04	3.8
3	PP	Year	6.76	4.3
4	IRR	–	0.16	0.19

434

435 From Table 10 it can be concluded that the PP is of 6.76 years, which is slightly higher than SPP.  
436 Considering the expected lifetime of 20 years for the system, this indicates the economic viability of the  
437 system, not far from that of many other systems for renewable energy capture and conversion. The IRR  
438 and NPV are equal to 0.16, and  $58.84 \times 10^6$  US\$, respectively. Like in all renewable energy systems, it  
439 must be emphasized that the real economic results will depend also on the environmental conditions, the  
440 most important environmental condition for solar-powered systems being solar radiation. By using the

441 MOPSO algorithm, the PP and SPP are reduced to 4.3 and 3.8 years, respectively. Also, the NPV and IRR  
442 are increased to  $63.34 \times 10^6$  and 0.19, respectively.

## 443 **5. Conclusions**

444 A lot of research has been made in the subject of heliostat solar field integrated with other systems to  
445 produce electricity, heating, and cooling. However, no significant research has been conducted concerning  
446 the single heliostat solar field, and especially its energy, exergy, and economic analyses. Also, optimization  
447 of this field has not been done before. The model of the heliostat field includes a lot of related geometric  
448 information leading to the optic characteristics and efficiency of these systems. The whole system energy  
449 and exergy performance depends also on the profile of the thermal energy storage, depending on the solar  
450 energy capture and the thermal energy use, this depending on the energy use profile. As the focus is on  
451 the heliostat system receiver, it is assumed that the net thermal energy is consumed at the same rate as it  
452 is captured. The model for evaluation of the energy and exergy performances of these systems includes  
453 also the location and environment conditions, a good performance being obtained with the properly  
454 designed equipment and operation together with the expected environmental conditions. The economic  
455 input data are of major relevance for the evaluation of the economic system's viability; however, they are  
456 only estimating, that can experience considerable unpredictable changes during the system's lifetime due  
457 to reduction in performance caused by depreciation. MOPSO optimization algorithm is carried out for 7  
458 parameters of the heliostat field. Two objective functions including EXE and payback period are considered  
459 for this optimization. Once the model and its implementation were validated by comparison with information  
460 obtained from the literature, it was for the specific system under analysis when operating in Tehran City.  
461 Detailed yearly environment data from Tehran City, with emphasis on the available solar radiation, allows  
462 anticipation of the best periods of the system's operation. Results show that the heliostat optical efficiency  
463 presents only slight changes during a year, being maximum in July and minimum in December, and having  
464 a yearly average value slightly above 50%. The monthly averaged absorbed solar power, the monthly  
465 averaged outlet temperature from the solar receiver, and the monthly averaged net energy absorbed by the  
466 solar receiver follow essentially similar patterns along a year, strongly dictated by the net heat received in  
467 each month, with maximum value in July and minimum value in December. The monthly averaged solar  
468 ENE of the solar tower changes slightly during a year, with a maximum value in July (49.4%) and minimum  
469 value in December (42.6%), with an average value close to 46%. The monthly averaged solar exergy  
470 efficiency of the heliostat presents more changes than the monthly averaged solar ENE along a year, by  
471 the maximum in July (34.7%) and minimum in December (26.2%), with an average value close to 31%.  
472 From economic analysis are highlighted a PP is of 6.76 years, slightly higher than the SPP of 6.04 years.  
473 These are not far from that of many other systems for renewable energy capture and conversion, indicating  
474 the economic viability of the system considering its expected lifetime operation for 20 years. The results of  
475 the optimization reveal that the annual average energy rose to 49.9% and the EXE increase to 34.3. Also,  
476 the payback period of the heliostat field decrease from 6.76 to 4.3 years.

478 **Nomenclature****Acronyms:**

CSP	Concentrated solar power
ENE	Energy efficiency
EXE	Exergy efficiency
GA	Genetic algorithm
IRR	Internal Rate of Return
LCoE	Levelised Cost of Electricity
MOPSO	Multi-Objective Particle Swarm Optimization
NPV	Net Positive Value
PP	Payback Period
PSO	Particle Swarm Optimization
SPP	Simple Payback Period

**Symbols:**

A, B	Constant in equation (5)
$A_{ap}$	Total aperture area ( $m^2$ )
$A_{cell,i}$	Area of cell i ( $m^2$ )
$A_{hel}$	Area of one heliostat ( $m^2$ )
$A_{land}$	Heliostat field land area ( $m^2$ )
$A_{re}$	Solar receiver area ( $m^2$ )
d	Heliostat - receiver distance (m)
D	Reflected area diameter (m)
$D_{re}$	Receiver's diameter (m)
desp	Extra separation between adjacent heliostats (m)
DM	Distance between adjacent heliostats centers (m)
ex	Specific exergy (J/kg)
g	Gravitational acceleration ( $m/s^2$ )

$G_b$	Direct normal irradiance ( $W/m^2$ )
$h$	Specific enthalpy ( $J/kg$ )
$H$	Height (m)
$h_{forced}$	Forced convection heat transfer coefficient ( $W/(m^2K)$ )
$h_s$	Angle of the solar hour (degrees)
$k_m$	Thermal conductivity ( $W/(m.K)$ )
$l$	Reflector length (m)
$L$	Height of absorbing area (m)
$L_H$	Heliostat height (m)
$L_W$	Heliostat width (m)
$L_{loc}$	Location longitude (degrees)
$L_{st}$	Local standard meridian (degrees)
$\dot{m}$	Mass flow rate ( $kg/s$ )
$N$	Number of days of a year in equation (20)
$Nu$	Nusselt number
$N_{hel}$	Total number of heliostats
$N_{hel_1}$	The number of first zone heliostats in every line
$N_{hel,cell,i}$	The heliostats' number in cell $i$
$N_{row_i}$	The number of heliostats rows
$\dot{Q}$	Heat transfer rate ( $W$ )
$r$	Discount factor
$R$	Distance between each heliostat and the base of the tower (m)
$R$	Specific gas constant ( $J/kg.K$ )
$R_a$	Receiver radius (m)
$R_H$	Receiver height (m)
$r_{ap}$	Effective size of receiver opening (m)
$r_{cell,i}$	Distance of the receiver and the cell center (m)
$R_i$	Radial distance between the first row of $i$ th field and the tower (m)
$r_{int}$	Inner radius of the concentric piping (m)

$r_{outer}$	Outer radius of the concentric piping (m)
$Re$	Reynolds number
$s$	Specific entropy (J/kg.K)
$T$	Temperature (K)
$U_{wind}$	Wind velocity (m/s)
$V$	Velocity (m/s)
$\dot{W}$	Work rate (W)
$x_i$	Mass fraction of component i
$y_i$	Molar fraction of component i
$z$	Height (m)
$z_0$	Investment cost (US\$)
$Z_{cont}$	Additional funding required for unexpected technological and regulatory issues (US\$)
$z_f$	Annual cash flow (US\$)
$Z_i$	Capital investment of component i (US\$)

**Greek symbols:**

$\alpha$	Absorption angle of the solar receiver (degrees)
$\beta$	Parameter in equation (2)
$\beta_{hs}$	Angle of rotation of incident solar radiation (degrees)
$\delta$	Deflection angle (degrees)
$\delta_s$	Solar declination (degrees)
$\varepsilon$	Emissivity of a surface
$\varepsilon_{surf}$	Errors caused by angular deviation
$\varepsilon_{track}$	Errors caused by tracking
$\eta$	Efficiency
$\theta_R$	Angle of received reflected irradiation from heliostat field (degrees)
$\theta_s$	Angle of solar incidence (degrees)
$\theta_z$	Angle of solar zenith (degrees)
$\lambda_s$	Angle between vertical direction and reflected irradiation (degrees)

$\rho_{\text{cell},i}$	Density of heliostats in cell i
$\sigma$	Constant of Stefan-Boltzmann ( $\text{W}/\text{m}^2\cdot\text{K}^4$ )
$\sigma_1$	Parameter in equation (34)
$\alpha_s$	Angle of solar altitude (degrees)
$\varphi$	Latitude angle (degrees)
$\varphi'$	Solar azimuth angle (degrees)
$\varphi_s$	Angle of solar azimuth (degrees)
$\omega$	Sunset hour angle (degrees)
$\Delta\text{az}_1$	Azimuth angular spacing (degrees)
$\Delta R_{\text{min}}$	Minimum radial increase of the field (m)

**Subscripts:**

0	environment condition
abs	absorbed
amb	ambient
at	atmospheric attenuation
ch	chemical
conv	convection
cos	cosine
dec	decommissioning
hel	heliostat
i	line i of the field
if	indirect factors
in	inlet stream
Ins	installation
lab	labor
lat	latitude
min	minimum
om	operation and maintenance
opr	operator

opt	optic
out	outlet stream
p	pump
rad	radiation
re	receiver
ref	rate of mirror reflectivity
S	sun
s&b	shadowing and blocking
surf	surface
tec	technician
T	tower

479 **Appendix A. Solar radiation modeling**

480 The solar time is evaluated as [64-66]:

$$\text{Solar time} = \text{Standard time} + E - 4(L_{st} - L_{loc}) \quad (\text{A.1})$$

481 where  $L_{loc}$  is the location longitude,  $L_{st}$  is the local zone time standard meridian, and  $E$  is obtained as [64-  
482 66]

$$E = 229.2(0.000075 + 0.001868\cos\beta - 0.04089\sin 2\beta - 0.014615\cos 2\beta - 0.032077\sin\beta) \quad (\text{A.2})$$

483 In Eq. (2)  $\beta$  is equal to  $\frac{(n-1)360}{365}$ , where for January first  $n$  is equal to 1. The sunset hour angle is evaluated  
484 as [64-66]

$$\omega = \arccos(\tan(\varphi)\tan(\delta)) \quad (\text{A.3})$$

485 where  $\delta$  denotes the angle of deflection and  $\varphi$  the location latitude. The angle of deflection  $\delta$  can be  
486 evaluated as [25]

$$\delta = 23.45\sin\left(\frac{360(284 + n)}{365}\right) \quad (\text{A.4})$$

487 The direct normal irradiance  $G_p$  is obtained as [25]

$$G_b = A \cos(\theta_z) \exp\left(\frac{-B}{\cos(\theta_z)}\right) \quad (\text{A.5})$$

488 where  $\theta_z$  denotes the angle of solar zenith, and A and B are constants adapted from Ref [25]. These  
 489 constants are based on the average metrological data during 10 years. The angle of solar zenith can be  
 490 evaluated as [67]

$$\theta_z = 90^\circ - \alpha_s \quad (\text{A.6})$$

491 where the  $\alpha_s$  is the solar altitude angle.

492 The angle of solar altitude is obtained as follows [68]:

$$\alpha_s = \sin^{-1}[\sin(\phi) \cdot \sin(\delta_s) + \cos(\phi) \cdot \cos(\delta_s)] \quad (\text{A.7})$$

493 The angle of the solar hour can be expressed as [67]:

$$h_s = 15^\circ \times (\text{Solar time} - 12) \quad (\text{A.8})$$

494 where solar time defines the time that the sun was shining for a day.

495 The solar azimuth angle can be obtained as [55]

$$\varphi' = \sin^{-1}\left(\frac{\sin(h_s) \cdot \cos(\delta_s)}{\sin(\theta_z)}\right) \quad (\text{A.9})$$

496 where  $\theta_z$  is the angle of solar zenith. The conditions for the angle of the solar hour can be expressed as  
 497 follows [55]:

$$\text{If } \cos(h_s) \geq \left(\frac{\tan(\delta_s)}{\tan(\phi_{\text{lat}})}\right), \quad \varphi_s = 180^\circ - \varphi' \quad (\text{A.10})$$

$$\text{else } \varphi_s = 180^\circ + \varphi' \quad (\text{A.11})$$

498 where  $\varphi_s$  is the angle of surface azimuth.

499 The angle of surface azimuth is evaluated as [55]:

$$\text{If } \varphi_s - \varphi' > 0, \quad \varphi_{\text{surf}} = \varphi' + 90^\circ \quad (\text{A.12})$$

$$\text{else } \varphi_{\text{surf}} = \varphi' - 90^\circ \quad (\text{A.13})$$

500 where subscript surf means surface.

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