Declaration

To the best of my knowledge I do hereby declare that this thesis is my own work. It has not been submitted in any form of another degree or diploma to any other university or other institution of education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

Place: Amman, Jordan          Date: 14th February, 2012          Name: Ahmad (Elhaj Yasin)

Signature:
Abstract

The most serious challenge of development in Jordan is the lack of water and conventional energy resources. In light of this challenge, Jordan has an ambitious target for the share of renewable energies in the national energy mix. Solar energy is one of the renewable resources that has high potentials in the country specially in the southern part. One of the proven solar technology is the parabolic trough which can be utilized for electricity generation and solar cooling as well as for water desalination.

The aim of this study was to investigate the technical and economic aspects of parabolic trough performance in Jordan. The technical aspect was addressed by developing an empirical mathematical model for the performance of a parabolic trough demonstration plant installed in the Dead Sea area. While the economic aspect was addressed through the estimation of the levelized cost of electricity (LCOE) generated by a 50MW plant (similar to Andasol 1 plant in Spain) in Ma’an, south Jordan.

Photogrammetric test was conducted on the parabolic trough collector to determine the optical quality. The total optical error was evaluated to be 20.6 mrad which resulted in an intercept factor at normal incidence of 0.72. The empirical parameters of the overall performance model were determined by applying the multiple linear regression (MLR) tool on a series of measurements for the system performance. The developed model suggests that the optical losses in the system are much higher than thermal. Where at normal incidence (peak optical efficiency) and a mean heat transfer fluid temperature of 80°C, the system losses were modeled to be 47% optical and 11% thermal.

The LCOE for the proposed parabolic trough plant in Ma’an was estimated to be 20.96 ¢/kWh for a base-case scenario and 17.89 ¢/kWh for an incentive scenario (tax exemptions and low interest rate) which is still high compared to the current cost of electricity using fossil fuel in Jordan (9.64 ¢/kWh). Sensitivity analysis revealed that the LCOE is most sensitive to solar field cost (10% less cost of solar field ➔ 4.3% less LCOE) and then to debt fraction (10% less cost of solar field ➔ 2.8% less LCOE).
Acknowledgment

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Finally, thanks to family and friends for their support, encouragement and inspiration.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Declaration</td>
<td>i</td>
</tr>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Acknowledgment</td>
<td>iii</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iv</td>
</tr>
<tr>
<td>List of Tables</td>
<td>vii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>viii</td>
</tr>
<tr>
<td>List of Symbols</td>
<td>xi</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1. Global energy consumption</td>
<td>1</td>
</tr>
<tr>
<td>1.2. Energy in Jordan</td>
<td>1</td>
</tr>
<tr>
<td>1.3. Thesis objectives</td>
<td>3</td>
</tr>
<tr>
<td>2. Concentrated Solar Power Technologies</td>
<td>6</td>
</tr>
<tr>
<td>2.1. Dish/Stirling Engine</td>
<td>6</td>
</tr>
<tr>
<td>2.2. Power Tower</td>
<td>10</td>
</tr>
<tr>
<td>2.3. Linear Fresnel Reflectors</td>
<td>14</td>
</tr>
<tr>
<td>2.4. Parabolic Trough</td>
<td>18</td>
</tr>
<tr>
<td>Technical Part</td>
<td></td>
</tr>
<tr>
<td>3. Description of System Under Study</td>
<td>23</td>
</tr>
<tr>
<td>3.1. General description</td>
<td>23</td>
</tr>
<tr>
<td>3.2. Principle of operation</td>
<td>24</td>
</tr>
<tr>
<td>3.3. Solar field</td>
<td>26</td>
</tr>
<tr>
<td>4. Performance Model for the Parabolic Trough Field</td>
<td>29</td>
</tr>
<tr>
<td>4.1. Performance model development</td>
<td>32</td>
</tr>
<tr>
<td>4.2. Intercept factor</td>
<td>35</td>
</tr>
<tr>
<td>4.2.1. Optical errors</td>
<td>36</td>
</tr>
</tbody>
</table>
4.2.2. *Optical measurements* ................................................................. 39
4.3. Angle of incidence calculations .......................................................... 41
  4.3.1. *Basic angles* .............................................................................. 42
  4.3.2. *Solar angles* .............................................................................. 44
  4.3.3. *Angle of incidence* ................................................................. 45
4.4. Shading losses ....................................................................................... 48
4.5. Incidence angle modifier ....................................................................... 50
4.6. Piping heat losses .................................................................................. 51

5. Experimental Test and Results ............................................................. 55
  5.1. Optical quality test (Photogrammetric test) ......................................... 55
  5.1.1. *Test setup and procedure* .......................................................... 55
  5.1.2. *Measurements analysis and results* ............................................. 57
  5.2. Overall performance model ............................................................... 65
  5.2.1. *Measurements conditions and data* ........................................... 65
  5.2.2. *Model parameters identification* ................................................ 68
  5.2.3. *Results and efficiency curves* .................................................... 69
  5.2.4. *Performance model uncertainty* ................................................ 74
  5.3. Conclusions and recommendations ................................................... 75

**Economics Part**

6. Cost of Electricity Generation by 50MW Parabolic Trough Plant in Ma’an ................................................................. 78
  6.1. Plant site ......................................................................................... 78
  6.2. Solar radiation data .......................................................................... 80
  6.3. Power plant ...................................................................................... 81
    6.3.1. *Solar field* ............................................................................. 82
    6.3.2. *Power block* ......................................................................... 84
    6.3.3. *Storage system* ..................................................................... 85
  6.4. Energy yield simulation ................................................................. 85
  6.5. Economic and financial analysis ..................................................... 88
    6.5.1. *Plant costs* .......................................................................... 88
    6.5.2. *Financial parameters* ........................................................... 91
6.5.3. Financial simulation results ........................................... 92
6.5.4. Sensitivity analysis ....................................................... 95
6.6. Conclusions ....................................................................... 97

References ............................................................................. 99

Appendix A: Test images samples & 3D Aicon output ................. A1
Appendix B: Matlab code for slope errors calculations ............... B1
Appendix C: Sample calculation of performance model terms........ C1
Appendix D: Thermophysical Properties of air and water .......... D1
Appendix E: Average daily profile of electric power generated by Ma’an plant ................................................................. E1
### List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Experimental power tower plants</td>
<td>13</td>
</tr>
<tr>
<td>2.2</td>
<td>Characteristics of Solar Electric Generating Systems SEGS I through IX</td>
<td>22</td>
</tr>
<tr>
<td>3.1</td>
<td>Characteristics of PTC-1800 collector</td>
<td>26</td>
</tr>
<tr>
<td>4.1</td>
<td>Test conditions and permitted deviations</td>
<td>33</td>
</tr>
<tr>
<td>5.1</td>
<td>A sample of the slope calculations output (stripe1)</td>
<td>59</td>
</tr>
<tr>
<td>5.2</td>
<td>The average deviation of the receiver location from the focus</td>
<td>60</td>
</tr>
<tr>
<td>5.3</td>
<td>Results of receiver displacement errors</td>
<td>62</td>
</tr>
<tr>
<td>5.4</td>
<td>System measurements for empirical parameters identification</td>
<td>66</td>
</tr>
<tr>
<td>5.5</td>
<td>The results of empirical parameters identification</td>
<td>70</td>
</tr>
<tr>
<td>5.6</td>
<td>The residual (error) of the modeled values y*</td>
<td>70</td>
</tr>
<tr>
<td>5.7</td>
<td>Measurement samples and results of model validation</td>
<td>71</td>
</tr>
<tr>
<td>5.8</td>
<td>The empirical parameters for no-wind-dependence regression</td>
<td>73</td>
</tr>
<tr>
<td>6.1</td>
<td>Characteristics of ET-150</td>
<td>83</td>
</tr>
<tr>
<td>6.2</td>
<td>Operational Characteristics of the proposed plant</td>
<td>87</td>
</tr>
<tr>
<td>6.3</td>
<td>comparison of parabolic trough plants in Jordan</td>
<td>87</td>
</tr>
<tr>
<td>6.4</td>
<td>Estimated investment cost of Andasol-like power plant</td>
<td>89</td>
</tr>
<tr>
<td>6.5</td>
<td>Capital and annual costs for the proposed plant</td>
<td>90</td>
</tr>
<tr>
<td>6.6</td>
<td>Financial parameters for the base case scenario</td>
<td>91</td>
</tr>
<tr>
<td>6.7</td>
<td>Financial parameters for the incentive scenario</td>
<td>92</td>
</tr>
<tr>
<td>6.8</td>
<td>Financial indices for the plant</td>
<td>93</td>
</tr>
<tr>
<td>D.1</td>
<td>Thermophysical properties of air at atmospheric pressure (101.3 kPa)</td>
<td>D1</td>
</tr>
<tr>
<td>D.2</td>
<td>Thermophysical properties of water</td>
<td>D2</td>
</tr>
</tbody>
</table>
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Primary energy consumption in Jordan (2001-2010)</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Printing press driven by solar radiation</td>
<td>6</td>
</tr>
<tr>
<td>2.2</td>
<td>The Vanguard dish system</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>17m - Schlaich-Bergermann dishes in Riyadh</td>
<td>9</td>
</tr>
<tr>
<td>2.4</td>
<td>SAIC/STM dish (1st generation)</td>
<td>9</td>
</tr>
<tr>
<td>2.5</td>
<td>The power tower concentration</td>
<td>10</td>
</tr>
<tr>
<td>2.6</td>
<td>The solar tower – Rankin power plant</td>
<td>11</td>
</tr>
<tr>
<td>2.7</td>
<td>Planta Solar-20 Plant</td>
<td>13</td>
</tr>
<tr>
<td>2.8</td>
<td>Basic configuration of LFR system</td>
<td>14</td>
</tr>
<tr>
<td>2.9</td>
<td>Compact LFR system</td>
<td>15</td>
</tr>
<tr>
<td>2.10</td>
<td>Photos of Francia’s first LFR prototype</td>
<td>16</td>
</tr>
<tr>
<td>2.11</td>
<td>Parabolic trough collector</td>
<td>18</td>
</tr>
<tr>
<td>2.12a</td>
<td>Parabolic trough field with storage system in Rankine power cycle</td>
<td>19</td>
</tr>
<tr>
<td>2.12b</td>
<td>Parabolic trough field in integrated solar combined cycle (ISCC)</td>
<td>19</td>
</tr>
<tr>
<td>2.13</td>
<td>Shuman-Boys solar power plant, Egypt, 1913</td>
<td>21</td>
</tr>
<tr>
<td>3.1</td>
<td>The parabolic troughs in the system under study</td>
<td>23</td>
</tr>
<tr>
<td>3.2</td>
<td>Schematic diagram of the system under study</td>
<td>25</td>
</tr>
<tr>
<td>3.3</td>
<td>Solar field layout</td>
<td>27</td>
</tr>
<tr>
<td>3.4</td>
<td>PTC1800 structure and connection details</td>
<td>28</td>
</tr>
<tr>
<td>3.5</td>
<td>Onsite weather station</td>
<td>28</td>
</tr>
<tr>
<td>4.1</td>
<td>Potential optical errors in parabolic trough collector</td>
<td>37</td>
</tr>
<tr>
<td>4.2</td>
<td>Photogrammetric measurements of Euro-Trough collector</td>
<td>40</td>
</tr>
<tr>
<td>4.3</td>
<td>Setup of automatic deflectometric measurements</td>
<td>41</td>
</tr>
<tr>
<td>4.4</td>
<td>Basic angles for the location Q</td>
<td>42</td>
</tr>
<tr>
<td>4.5</td>
<td>Variation of declination angle</td>
<td>44</td>
</tr>
<tr>
<td>4.6</td>
<td>Earth surface coordinate system for observer at point Q showing the solar</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>azimuth angle $\beta$, the solar altitude angle $\alpha$</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.7: A fixed aperture with its orientation defined by the tilt angle ($\hat{\lambda}$) and the aperture azimuth angle ($\Omega$)………………………………………………………….. 46
Figure 4.8: A single-axis tracking aperture rotating about the axis $r$………………… 46
Figure 4.9: Single axis tracking system coordinates…………………………………….. 47
Figure 4.10: Rotation of the $u, b, r$ coordinates from the $z, e, n$ coordinates about the z-axis. (diagram shows view looking downward on the surface of the earth)………… 47
Figure 4.11: Mutual collector shading…………………………………………………………… 48
Figure 4.12: Solar profile angle………………………………………………………………… 49
Figure 4.13: Incidence angle modifier $K(\theta)$ versus $\theta$, from Equation (4.4.1)…………………………………….. 51
Figure 4.14: A cross section of the solar field pipe………………………………………… 52
Figure 5.1: Photogrammetry test setup for our system……………………………………… 56
Figure 5.2: Image acquisition of the test setup……………………………………………… 56
Figure 5.3: 3D-Coordinate system for surface analysis…………………………………….. 57
Figure 5.4: Division of collector surface in stripes for slope error calculations………… 58
Figure 5.5: Surface element containing adjacent measured points……………………… 58
Figure 5.6: Frequency distribution of local slope errors…………………………………… 60
Figure 5.7a: Local receiver displacement error calculations……………………………… 61
Figure 5.7b: Local receiver displacement error calculations……………………………… 62
Figure 5.8: Intercept factor vs ($\sigma_{t, o} C$) for different rim angles for a cylindrical receiver (Gaussian approximation)………………………………………………………….. 64
Figure 5.9: Intercept factor for the tested trough…………………………………………… 65
Figure 5.10: Comparison of measured and modeled efficiency for model validation…… 71
Figure 5.11: Solar field efficiency curve at different values of $\theta$. ($u = 1.0$ m/s)…………… 72
Figure 5.12: Solar field efficiency curve at different values of $u$. ($\theta = 0^\circ$)………………… 73
Figure 5.13: The efficiency curves modeled with and without the wind-dependence parameter $c_4$. ($\theta = 0^\circ$)………………………………………………………………………………… 74
Figure 6.1: Solar map of Jordan with average daily sum of direct normal irradiation/m$^2$….. 79
Figure 6.2: electric power system of Jordan......................................................... 79
Figure 6.3: The site of the proposed plant.......................................................... 80
Figure 6.4: Schematic diagram of the parabolic trough plant with storage system.... 81
Figure 6.5: Solar field layout for the proposed plant.......................................... 83
Figure 6.6: Monthly net electric output of the proposed plant............................. 86
Figure 6.7: Annual energy flow through the proposed plant............................... 86
Figure 6.8: Share of the plant items in the total capital cost............................... 90
Figure 6.9: After-tax cashflow for the base case scenario................................... 93
Figure 6.10: After-tax cashflow for the incentive scenario................................. 93
Figure 6.11: Sensitivity of LCOE (base case) to investment cost........................ 95
Figure 6.12: Sensitivity of LCOE (base case) to financial parameters................. 95
Figure 6.13: Sensitivity of LCOE (incentive case) to investment cost.................... 96
Figure 6.14: Sensitivity of LCOE (incentive case) to financial parameters............ 96
Figure A.1.1: Images for photogrametric test (sample 1).................................... A1
Figure A.1.2: Images for photogrametric test (sample 2).................................... A1
Figure A.2.1: Image processing by 3D-Aicon software...................................... A2
Figure A.2.2: Recognition of surface points and camera positions...................... A2
Figure A.2.3: Numbering of coded and non-coded targets................................. A3
Figure A.2.4: Coordinates of the non-coded targets in 3D view and tabulated form... A3
Figure E.1: Average daily profile of the generated electric power by the power plant in Ma’an for the months January, February & March................................. E1
Figure E.2: Average daily profile of the generated electric power by the power plant in Ma’an for the months April, May & June........................................... E1
Figure E.3: Average daily profile of the generated electric power by the power plant in Ma’an for the months July, August & September............................... E2
Figure E.4: Average daily profile of the generated electric power by the power plant in Ma’an for the months October, November & December....................... E2
List of Symbols

- Nomenclature

$A_c$  
Aperture area of the collector, \([\text{m}^2]\)

$A_a$  
Total aperture area for the solar field, \([\text{m}^2]\)

$A_{abs}$  
Absorber outer surface area, \([\text{m}^2]\)

$A_o$  
Outer surface area of the insulated pipe, \([\text{m}^2]\)

$b$  
Coefficient of expansion for air, \([\text{1/K}]\)

$\bar{c}$  
Average specific heat of the HTF between inlet and outlet, \([\text{J/kg.K}]\)

$c_1$  
Heat loss coefficient at \((T_m - T_a)=0\), \([\text{W/m}^2\cdot\text{K}]\)

$c_2$  
Temperature dependence of the heat losses, \([\text{W/m}^2\cdot\text{K}^2]\)

$c_3$  
Effective thermal capacitance, \([\text{J/m}^2\cdot\text{K}]\)

$c_4$  
Wind speed dependence of the heat losses, \([\text{J/m}^3\cdot\text{K}]\)

$c_{pw}$  
Specific heat of water, \([\text{J/kg.K}]\)

$c_{pa}$  
Specific heat of air at \(T_a\), \([\text{J/kg.K}]\)

$C$  
Geometric concentration ratio

$D_3$  
Outer diameter of insulated pipe, \([\text{m}]\)

$D_2$  
Pipe outer diameter, \([\text{m}]\)

$D_1$  
Pipe inner diameter, \([\text{m}]\)

$d_x$  
Receiver displacement in x-direction, \([\text{mm}]\)

$d_z$  
Receiver displacement in z-direction, \([\text{mm}]\)

$F_R$  
Collector heat-removal factor

$F_{RS}$  
Solar field row shading factor

$f_{RS}$  
Row shading factor

$f$  
Moody friction factor

$f$  
focal length \([\text{mm}]\)

$F(\theta)$  
Angular acceptance function

$g$  
Gravitation = 9.81, \([\text{m/s}^2]\)

$G$  
Global irradiance on a horizontal surface, \([\text{W/m}^2]\)

$G_b$  
Beam irradiance incident on the aperture \((G_n \cos\theta)\), \([\text{W/m}^2]\)

$G_d$  
Diffuse irradiance, \([\text{W/m}^2]\)

$G_n$  
Direct normal (beam) irradiance, \([\text{W/m}^2]\)

$G_{0,\text{eff}}$  
Effective solar constant, \([\text{W/m}^2]\)
heat transfer coefficient inside the pipe, \([W/m^2.K]\) 
\(h_a\) Heat transfer coefficient at the insulation outer surface, \([W/m^2.K]\) 
\(K\) Incidence angle modifier 
\(k_p\) Thermal conductivity of pipe, \([W/m.K]\) 
\(k_i\) Thermal conductivity of insulation, \([W/m.K]\) 
\(k_w\) Thermal conductivity of water, \([W/m.K]\) 
\(k_a\) Thermal conductivity of air, \([W/m.K]\) 
\(k_T\) Hourly clearness index 
\(L_p\) Total pipe length, [m]. 
\(m\) Mass flow rate of the heat-transport fluid (HTF), [kg/s] 
\(N\) Day number 
\(\dot{Q}_u\) Solar collector useful output, \([W/m^2]\) 
\(\dot{Q}_{SF}\) Useful output from the solar field, [W] 
\(S\) Row spacing, [m] 
\((S_x)_m\) Measured local surface slope [mrad] 
\((S_x)_d\) Designed local surface slope [mrad] 
\(\Delta S_x\) Local surface slope error [mrad] 
\(t\) Time, [s] 
\(t_s\) Solar time, [hour] 
\(T_o\) Heat transfer fluid outlet (from the collector) temperature, [K] 
\(T_i\) Heat transfer fluid inlet (to the collector) temperature, [K] 
\(T_a\) Ambient temperature, [K] 
\(T_{abs}\) Average temperature of absorber surface, [K] 
\(T_m\) Mean temperature of the heat transfer fluid across the collector or the solar field, [K] 
\(\Delta T\) Temperature difference between ambient and the pipe outer surface, [K]. 
\(T_{in}\) Heat transfer fluid inlet (to the solar field) temperature, [K] 
\(T_{out}\) Heat transfer fluid outlet (from the solar field) temperature, [K] 
\(u\) Wind speed, [m/s] 
\(U_L\) Overall heat loss coefficient from absorber surface, \([W/m^2.K]\) 
\(U_p\) Overall heat transfer coefficient of the insulated pipe, \([W/m^2.K]\) 
\(V\) Average velocity of the fluid, [m/s]
\( \dot{V} \)  
Volume flow rate, \([m^3/s]\)

\( W \)  
Collector width, \([m]\)

\( W_t \)  
Solar field total width, \([m]\)

\( W_e \)  
Collector effective width, \([m]\)

\( (W_e)_t \)  
Solar field total effective width, \([m]\)

- Dimensionless groups

\( Gr \)  
Grashof number

\( Nu \)  
Nusselt number

\( Pr \)  
Prandtl number

\( Ra \)  
Rayleigh number

\( Re \)  
Reynolds number

- Greek symbols

\( \eta_c \)  
Solar collector overall efficiency

\( \eta_{SF} \)  
Solar field overall efficiency.

\( \eta_{op} \)  
Optical efficiency

\( \eta_{op,n} \)  
Optical efficiency at normal incidence

\( \eta_{op,d} \)  
Optical efficiency for diffuse irradiance

\( \theta \)  
Angle of incidence

\( \theta_z \)  
Solar zenith angle

\( \theta_p \)  
Position angle

\( \theta_d \)  
Receiver displacement error, \([\text{mrad}]\)

\( \bar{\rho}_w \)  
Average density of the water between inlet and outlet temperatures.

\( \rho_w \)  
Density of water, \([\text{kg/m}^3]\)

\( \rho \)  
Tracking angle

\( \rho_m \)  
Average specular reflectance of the mirror at normal incidence

\( \tau \)  
Transmittance of the receiver glass envelope

\( \alpha \)  
Solar altitude angle

\( \alpha_p \)  
Solar profile angle

\( \alpha_c \)  
Absorptance of the absorber surface coating

\( \gamma_n \)  
Intercept factor at normal incidence

\( \psi \)  
Rim angle
σ_{tot}  Standard deviation of the total errors, [mrad]
σ_{optical}  Standard deviation of the total optical errors, [mrad]
σ_{slope}  Standard deviation of slope errors, [mrad]
σ_{specular}  Standard deviation of specular errors, [mrad]
σ_{displacement}  Standard deviation of receiver displacement errors, [mrad]
σ_{tracking}  Standard deviation of tracking errors, [mrad]
σ_{sun}  Root mean square (RMS) width of the sun, [mrad]
ω  Hour angle
φ  Latitude angle
δ  Declination angle
β  Solar azimuth angle
Ω  Aperture azimuth angle
κ  Tilt angle
μ_{w}  Dynamic viscosity of water, [N.s/m^{2}]
μ_{a}  Dynamic viscosity of air, [N.s/m^{2}]

- Abbreviations
WEO  World Energy Outlook
CO  Crude Oil
NG  Natural Gas
DNI  Direct Normal Irradiance
DLR  German Aerospace Center
CSP  Concentrated Solar Power
MEMR  Ministry of Energy and Mineral Resources
NERC  National Energy Research Center
SAM  System Advisor Model
HTF  Heat Transfer Fluid
LFR  Linear Fresnel Reflectors
CLFR  Compact Linear Fresnel Reflectors
DSG  Direct Steam Generation
ISG  Indirect Steam Generation
IPH  Industrial Process Heat
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>IPTC</td>
<td>Parabolic Trough Collector</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>LCT</td>
<td>Local Clock Time</td>
</tr>
<tr>
<td>LC</td>
<td>Longitude Correction</td>
</tr>
<tr>
<td>DLS</td>
<td>Daylight Savings</td>
</tr>
<tr>
<td>IAM</td>
<td>Incidence Angle Modifier</td>
</tr>
<tr>
<td>MLR</td>
<td>Multiple Linear Regression</td>
</tr>
<tr>
<td>TMY3</td>
<td>Typical Meteorological Year 3</td>
</tr>
<tr>
<td>TMY2</td>
<td>Typical Meteorological Year 2</td>
</tr>
<tr>
<td>ACC</td>
<td>Air Cooled Condenser</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>LCOE</td>
<td>levelized Cost of Electricity</td>
</tr>
<tr>
<td>NEPCO</td>
<td>National Electric Power Company</td>
</tr>
<tr>
<td>IPP</td>
<td>Independent Power Producer</td>
</tr>
<tr>
<td>MENA</td>
<td>Middle East North Africa</td>
</tr>
<tr>
<td>SAM</td>
<td>System Advisor Model</td>
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<td>ACC</td>
<td>Air-Cooled Condenser</td>
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</table>

- **Units**

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<td>Watt</td>
</tr>
<tr>
<td>J</td>
<td>Joule</td>
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<tr>
<td>Mtoe</td>
<td>Million tons of oil equivalent</td>
</tr>
<tr>
<td>Ttoe</td>
<td>Thousand tons of oil equivalent</td>
</tr>
<tr>
<td>TWh</td>
<td>Terawatt hour</td>
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<td>MWh</td>
<td>Megawatt hour</td>
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<tr>
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</table>

<table>
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<th>Unit</th>
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<td>horse power</td>
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<td>rad</td>
<td>radian</td>
</tr>
<tr>
<td>mrad</td>
<td>milliradian</td>
</tr>
<tr>
<td>s</td>
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</tr>
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<td>l</td>
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<td>$</td>
<td>US dollar</td>
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<tr>
<td>¢</td>
<td>US dollar cent</td>
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</table>
1. Introduction

1.1. Global energy consumption

According to the World Energy Outlook 2009 (WEO-2009), the world primary energy demand is projected to increase by 1.5% per year between 2007 and 2030, from just over 12,000 million tons of oil equivalent (Mtoe) to 16 800 Mtoe, with an overall increase of 40%. Developing Asian countries are the main drivers of this growth, followed by the Middle East.\[1\]

In 2008, around 81.3% of the world’s primary energy was supplied from Oil, Gas and Coal products; resulting in around 29,381 million ton of CO\textsubscript{2} which is a major source of the global warming problem.\[2\]

Besides the environmental impact of the extensive use of fossil fuels, the unstable oil prices the world witnesses since the seventies has a great influence on the investment in the energy market and consequently on the development plans worldwide.

The limited resources of Oil and Gas and the unstable prices as well as their environmental impact has made the search for alternative energy resources an indispensable approach in order to have a sustainable supply of energy. Renewable energies including solar, wind, hydropower and biomass are considered to be attractive alternatives that are highly abundant, sustainable and environmentally friendly resources.

1.2. Energy in Jordan

Jordan as a developing country has experienced an average growth rate of primary energy demands of 4.3% per year over the past ten years. The consumption has risen from 5150 up to 7357 thousand ton oil equivalent (Ttoe) as illustrated in figure 1.1; which was plotted according to the data obtained from the Ministry of
Energy and Mineral Resources\textsuperscript{[3]}. The growth rate is expected to continue at high rate (5.6\%)\textsuperscript{[4]} until 2020 according to the anticipated medium demand scenario.

![Figure 1.1: Primary energy consumption in Jordan (2001-2010).](image)

The most serious challenge of development in Jordan is the lack of water and energy resources. In 2010, Jordan covered 96\% of the energy demands by crude oil (CO) and natural gas (NG) while renewable energy resources supplied about 2\% of the total primary energy.

In addition, around 96\% of the energy resources was imported in the form of CO and NG that are being produced locally but in very minimal quantities which makes these resources very limited and results in an unsolicited burden on the general budget. This burden has led the government to remove the fuel subsidies gradually until 2008.

In view of the situation explained above (high growth rate, lack of resources and high energy price), the government of Jordan has adopted an updated master strategy of energy sector for the period (2007-2020) in order to confront the future energy challenges that impede development in various sectors. In this strategy, Jordan has a clear vision and ambitious targets in minimizing the dependency on
the imported NG and CO by utilizing the renewable energy resources and exploiting the oil shale which exists in high reserves in the country.

In renewable energy domain, the target of the strategy is to reach a contribution percentage in the total energy mix of 7% by 2015\textsuperscript{[4]} and 10% by 2020\textsuperscript{[4]}. The estimated investment for such target is about (1415-2115) million US$ as suggested by the plan.

As Jordan is located in the middle east, it enjoys high levels of Direct Normal Irradiance (DNI) especially in the southern and eastern parts. The high DNI offers a high potential for the utilization of concentrated solar thermal power (CSP) plants for electricity generation, solar cooling and process heating as well as for water desalination.

MED-CSP study which was conducted by DLR (German Aerospace Center), suggests that the economic potential of CSP for electricity generation in Jordan is 6429 TWh/year\textsuperscript{[5]} compared to a potential of 2.0 TWh/year\textsuperscript{[5]} for wind energy. Accordingly, the energy strategy recommended the completion of the studies of implementing CSP and photovoltaic (PV) projects for electricity generation with a capacity of 300 – 600 MW.

The Ministry of Energy and Mineral Resources (MEMR) in cooperation with the National Energy Research Center (NERC) are conducting activities to maximize the use of solar energy. These activities include proposals and feasibility studies for CSP projects as well as analysis and evaluation of the solar radiation measurements which were taken at seven sites in the country.

**1.3. Thesis objectives**

As part of the activities proposed by the European Commission sixth Framework Program (International Cooperation – INCO), The REACT (self-sufficient renewable energy air-conditioning system for Mediterranean countries) project
aims at the introduction of an advanced and innovative hybrid solar hot water and air-conditioning system in target Mediterranean Partner Countries (MPC).\[^6\]

Following the objectives of the project, a demonstration plant that uses heat from parabolic trough solar collector (PTSC) was installed in a hotel in the Dead Sea area.

This thesis falls under the scope of the enerMENA project implemented by DLR in the MENA region in cooperation with local teams from the partner countries in the region. EnerMENA project aims at offering technological cooperation and targeted support of countries in the region which are about to implement their first CSP plants. Possibilities for enhancements during the plants start up and operation are being analyzed and implemented to increase the efficiency of the solar power plant section. The focuses of the project are:

- Analysis and optimization of CSP plants
- Dissemination of CSP technology
- Multiplication of local know-how

This thesis consists of two parts: the first one investigates the optical and thermal performance of the parabolic trough field installed in the Dead Sea area. In light of the targets and focuses of enerMENA project, the objectives of this part are to provide:

- An overview of the historical development and the principle of operation of the different CSP technologies.
- A detailed investigation of the optical and thermal performance of parabolic trough by developing an empirical mathematical model for the overall performance of the Dead Sea plant based on the available measurements.
• A description of the test procedure for the assessment of optical efficiency and the analysis of the results using one of the well known measurement methods (photogrammetry).

The second part addresses the financial and economical aspects of parabolic trough power plants. As the cost of power generation by CSP technologies is of a great importance for the promotion of the technologies to be proven as competitive alternative to the conventional oil or gas fired power plants; this thesis tackles the economic aspect by investigating the cost of electricity generation by a 50 MW parabolic trough power plant in Ma’an area in southern part of Jordan using the simulation tool SAM (System Advisor Model).
2. Concentrated Solar Power Technologies

The use of solar energy by the mankind dates back to the seventh century B.C. when the heat from the sun was concentrated by glass and mirror to light fire. Today, heat from the sun is utilized by modern technologies to generate power and other advanced applications.

This chapter gives an overview of the basic types of CSP technologies and their historical development. These types are the dish/Stirling engine, the central tower, the linear Fresnel reflectors and finally the parabolic trough.

2.1. Dish/ Stirling Engine

In 1882, Monsieur Abel Pifre, a French Engineer, demonstrated the solar engine shown in figure 2.1 below invented by him.

![Figure 2.1: Printing press driven by solar radiation.][7]

It consists of a parabolic mirror, in the focus there was placed a cylindrical steam boiler. The steam generated by the reflected sun-rays actuates a small vertical engine of 2/5 horse power (hp) driving a printing-press.
2.1.1. System description

The dish engine is a point focusing system, it can acquire a high concentration ratio and practically high temperatures (over 1480 °C) of the working fluid\textsuperscript{[11]}. A number of thermodynamic cycles and working fluids have been considered for dish/engine systems. These include Rankine cycle, using water or an organic working fluid; Brayton cycles, both open and closed; and Stirling cycles. Stirling engines are a leading candidate for dish/engine systems because their external heating makes them adaptable to concentrated solar flux and because of their high efficiency.

Nowadays, the dish/Stirling technology utilizes a parabolic dish concentrator that tracks the sun and focuses solar energy into a receiver, usually of cavity type because of the low overall heat loss rate\textsuperscript{[11]}, the receiver located at the focal point of the paraboloid that absorbs the energy and transfer it to a Stirling engine for the generation of electrical power using Helium or Hydrogen as working fluid.

Dish/Stirling systems are characterized by high efficiency, modularity, autonomous operation, and a hybrid capability (the ability to operate on either solar energy or a fossil fuel, or both). The autonomous operation makes the system suitable for small applications in remote areas such as water pumping.

The main challenge is that, unlike trough and solar power towers, Stirling dish technology is not suitable to operate with thermal storage. The only and more costly option is to use electrical storage, for instance by means of batteries.

2.1.2. Historical development

Over the period (1982-1985), Advanco corporation built Vanguard system in southern California, delivering 25 kW\textsubscript{e} (kW electrical) nominal output module shown in figure 2.2, the dish has 10.5m diameter and achieved solar-to-electric net conversion efficiency of 29.4\%\textsuperscript{[8]}. The efficiency here is defined as the net
electrical power delivered to the grid, taking into account the electrical power needed for parasitics, divided by the direct normal irradiation (DNI) incident on the area of the mirrors. Some operational problems were reported during the 18-month operation of the system such as excessive noise, vibration and failure of circuit boards\textsuperscript{[9]}.

In 1984, two 17m-diameter Stirling dish systems as depicted in figure 2.3 below were installed and operated in Riyadh in Saudi Arabia by Schlaich-Bergermann und Partner from Stuttgart, Germany. The capacity of each system was 50kWe. The systems have achieved a net electrical output of 53kW and a solar to electric efficiency of 23\% at an insolation of 1000 W/m\textsuperscript{2}.\textsuperscript{[10]}

![Figure 2.2: The Vanguard dish system.\textsuperscript{[9]}](image)

In 1993, the team of Science Applications International Corporation (SAIC) and Stirling Thermal Motor (STM) designed and built a first generation of the
dish/Stirling system shown in figure 2.4. the system produced 21.6kWe at a 24% conversion efficiency and 1000 W/m² solar insolation.

![Figure 2.3: 17m - Schlaich-Bergermann dishes in Riyadh.](image)

In March 2008, Stirling, in conjunction with Sandia National Laboratories, achieved a new world record of solar-to-grid system conversion efficiency of 31.25%, significantly beating the previous record set in 1984 – 29.4%.

![Figure 2.4: SAIC/STM dish (1st generation).](image)
Currently, there is a dish/stirling plant in operation in Arizona, United States. The plant started production on January 1, 2010. It consists of 60 dishes with a capacity of $25.0\text{kW}_e$ each providing a total capacity of $1.5\text{MW}_e$.\textsuperscript{[12]}

2.2. Power Tower.

2.2.1. System description

This system is also known as “Central Receiver” system. The basic configuration of the concentration system is illustrated in figure 2.5.

![Figure 2.5: The power tower concentration.\textsuperscript{[11]}](image)

The system is considered as point-focusing system. It consists of sun-tracking mirrors called heliostats installed on the ground level surrounding a central receiver mounted on top of a tower that could extend to hundreds of meters. The heliostats reflect the incident radiation on the receiver which heats the working fluid of the power generation cycle. The large size of the receiver and the temperature achieved by the system (over 500°C) makes the system suitable for utility-scale applications of large capacity reaching several hundreds of MW\textsubscript{e}. One of the advantages of this power tower over the dish engine is the capability of
utilizing thermal storage, which has relatively low cost to achieve more operating hours.

Usually, the tower system operates in conjunction with the molten salt -heat transfer fluid (HTF) - tanks as a steam generator in steam Rankin cycle as illustrated in figure 2.6 below which represents a typical configuration of solar power tower plant.

![Figure 2.6: The solar tower – Rankin power plant.][13]

Nitrate salt mixtures can be used as both a heat transfer fluid and a storage medium at temperatures of up to 565°C. However, most mixtures currently being considered freeze at temperatures around 140 to 220°C (285 to 430°F) and thus must be heated when the system is shutdown. They have a good storage potential because of their high volumetric heat capacity. Steam has been used as a heat transfer fluid at a pressure of 10MPa. Although its cost is lower than that of other types of fluids, the use of water as a high-temperature storage medium is difficult because of the high pressures involved.[14]

The layout of the heliostats is designed to optimize the annual performance of the plant where the cost and the heliostats optical losses are the main variables. It also
depends on the type of the receiver used. There are basically two types of receivers: cavity receiver which accepts the concentrated radiation through an aperture, then the radiation is absorbed by the internal walls. And external receiver which accepts the concentrated radiation from all around its external walls. Accordingly, the heliostats are installed to reflect radiation from all directions on an external receiver, and from selected directions on a cavity receiver.

One of the main concerns with power tower technology is the high consumption of water for cooling (steam condensation) and for cleaning the mirrors. This is a challenge when we consider that the plants are typically constructed in the desert which by nature lacks water resources.

2.2.2. Historical development

Since the early 1980s, many experimental power towers plants have been constructed around the world. These experimental facilities were built to prove that solar power towers can produce electricity and to improve on the individual system components\textsuperscript{[15]}. In Table 2.1, these facilities are listed along with some of their most important characteristics.

Currently, the largest power tower grid-connected plant in operation is Planta Solar-20 located in Sevilla, Spain. The capacity of the plant is 20MW starting the production in April 2009 with 1255 heliostats. The receiver used in the plant is of cavity type with a tower height of 165m. the heat transfer fluid used is water with a storage capacity of one hour\textsuperscript{[12]} . the plant is shown in figure 2.7 below.

Expected to start production in October 2013, Ivanpah Solar Electric Generating Station in California,US will be the largest commercial power tower plant with a net capacity of 370MW\textsubscript{e} utilizing 214,000 heliostats. the planned annual electric power generation is 1,079,232 MWh/yr with an annual Solar-to-Electricity Efficiency of 28.72\%\textsuperscript{[12]}. 
Table 2.1: Experimental power tower plants.\textsuperscript{[15]}

<table>
<thead>
<tr>
<th>Project</th>
<th>Country</th>
<th>Power Output (MWe)</th>
<th>Heat Transfer Fluid</th>
<th>Storage Medium</th>
<th>Operation Began</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSPS</td>
<td>Spain</td>
<td>0.5</td>
<td>Liquid Sodium</td>
<td>Sodium</td>
<td>1981</td>
</tr>
<tr>
<td>EURELIOS</td>
<td>Italy</td>
<td>1</td>
<td>Steam</td>
<td>Nitrate Salt/Water</td>
<td>1981</td>
</tr>
<tr>
<td>SUNSHINE</td>
<td>Japan</td>
<td>1</td>
<td>Steam</td>
<td>Nitrate Salt/Water</td>
<td>1981</td>
</tr>
<tr>
<td>Solar One</td>
<td>USA</td>
<td>10</td>
<td>Steam</td>
<td>Oil/Rock</td>
<td>1982</td>
</tr>
<tr>
<td>CESA-1</td>
<td>Spain</td>
<td>1</td>
<td>Steam</td>
<td>Nitrate Salt</td>
<td>1983</td>
</tr>
<tr>
<td>MSEE/Cat B</td>
<td>USA</td>
<td>1</td>
<td>Molten Nitrate</td>
<td>Nitrate Salt</td>
<td>1984</td>
</tr>
<tr>
<td>THEMIS</td>
<td>France</td>
<td>2.5</td>
<td>Hi-Tec Salt</td>
<td>Hi-Tec Salt</td>
<td>1984</td>
</tr>
<tr>
<td>SPP-5</td>
<td>Russia</td>
<td>5</td>
<td>Steam</td>
<td>Water/Steam</td>
<td>1986</td>
</tr>
<tr>
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<td>Spain</td>
<td>1</td>
<td>Air</td>
<td>Ceramic</td>
<td>1993</td>
</tr>
<tr>
<td>Solar Two</td>
<td>USA</td>
<td>10</td>
<td>Molten Nitrate Salt</td>
<td>Nitrate Salt</td>
<td>1996</td>
</tr>
</tbody>
</table>

Note: the Nitrate salt consists of 60\% NaNO\textsubscript{3} and 40\% KNO\textsubscript{3}.

Figure 2.7: Planta Solar-20 Plant.
2.3. Linear Fresnel Reflectors (LFR)

2.3.1. System description

It is a line-focusing system. The classical LFR uses modular, flat mirrors that track the sun to focus the sun's heat onto long, elevated tubular receiver (absorber) through which water flows. The concentrated sunlight boils the water in the tubes, generating hot water, saturated or superheated steam for use in power generation in steam Rankin cycle for instance or for process heat in industrial applications. Figure 2.8 below illustrates the basic configuration of the system.

![Figure 2.8: Basic configuration of LFR system.](image)

One fundamental difficulty with the LFR technology is the avoidance of shading of incoming solar radiation and blocking of reflected solar radiation by adjacent reflectors. Shading and blocking can be reduced by using higher absorber tower which increases cost, or by increasing absorber size which allows increased spacing between reflectors remote from the absorber which leads to more ground usage and more thermal losses and shading by the absorber.\(^{[16]}\)

A development of the traditional system is the Compact Linear Fresnel Reflector (CLFR) system. CLFR utilizes multiple absorbers within the vicinity of the
reflectors as shown in figure 2.9 below. This development makes the technology capable of supplying electricity in the multi megawatt range.

![Figure 2.9: Compact LFR system][16]

The arrangement utilized in CLFR allows for minimum blocking of reflected radiation between adjacent mirrors which means the avoidance of large mirror spacing. It also allows for lower absorber height which eventually means lower investment cost.

One of the basic advantages of the LFR which makes the system less expensive than other CSP systems is the use of water as the heat transfer fluid which eliminates the expensive and hazardous thermal oil as heat transfer fluid and eliminates the extra cost of oil/water heat exchanger. The use of water as HTF in other technologies like parabolic trough is now under development. An additional advantageous feature of the technology is that the moving parts are accessible which allows for easier maintenance of the system. Also, the absorber/heat transfer loop is isolated from the reflector field and does not move, thus avoiding the high cost of flexible high pressure lines or rotating joints.
2.3.2. **Historical development**

Giovanni Francia, an Italian Mathematician, developed the first system that applies the LFR technology. He designed and built the first LFR prototype shown in figure 2.10 in 1963 and tested it in 1964 at Lacédémone-Marseilles solar station. The plant generated 38 kg/h of steam at 100 atmospheric pressure and 450°C [17].

![Figure 2.10: Photos of Francia’s first LFR prototype.][17]

While point focus systems dominated Fresnel reflector development in the subsequent decades, there was development work carried out on linear Fresnel systems by the American corporation FMC on 10 and 100 MW plants in the late 1970's, but the work was stopped for lack of funding just as the first components were about to be field tested. [18]

Development began on the Australian design of CLFR at the University of Sydney in 1993 and it was patented in 1995. Interest rose within the Australian utility industry, Austa Energy and Stanwell Corporation agreed to develop a plant under the Australian Greenhouse Renewable Energy Showcase scheme in 1999. Unfortunately, the Austa group was abolished shortly after and their developmental expertise was lost to the project [19]. Since 1999 progress has been
slow but steady technically and a very efficient and simple design has been evolved now using an advanced cavity receiver.

Linear Fresnel applications are mostly on experimental stage. Companies working in the field claim higher efficiency and lower costs per kWh than its direct competitor, parabolic trough, due to high density of mirrors.

Currently, a demonstration project is in operation since October 2008 in California, US. The project utilizes CLFR field with aperture area of 26,000 m² driving a turbine with 5.0MW_e net capacity at 40 bar pressure.\textsuperscript{[12]}

Another prototype plant was constructed in Murcia, Spain. The technology utilized in the project is CLFR with Single-tank thermocline storage system incorporated in Puerto Errado 1 power plant which started production in March 2009. The gross capacity of the turbine 1.4MW_e at 55 bar and 270°C.\textsuperscript{[12]}

Puerto Errado 2 power plant is now under construction in the same area of Puerto Errado 1. The plant has the same operational parameters as in Puerto Errado 1 with a gross capacity of 30MW_e.\textsuperscript{[12]}

Finally, Solar Dawn is a 250 MW CLFR thermal gas hybrid power plant that is proposed in Round 1 of the Australian Government’s Solar Flagships Program. The proposed Solar Dawn power plant will be built near Chinchilla in South-West Queensland. It is expected that the proposed project will commence operation in early 2015 following the finalization of project development in December 2011 and three years of construction. While designed as a standalone solar thermal power plant, it will have the added benefit of a gas boiler back-up system so electricity can be provided at any time.\textsuperscript{[20]}
2.4. Parabolic Trough

2.4.1. System description

This technology uses reflectors curved around one axis using a linear parabolic shape, which has the property of collecting parallel rays along a single line focus with a tubular receiver located along the focus line. The collector continuously tracks the sun to ensure the reflection of the sun rays on the receiver. The basic configuration is illustrated in Figure 2.11.

![Parabolic Trough Collector Diagram](image)

Figure 2.11: Parabolic trough collector.

Parabolic trough is the most established CSP technology. This is primarily due to the currently existing large-scale commercial solar power plants with a total installed capacity of hundreds of Megawatts.

The current designs of parabolic trough power plants utilizes the solar field to heat oil (HTF) that will be used either for water preheating or a steam generator through heat exchangers in Rankine or combined power cycles. Typical configurations of both options are shown in figure 2.12.
As in LFR and power tower, thermal storage system at relatively low cost can be integrated in parabolic trough power plant which will extend the hours of operation of the plant and smooth out the plant output.

Figure 2.1: Parabolic trough field with storage system in Rankine power cycle.

Another configuration that is now under investigation and demonstration is the direct steam generation (DSG). In DSG, water will be circulated through the receiver and converted into steam without the use of heat exchangers and HTF.

Figure 2.11.b: Parabolic trough field in integrated solar combined cycle (ISCC).
DSG provide a promising potential for the reduction of electricity generation cost by eliminating the need for some components as mentioned before. It should also improve the solar field operating efficiency due to lower average operating temperatures and lower thermal losses.

However, the use of DSG in parabolic troughs for thermal storage capacity has a number of implications. DSG power plants should adapt storage systems for latent and sensible heat storage due to the evaporation of steam in the absorber tubes while in indirect steam generation (ISG) parabolic trough power plants, sensible heat storage system such as molten salt is suited to store energy.

2.4.2. Historical development

Around 1883, Captain John Ericsson used a longitudinal parabolic concentrator to operate a steam engine for pumping water. His experiments with solar engines never advanced beyond the prototype stage.

The world’s very first documented parabolic trough plant was built in Maadi, Egypt in 1913. The system consisted of five collectors oriented in a north-south direction with a mechanical tracking system. Each collector was 62m in length and 4m in width with a spacing of 7.6m\textsuperscript{21}. The system generated steam that was used to power water pump for irrigation purposes. During one test, the engine actually produced 50 to 60 hp continuously for 5 hours\textsuperscript{11}. The system is shown in figure 2.13.

Recent development of parabolic trough power plants took place in the U.S. in mid-1970s and in Europe in 1980s\textsuperscript{22}. Parabolic trough collectors capable of generating temperatures greater than 500ºC (932ºF) were initially developed for IPH applications. Much of the early development was conducted by or sponsored through Sandia National Laboratories in New Mexico.
The development was culminated with the construction of the International Energy Agency (IEA) Small Solar Power Systems Project/Distributed Collector System (SSPS/DCS) in Tabernas, Spain, in 1981. This facility consisted of two parabolic trough solar fields with a total mirror aperture area of 7602 m$^2$. The fields used the single-axis tracking Acurex collectors and the double-axis tracking parabolic trough collectors developed by M.A.N. of Munich, Germany.

In 1982, Luz International Limited (Luz) developed a parabolic trough collector for IPH applications. Starting in 1985, Luz built eight parabolic trough power plants in California, U.S. The characteristics of the plants are shown in table 2.2. The plants are designed to produce full electrical power with steam supplied either by solar field or by natural gas (via the gas-fired boiler).

There are other operational parabolic trough power plants in the U.S. such as Nevada Solar One plant with 72 MW$_e$ net capacity and Martin Next Generation Solar Energy Center plant with a net capacity of 75 MW$_e$. 

Figure 2.13: Shuman-Boys solar power plant, Egypt, 1913.
The first parabolic trough power plant in Europe is Andasol 1 in Spain. The construction of the plant started in 2006 and the power production began in November 2008. Andasol 1 is the first parabolic trough power plant with storage system where 7.5 hours storage system is integrated in the plant.

There are many other plants in Spain of similar characteristics either operational such as Anadasol 2 (50 MW with 7.5h storage) and Majadas 1 (50 MW with storage), or under construction like Vallesol 50 (50 MW with 7.5h storage).[12]

In the Middle East and North Africa (MENA) region, recent implementation of parabolic trough plants has taken place. Two Integrated Solar Combined Cycle utilizing parabolic trough are now in operation since mid-2011, the first one is ISCC Algeria in Hassi R’mel, Algeria with a capacity of 25MWₑ, the second one is ISCC Morocco in Ain Beni Mathar, Morocco with a capacity of 470MWₑ. another ISCC plant is under construction now in Egypt. The plant, ISCC Al Kuraymat, has a capacity of 140MWₑ with a solar share of 20MWₑ. There are many other plants under development now in the MENA region as part of the renewable energy targets of the MENA countries and as an output of the collaboration with the European countries.
3. Description of the System Under Study

3.1. General description

This chapter provides a description of the system being tested and investigated in this study which is installed on the rooftop of the Dead Sea Medical Resort in Jordan. Geographically, the system site is located at latitude 31.714°N and longitude 35.586°E, the site elevation is 396 below sea level.

A photograph of the installed parabolic troughs is shown in figure 3.1 where a set of parabolic troughs are used to generate hot water to drive a two-stage ammonia absorption chiller in summer and to pre-heat domestic hot water in winter.

Figure 3.1: The parabolic troughs in the system under study.
3.2. Principle of operation

Figure 3.2 depicts a schematic diagram for the part of the system that is of our interest in this study. This part is associated with the operation and performance of the solar collectors.

The solar field continuously tracks the sun (using electrically-driven hydraulic tracking system) and transfer the collected energy to the HTF which is the water that flows through the receivers of the solar collectors. The water is circulated in the system by means of water pump (P-1).

The switch-over between summer and winter operation is achieved through controlling the motorized three-way valves (V-8 and V-12). In summer, the HTF follows the path (A B C D E H) where the HTF is used to supply the heat required to evaporate the refrigerant (ammonia) in the generator section of the absorption chiller.

In winter, the flow path of the HTF is changed to (A B E F G H). the HTF transfers the heat collected in the solar field to the hotel domestic water (pre-heating) through the heat exchanger. Unfortunately, there is no available information on the design temperatures and pressures in the project documents in hand.

Sensors are installed at several locations as shown in the figure to continuously measure the operating temperature and pressure as well as the water flow rate of the HTF for the purposes of testing and monitoring.

The expansion tank (ET-1), which is fed from Nitrogen bottle, protects the system from excessive pressure resulting from the expansion of the working fluid. Finally, manually operated valves (V-1 through V-11) are provided to isolate the components during maintenance activities.
Figure 3.2: Schematic diagram of the system under study.
3.3. Solar field

The layout of the solar field is shown in figure 3.3. It consists of three rows of parabolic solar collectors connected in series with a total number of fourteen collectors. In the original design the number was sixteen, but due to space limitations the number was reduced in order to be accommodated in the available space.

As shown in the figure, the collectors are installed such that the tracking axis is oriented at $71^\circ$ counter clockwise from north to east. This orientation was imposed by the orientation of the building. The type of installed collectors is PTC-1800 developed by the German company SOLITEM GmbH. The reflector consists of 0.8mm Aluminum sheets covered with Aluminum coating. The characteristics of the PTC-1800 collector are listed in table 3.1 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PT-1800 Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rim Angle (degrees)</td>
<td>60.0</td>
</tr>
<tr>
<td>Focal Length (mm)</td>
<td>780.0</td>
</tr>
<tr>
<td><strong>Mirror</strong></td>
<td></td>
</tr>
<tr>
<td>Length (mm)</td>
<td>5090.0</td>
</tr>
<tr>
<td>Aperture Width (mm)</td>
<td>1800.0</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>260.0</td>
</tr>
<tr>
<td>Aluminim Coating (mm)</td>
<td>0.50</td>
</tr>
<tr>
<td>Solar-weighted reflectance</td>
<td>0.850</td>
</tr>
<tr>
<td><strong>Absorption Tube</strong></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Coating</td>
<td>Black chrome</td>
</tr>
<tr>
<td>External Diameter (mm)</td>
<td>38.00</td>
</tr>
<tr>
<td>Wall Thickness (mm)</td>
<td>1.25</td>
</tr>
<tr>
<td>Solar absorptance</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>Glass Envelope</strong></td>
<td></td>
</tr>
<tr>
<td>External Diameter (mm)</td>
<td>65.00</td>
</tr>
<tr>
<td>Wall Thickness (mm)</td>
<td>2.20</td>
</tr>
<tr>
<td>transmittance</td>
<td>0.92</td>
</tr>
</tbody>
</table>
Figure 3.3: Solar field layout.
The HTF is distributed among the collectors through 38mm steel pipe which is insulated with 80mm Rockwool. The absorber tube is connected to the distribution pipe via stainless steel flexible connectors as illustrated in the detail in figure 3.4.

Figure 3.4: PTC1800 structure and connection details.

The onsite weather station shown in figure 3.5 includes anemometer that measures the wind speed, Pyranometer that measures the global irradiance on a horizontal surface and an air temperature sensor that measures the ambient temperature.

Figure 3.5: Onsite weather station.
4. Performance Model for the Parabolic Trough Field

The purpose of this chapter is to develop an empirical mathematical model that characterizes the performance of the solar field under different operating conditions for the system under study (figure 3.3). The parameters that will be used to estimate the performance are the solar field efficiency and the useful heat output from the solar field.

For solar collectors in general, the collector overall efficiency $\eta_c$ is defined as the ratio between the useful output $\dot{Q}_u$ [W] delivered by the collector to the global irradiance $G$ [W/m$^2$] incident on the collector aperture area $A_c$ [m$^2$]

$$\eta_c = \frac{\dot{Q}_u}{A_c G} \quad (4.1)$$

The global irradiance $G$ on a horizontal surface consists of two parts: the beam irradiance $G_n$ and the diffuse irradiance $G_d$.

$$G = G_n \cos \theta_z + G_d \quad (4.2)$$

Where $\theta_z$ (solar zenith angle) is the angle between the solar beam and the normal of a horizontal surface.

The amount of the beam irradiance received by the collector aperture $G_b$ is less than the normal beam irradiance due to the cosine loss caused by the angle of incidence $\theta$ between the aperture normal and $G_n$ (section 4.3). The relation between the two irradiances is

$$G_b = G_n \cos \theta \quad (4.3)$$

Concentrating solar collectors operate on the principle of concentrating the beam irradiance in clear sky conditions (low diffuse radiation). Therefore, the contribution of diffuse radiation in the useful power output and the collector efficiency will be neglected in the model development.
So, for parabolic trough collectors, the global irradiance in the dominator of equation 4.1 is replaced with the beam irradiance received by the aperture $G_b$.

For a concentrating collector, the useful output $Q_u$ can be expressed as

$$
\dot{Q}_u = \dot{m} \bar{c} (T_o - T_i) = A_c G_b \eta_{op}(\theta) - A_{abs} U_L (T_{abs} - T_a) \quad (4.4)
$$

Where

- $\dot{m}$: mass flow rate of the HTF (water in our system), [kg/s]
- $\bar{c}$: average specific heat of the HTF between inlet and outlet, [J/kg.K]
- $T_o$: HTF outlet temperature, [K]
- $T_i$: HTF inlet temperature, [K]
- $T_a$: ambient temperature, [K]
- $T_{abs}$: the average absorber surface temperature, [K]
- $A_{abs}$: absorber outer surface area, [m²]
- $U_L$: overall heat loss coefficient from absorber surface, [W/m².K]
- $\eta_{op}(\theta)$: Optical efficiency of the collector as function of $\theta$

It is easier to express $\dot{Q}_u$ as a function of the fluid inlet temperature $T_i$ due to the difficulty of measuring the absorber surface temperature $T_{abs}$

$$
\dot{Q}_u = A_c F_R [G_b \eta_{op}(\theta) - (A_{abs} / A_c) U_L (T_i - T_a)] \quad (4.5)
$$

Where $F_R$ is “the collector heat-removal factor” defined as the ratio of the actual power output of the collector to the imaginary output if the whole absorber surface was isothermal at the fluid-inlet temperature. A detailed derivation of equation 4.5 is available in reference[23].

The optical efficiency $\eta_{op}(\theta)$ is defined as the amount of radiation absorbed by the absorber tube divided by the amount of direct normal radiation incident on the aperture area. The optical efficiency when the incident radiation is normal to the aperture ($\theta = 0'$) is given as
\[ \eta_{op,n} = \rho_m (\tau \alpha_c)_e \gamma_n \]  

(4.6)

where \( \rho_m \): average specular reflectance of the mirror at normal incidence
\( \tau \): transmittance of the glass envelope
\( \alpha_c \): absorptance of the absorber surface coating
\( (\tau \alpha_c)_e \): the effective product of \( \tau \) and \( \alpha_c \)
\( \gamma_n \): intercept factor (fraction of the reflected radiation that is intercepted by the receiver) at normal incidence.

The optical efficiency varies with the variation of the angle of incidence \( \theta \). This variation is quantified by the incidence angle modifier \( K(\theta) \) (see section 4.5). Additionally, as the solar field consists of multiple rows of collectors, optical losses will occur due to mutual shading of collector rows. The mutual row shading losses are accounted for by the solar field row shading factor \( F_{RS} \) (see section 4.4).

There are additional losses associated with the cleanliness of the reflector. However, for the system under study, the reflectors will be cleaned immediately prior to operation (for measurement purposes). Therefore, the losses related to cleanliness will be overlooked in the analysis of the system performance.

Accordingly, the optical efficiency equation that accounts for optical losses at any angle of incidence is given by

\[ \eta_{op}(\theta) = F_{RS} K(\theta) \rho_m (\tau \alpha_c)_e \gamma_n \]  

(4.7)

the values of \( \rho_m \), \( \tau \), and \( \alpha_c \) for the collectors under study are given in table 3.1. The determination of the intercept factor is explained in section 4.2 which also introduces three methods for measuring the optical quality of parabolic trough collectors.
4.1. Performance model development

Performance model is a method for the characterization of the efficiency and the useful output of the solar collector. When testing for collector performance, heat output is calculated from measurements of mass flow rate of HTF and temperature difference between inlet and outlet of the collector.

Reference [24] introduces the following performance model for parabolic trough using the mean HTF temperature ($T_m$) across the collector

\[
T_m = \frac{(T_o + T_i)}{2} \quad (4.1.1)
\]

\[
\eta_c = \frac{\dot{Q}_u}{(G_b A_c)} = K(\theta) \eta_{op,n} - \left[c_1 (T_m - T_a)/ G_b \right] - \left[c_2 (T_m - T_a)^2/ G_b \right] \quad (4.1.2)
\]

where the coefficients $c_1$ and $c_2$ are determined by a curve fit to test data. The nonlinearity of equation 4.1.2 caused by the addition of the term $(T_m - T_a)^2$ is a simplified approach to account for the temperature dependence of $U_L$ (equation 4.5) which is quite complex because $U_L$ represents the conductive, convective, and radiative losses combined together.

The European Standard EN 12975 “Thermal solar systems and components – Solar Collector” includes two alternative test methods for the thermal performance characterization of solar thermal collectors: steady-state test and quasi-dynamic test. The testing conditions requirements for both tests are shown in table 4.1.

The basic equation for the steady-state model for near normal incidence angle is

\[
\eta_c = \frac{\dot{Q}_u}{(G_b A_c)} = \eta_{op,n} - \left[c_1 (T_m - T_a)/ G_b \right] - \left[c_2 (T_m - T_a)^2/ G_b \right] \quad (4.1.3)
\]

In quasi-dynamic test, the effect of the angle of incidence on the optical efficiency should be included (the incidence angle modifier). Furthermore, the equation is complemented by terms for diffuse irradiance (because, unlike in steady state test, there is no precondition for the fraction of the diffuse irradiance) and the effective
thermal capacity of the system\cite{26}. Thus, the specific power output in quasi-
dynamic test is given by

\[
\dot{Q}_u / A_c = G_b K(\theta) \eta_{op,n} + G_d \eta_{op,d} - c_1 (T_m - T_a) - c_2 (T_m - T_a)^2 - c_3 dT_m/dt \quad (4.1.4)
\]

Where \( G_d \): diffuse irradiance

\( \eta_{op,d} \): optical efficiency for diffuse irradiance

Table 4.1: Test conditions and permitted deviations.\cite{25}

<table>
<thead>
<tr>
<th>Parameter</th>
<th>steady-state</th>
<th>quasi-dynamic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>value</td>
<td>Deviation from the mean</td>
</tr>
<tr>
<td>Global solar irradiance ( G )</td>
<td>&gt; 700 W/m²</td>
<td>± 50 W/m²</td>
</tr>
<tr>
<td>Incidence angle of the beam irradiance ( \theta )</td>
<td>&lt; 20°</td>
<td>-</td>
</tr>
<tr>
<td>Diffuse fraction ( G_d/G )</td>
<td>&lt; 30 %</td>
<td>-</td>
</tr>
<tr>
<td>Surrounding air temperature ( t_a )</td>
<td>-</td>
<td>± 1 K</td>
</tr>
<tr>
<td>Surrounding air speed ( u )</td>
<td>3 m/s ± 1 m/s</td>
<td>-</td>
</tr>
<tr>
<td>Collector inlet temperature ( t_i )</td>
<td>-</td>
<td>± 0.1 K</td>
</tr>
</tbody>
</table>

Since the control capabilities of the system under study do not allow for the
achievement of the strict conditions for steady-state test, equation (4.1.4) will be
the base of the performance model for our system that will allow the estimation of
the solar field output under any versatile operation and weather conditions based
on the measurement data explained in the chapter 5. Nonetheless, corrections and
additional terms should be integrated in equation (4.1.4) to effectively represent
the conditions of our system.

Firstly, as stated before, the contribution of diffuse irradiance will be overlooked
especially that the system will be operated under clear sky conditions that are the
prevailing condition over the year in the Dead Sea area. So, the term “\( G_d \eta_{op,d} \)”
will not be included in the model of our system.
Secondly, since the system operates at various wind speeds, an additional term should be incorporated to account for the dependency of heat losses on the wind speed $u$. The wind-dependence term is $c_4 u (T_m - T_a)$.

Thirdly, equation (4.1.4) is a testing model for a single collector which does not involve heat losses in piping while the system under test consists of multiple collectors and piping network where additional heat losses will be present. Thus, a term for heat losses in piping should be added to equation (4.1.4) to be adequately representative of the system. This term is $\dot{Q}_p$ and it is discussed in section 4.6.

Finally, since the performance will be tested for the entire system rather than a single collector, the area of the collector $A_c$ will be replaced by the total aperture area for the solar field $A_a$ and the mutual shading effect should be included by the previously introduced row shading factor $F_{RS}$.

Consequently, the final performance model equations for our system is

$$\dot{Q}_{SF} = A_a (G_b F_{RS} K(\theta) \eta_{op,n} - c_1 (T_m - T_a) - c_2 (T_m - T_a)^2 - c_3 \frac{dT_m}{dt} - c_4 u (T_m - T_a)) - \dot{Q}_p \quad (4.1.5)$$

$$\dot{Q}_{SF} = \dot{m} c_b (T_{out} - T_{in}) \quad (4.1.6)$$

$$\eta_{SF} = \frac{\dot{Q}_{SF}}{(A_a G_b)} = F_{RS} K(\theta) \eta_{op,n} - c_1 (T_m - T_a)/G_b - c_2 (T_m - T_a)^2/G_b - c_3 \frac{dT_m}{dt}/G_b - c_4 u (T_m - T_a)/G_b - \dot{Q}_p / (A_a G_b) \quad (4.1.7)$$

$$T_m = (T_{out} + T_{in}) / 2 \quad (4.1.8)$$

Where $\eta_{SF}$: solar field (system) efficiency.

$\dot{Q}_{SF}$: useful output from the solar field, [W]

$A_a$ : total aperture area for the solar field, [m$^2$]

$T_{in}$ : HTF inlet (to the solar field) temperature, [K]

$T_{out}$ : HTF outlet (from the solar field) temperature, [K]

$T_m$ : HTF mean (across the solar field) temperature, [K]
\( t \): time, [s]
\( u \): wind speed, [m/s]
\( c_1 \): heat loss coefficient at \((T_m - T_a)=0\), [W/m\(^2\).K]
\( c_2 \): temperature dependence of the heat losses, [W/m\(^2\).K\(^2\)]
\( c_3 \): effective thermal capacitance, [J/ m\(^2\).K]
\( c_4 \): wind speed dependence of the heat loss, [J/ m\(^3\).K]
\((T_m - T_a)/G_b\): reduced temperature difference, [m\(^2\).K /W]

4.2. Intercept factor

The parabolic trough reflector has the shape of a cylindrical parabola that focuses parallel beams of radiation into a single line (the focus). The optical efficiency depends on the optical properties of the collector components and the intercept factor.

The intercept factor \( \gamma_n \) in equations 4.6 and 4.7 is defined as the fraction of the incident beam radiation that is intercepted by the receiver at normal incidence. Ideally, if the receiver is perfectly aligned along the focus and no mirror surface imperfections exist, and if sun were a point source, then the intercept factor is a function of the collector geometry characterized by the rim angle and the geometric concentration ratio (the ratio of aperture area to the absorber area).

However, in practice, there are optical errors associated with the operation of the collector that will affect the intercept factor in addition to the fact that solar rays are incident from different directions covering the solar disk. The intercept factor can be given in terms of collector geometry and optical errors as \(^{[27]}\)

\[
\gamma = \int_{-\infty}^{\infty} d\theta F(\theta) \frac{1}{\sqrt{2\pi} \sigma_{tot}} \exp \left( -\frac{\theta^2}{2\sigma_{tot}^2} \right) 
\]

\[(4.2.1)\]
\[
F(\theta) = \begin{cases} 
1 & \text{for } |\theta| < \theta_1 \\
\cot \frac{\psi}{2} \left( \frac{2\tan \frac{\psi}{2}}{\pi C \theta} - 1 \right) & \text{for } |\theta_1| < |\theta| < \theta_2 \\
0 & \text{for } |\theta| > \theta_2
\end{cases}
\]

(4.2.2)

With

\[
\theta_1 = \frac{\sin \psi}{\pi C} 
\]

(4.2.3)

\[
\theta_2 = \frac{2\tan \left( \frac{\psi}{2} \right)}{\pi C} 
\]

(4.2.4)

Where \(\psi\): the rim angle of the collector.

\(C\): the geometric concentration ratio.

\(F(\theta)\): angular acceptance function defined as the fraction of a uniform beam of parallel incident on the aperture at an angle \(\theta\) from the symmetry axis that would reach the receiver if the optics were perfect.

\(\sigma_{tot}\): the standard deviation of the total errors [mrad] (see section 4.2.1).

4.2.1. Optical errors

In reality, the solar rays are incident from a range of directions covering the solar disc. In addition, surface imperfections and receiver displacement are common results from manufacturing and assembly as well as the operation of concentrating collectors. The sun shape and the collector components imperfections are the sources of optical errors that are expected to take place during operation. Therefore, the intercept factor is a function of the geometry and the inaccuracies of the collector components. A comprehensive optical error analysis was presented by [Rabl & Bendt], the complete analysis is presented in reference [28] which follows a statistical characterization of the sun shape and the optical errors. The following discussion will be based on this analysis.

The various sources of optical errors are shown in figure 4.1. The optical errors can be characterized by a statistical distribution function. The error distributions are
usually well approximated by Gaussian or normal distribution with zero mean\textsuperscript{[27]}. Thus, the errors are represented by the standard deviation of the individual distribution assuming a zero mean as they usually have in solar applications\textsuperscript{[27]}.

The optical errors that are considered for the parabolic trough are:

- Slope errors: the deviation of the slope of mirror surface from the ideal parabolic shape.
- Specular errors: the non-specularity of the mirror surface.
- Tracking errors: associated with the accuracy of the tracking drive system.
- Receiver displacement error: the misalignment of the receiver with respect to the focal line of the collector.

All errors are assumed to be independent process and when averaged over time and the entire collector, they are assumed to have a normal distribution with zero mean.

Figure 4.1: Potential optical errors in parabolic trough collector.
Moreover, the solar rays are incident from different angles covering the solar disc causing oscillations in the Sun's shape and brightness. Approximation of the intensity distribution of the sun (solar brightness) across the solar disc by normal distribution is found to be adequately accurate for optical analysis of troughs when optical errors are large compared to the width of the sun\[^{37}\]. Thus, for statistical analysis of solar radiation intercepted by the collector, it is convenient to use the standard deviation of the solar brightness distribution as seen by the collector characterized by the root mean square (RMS) width of the sun $\sigma_{sun}$ [mrad].

A normal (Gaussian) distribution approximation for the optical errors and the sun shape permits the convolution calculations to reduce to a simple addition of the standard deviations and allows for the characterization of the errors with single error parameter\[^{37}\] $\sigma_{tot}$.

In equation 4.2.1, the standard deviation of the total errors (combined optical and sun shape) of the collector is given by

$$\sigma^2_{tot} = \sigma^2_{optical} + \sigma^2_{sun} \quad (4.2.5)$$

$$\sigma^2_{optical} = 4\sigma^2_{slope} + \sigma^2_{specular} + \sigma^2_{displacement} + \sigma^2_{tracking} \quad (4.2.6)$$

where $\sigma_{optical}$: standard deviation of the total optical errors [mrad]

$\sigma_{slope}$: standard deviation of slope errors [mrad]

$\sigma_{specular}$: standard deviation of specular errors [mrad]

$\sigma_{displacement}$: standard deviation of receiver displacement errors [mrad]

$\sigma_{tracking}$: standard deviation of tracking errors [mrad]
4.2.2. Optical measurements

The optical performance of the concentrating collectors is sensitive to the optical errors. In practice, there are many techniques of optical measurement used to analyze the optical errors and hence determining the intercept factor. Three of those techniques are briefly introduced hereinafter: photogrammetry, deflectometry, and absorber reflection.

The optical measurements for parabolic trough system under study was carried out using the photogrammetry test. The procedure and results are introduced in the next chapter.

4.2.2.1. Photogrammetry

Photogrammetry is a measurement technique that employs information from digital images to determine the geometric properties of objects\textsuperscript{[29]}. It is a valuable tool for the geometric analysis of large solar trough concentrators\textsuperscript{[30]}.

It involves the use of a set of photographs of a targeted collector, taken from different viewing positions, to obtain high-accuracy, three-dimensional (3-D) coordinate data of the target positions. The 3-D model is constructed using an evaluation software that analyze the digital photos of the targeted object. This method is useful for determining the slope deviation from the ideal shape of the collector. Figure 4.2 illustrates the setup of photogrammetric measurements for a Euro-Trough collector.

4.2.2.2. Deflectometry

Deflectometry uses the images of reflected regular patterns taken by a digital camera to calculate the local normal vectors of the reflecting surface using vector geometry\textsuperscript{[29]}. 
The system consists of the following basic components: a digital projector that projects regular line patterns on flat white target, a digital camera that takes images of the reflected line patterns seen in the mirror object, and a control unit. The specially developed evaluation software controls the measurement and uses digital image processing to calculate the local normal vectors of the reflecting surface.

The setup is shown in figure 4.3 where a digital camera near the target takes images of the mirror panels placed horizontally on a frame on the ground. The unambiguous identification of the reflected target points is achieved by codifying the target surface with a series of stripe patterns with sinusoidal brightness.

4.2.2.3. Absorber reflection method

This method was developed especially for evaluating the surface quality of the parabolic trough. Parabolic troughs concentrate the incoming parallel sunlight on a relatively small absorber placed in the focal line. Rays that come from the
absorber and are reflected on the concentrator take the same path, but in opposite direction.\textsuperscript{[31]}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{Setup of automatic deflectometric measurements.\textsuperscript{[29]}}
\end{figure}

A distant observer watching the concentrator observes the reflected image of the absorber tube, magnified due to the concentrating optics. The position of the reflection within the concentrator and the shape of its outer edges are very sensitive to variations in surface slope. This arrangement, known as distant observer technique, can be used to determine the normal vectors of the concentrator with high accuracy.\textsuperscript{[31]}

\section*{4.3. Angle of incidence calculations}

This section introduces the equations for the calculation of the angle of incidence ($\theta$) defined as the angle between solar rays and the surface normal. The angle of incidence has a major significance in evaluating the performance of the solar collectors. Let us first define the three basic angles (see figure 4.4): hour angle ($\omega$), latitude angle ($\phi$), and the declination angle ($\delta$).
4.3.1. Basic angles

4.3.1.1. Hour angle ($\omega$)

It is the angular distance between the meridian of the observer and the meridian whose plane contains the sun. The hour angle can be calculated by:

$$\omega = 15 (t_s - 12) \quad \text{(degrees)} \quad (4.3.1)$$

where $t_s$ is the solar time (equals 12 at solar noon) which is different from the local clock time (LCT). For any point on earth, the solar noon occurs when the point faces the sun and its meridian is in line with the solar rays. Solar time can be calculated (in hours) by:

$$t_s = LCT + \frac{EOT}{60} - LC - DLS \quad \text{(hours)} \quad (4.3.2)$$

Figure 4.4: Basic angles for the location Q.
where $EOT$ (equation of time) is a correction in minutes for the true solar time, $LC$ is the longitude correction in hours, and $DLS$ is the correction for daylight saving time which is one hour if the daylight saving time is in effect.

The equation of time varies over the year and can reach seventeen minutes. An approximation that is accurate within 30 seconds$^{[32]}$ of the equation of time is:

$$EOT = 0.258 \cos x - 7.416 \sin x - 3.648 \cos 2x - 9.228 \sin 2x \quad (\text{min}) \quad (4.3.3)$$

Where $x$ is an angle which is function of the day number $N$, starting from January 1$^{st}$ ($N = 1$)

$$x = \frac{360 (N-1)}{365.242} \quad (\text{degrees}) \quad (4.3.4)$$

the longitude correction accounts for the difference between local time and standard meridian time

$$LC = (\text{longitude of strd time zone meridian} - \text{local longitude})/15 \quad (\text{hour}) \quad (4.3.5)$$

For our system, the local longitude is 35.586$^\circ$ E and the longitude of standard time zone is 30$^\circ$ E.

4.3.1.2. Latitude angle ($\phi$)

The latitude angle is the angle between a line drawn from a point on the earth’s surface to the center of the earth, and the earth’s equatorial plane. Locations south of the equator have negative latitude angles and those to the north have positive latitude angles. The latitude angle of the system under study in this study is 31.71$^\circ$.

4.3.1.3. Declination angle ($\delta$)

It is the angle that solar orbit makes with the plane of the earth's equator. The angle varies as the earth rotates around the sun. the yearly variation of the declination angle is shown in figure 4.5.
Figure 4.5: Variation of declination angle\textsuperscript{32}.

Equation 4.3.6 is an approximation accurate within one degree\textsuperscript{32} for calculating the declination angle

\[ \sin \delta = 0.39795 \cos [0.98563(N-173)] \]

(4.3.6)

4.3.2. Solar angles

For solar power applications, we need to define the position of the sun relative to the site (any point on earth) in order to calculate the amount of solar energy that will be received by the solar system. The position of the sun can be described by two angles: the solar altitude angle ($\alpha$) and the solar azimuth angle ($\beta$). These angles are shown in figure 4.6.

Figure 4.6: Earth surface coordinate system for observer at point Q showing the solar azimuth angle $\beta$, the solar altitude angle $\alpha$. 
It is convenient to express the solar angles in terms of the three basic angles $\omega$, $\phi$ and $\delta$ in order to identify the sun’s position for any location at any time. Reference [32] provides a detailed derivation of the equations of solar angles as functions of the three basic angles.

4.3.2.1. Solar altitude angle ($\alpha$)

The solar altitude angle is the angle between the direction of the geometric center of the sun's apparent disk and a horizontal plane containing the observer. It is given by

$$\alpha = \sin^{-1}(\sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega) \quad \text{(degrees)} \quad (4.3.7)$$

4.3.2.2. Solar azimuth angle ($\beta$)

It is the angle, measured clockwise on the horizontal plane, from the north pointing coordinate axis to the projection of the sun’s central ray. It is calculated as

$$\beta' = \cos^{-1}\left[(\sin \delta \cos \phi - \cos \delta \sin \phi \cos \omega)/ \cos \alpha\right] \quad \text{(degrees)} \quad (4.3.8)$$

where if: $\sin \omega > 0$, then $\beta = 360^\circ - \beta'$

$\sin \omega \leq 0$, then $\beta = \beta'$

4.3.3. Angle of incidence ($\theta$)

As previously defined, the angle of incidence is the angle between the solar rays and the surface normal. Calculating $\theta$ is of great importance for solar system design and performance evaluation since the amount of collected solar energy is reduced by the cosine of this angle. Figure 4.7 depicts a fixed aperture that is oriented at angle $\Omega$ (aperture azimuth angle) and tilted at angle $\kappa$ (tilt angle). The angle of incidence for this aperture is given by

$$\cos \theta = \sin \alpha \cos \kappa + \cos \alpha \sin \kappa \cos (\Omega - \beta) \quad \text{(degrees)} \quad (4.3.9)$$
Figure 4.7: A fixed aperture with its orientation defined by the tilt angle ($\lambda$) and the aperture azimuth angle ($\Omega$)

For an aperture with a single-axis tracking system (such as parabolic trough), the aperture is rotated until the solar rays and the aperture normal are coplanar as illustrated in figure 4.8.

Figure 4.8: A single-axis tracking aperture rotating about the axis $r$. 
Figure 4.9: Single axis tracking system coordinates.

Figure 4.10: Rotation of the u, b, r coordinates from the z, e, n (fig. 4.5) coordinates about the z-axis (diagram shows view looking downward on the surface of the earth).

Figure 4.9 depicts a horizontal single-axis tracking aperture. The tracking angle ($\rho$) measures rotation about the tracking axis r with ($\rho=0$) when N is vertical. To describe this tracking scheme in terms of solar angles, the coordinates u, b, and r must be rotated by an angle $\Omega$ (see figure 4.10) from the z,e, and n coordinates that were used to describe the sun angles. The tracking angle can be calculated by\textsuperscript{[33]}

$$\tan \rho = \sin (\beta - \Omega) / \tan \alpha$$  \hspace{1cm} (4.3.10)

the value of the angle of incidence for this aperture is given by\textsuperscript{[33]}

$$\cos \theta = [1 - \cos^2 (\alpha) \cos^2 (\beta - \Omega)]^{1/2}$$  \hspace{1cm} (4.3.11)

for our system, the angle $\Omega = 71^\circ$. 

47
4.4. Shading losses

Shading losses are related to the field layout and the mutual shading between collectors that block the sun rays from reaching certain portion of the aperture area. The mutual shading effect is shown in figure 4.11 for collectors that have width \( W \) and spacing \( S \). For our system shown in figure 3.3, the spacing is 6.5m between the first and second rows and 4m between the second and third rows.

![Mutual collector shading](image)

In figure 4.11, \( W \) is the collector width which is 1800mm for PTC-1800. The effective collector width \( W_e \) is the non-shaded portion of the collector width. It can be written as

\[
W_e = X \cdot W \tag{4.4.1}
\]

Where \( X \in [0;1] \), A value of 0 for \( X \) means complete shading whereas a value of 1 for \( X \) means no shading of the collector. Also, \( X \) can be written as

\[
W/2 - W(1/2-X) = S \cdot \sin \alpha_p = X \cdot W
\]

\[
\Rightarrow X = S \cdot \sin \alpha_p / W \tag{4.4.2}
\]
Where $\alpha_p$ is the solar profile angle that is defined as the angle between the horizontal plane and the plane that contains the collector axis and the solar beam. From figure 4.12, $\alpha_p$ can written as

$$\tan \alpha_p = \tan \alpha \cdot \cos (90-\Omega) / \cos (\beta - 180) \quad (4.4.3)$$

![Figure 4.12: Solar profile angle.](image)

It is important to restrict $X$ to be in the interval $[0,1]$

$$X = \min \left[ \max(0; S \cdot \sin \alpha_p / W); 1 \right] \quad (4.4.4)$$

Substituting $X$ in equation 4.4.1 the effective can be finally written as

$$W_e = \min \left[ \max(0; S \cdot \sin \alpha_p / W); 1 \right]. W \quad (4.4.5)$$

We now define the row shading factor ($f_{RS}$) which accounts for the mutual row shading losses

$$f_{RS} = \frac{W_e}{W} \quad (4.4.6)$$
The total row shading effect in the solar field is expressed by the solar field row shading factor $F_{RS}$

$$F_{RS} = \frac{(W_e)_t}{W_t} \quad (4.4.7)$$

Where $(W_e)_t$ is the summation of the effective width $W_e$ for all collectors and $W_t$ is the summation of the total aperture width in the solar field.

**4.5. Incidence angle modifier**

Collector performance is always referenced to the normal irradiance that is normal to the aperture area. The effect of the angle of incidence in reducing the normal irradiance on the aperture area is included in the cosine factor (equation 4.3).

There are other losses related to the angle of incidence due to the variation of the mirror reflection and glass envelope absorption with the variation of the angle of incidence. The influence of these losses on the collector performance is measured by the incidence angle modifier $K(\theta)$.

The IAM (incidence angle modifier) is given as an empirical fit to experimental data for a given collector type. Thermal performance test for PTC-1800 was conducted at DLR facilities in Cologne, Germany. One of the results of this test was the IAM expressed in a polynomial function of $\theta$ (in degrees) as

$$K(\theta) = 1 - 5.782 \times 10^{-3} \theta + 1.485 \times 10^{-4} \theta^2 - 2.955 \times 10^{-6} \theta^3 \quad (4.5.1)$$

Since this IAM is a result of thermal test, the end losses as function of $\theta$ are included in this parameter. Figure 4.13 illustrates the variation of the IAM with $\theta$. 
4.6. Piping heat losses

A cross section in the solar field pipe is shown in figure 4.14 with the HTF flowing inside the pipe at temperature $T_m$ (the mean HTF temperature across the solar field), the heat losses from the HTF to the surroundings $\dot{Q}_p$ is governed by

$$\dot{Q}_p = U_p A_o (T_m - T_a) \quad (W) \quad (4.6.1)$$

$$A_o = \pi D^2 L_p \quad (m^2) \quad (4.6.2)$$

Where $A_o$: the outer surface area of the insulated pipe, [m$^2$].

$L_p$: total pipe length, [m].

$U_p$: the overall heat transfer coefficient of the insulated pipe, [W/m$^2$.K]
The basic model for calculating $U_p \text{[W/m}^2\text{.K]}$ is\textsuperscript{[34]}

$$U_p = \frac{1}{\frac{D_3}{D_1 h_m} + \frac{ln\left(\frac{D_2}{D_3}\right) D_3}{2 k_p} + \frac{ln\left(\frac{D_2}{D_3}\right) D_3}{2 k_i} + \frac{1}{h_a}} \quad (4.6.3)$$

Where $h_m$ : heat transfer coefficient inside the pipe at $T_m$ [W/m$^2$.K]

$h_a$ : heat transfer coefficient at the insulation outer surface at $T_a$ [W/m$^2$.K]

$k_p$ : thermal conductivity of pipe at $T_m$ [W/m.K]

$k_i$ : thermal conductivity of insulation at $T_m$ [W/m.K]

the thermal conductivity of carbon steel ranges from 55 W/m.K at 0.0°C to 45 W/m.K at 200°C \textsuperscript{[35]} while the thermal conductivity for Rockwool insulation ranges from 0.037 W/m.K at 50°C to 0.088 W/m.K at 300°C\textsuperscript{[34]}.

The calculations of the convective heat transfer coefficient $h_m$ will be carried out using the equations 4.6.4 - 4.6.8 for forced convection, equations 4.6.7 and 6.6.8 were introduced by Gnielinski \textsuperscript{[36]}.
\begin{align*}
  h_m &= k_w \frac{Nu}{D_1} \quad (4.6.4) \\
  Re &= D_1 V \frac{\rho_w}{\mu_w} \quad (4.6.5) \\
  Pr &= \frac{\mu_w c_{pw}}{k_w} \quad (4.6.6) \\
  Nu &= \frac{\left(\frac{1}{6}\right)(Re-1000)Pr}{1+12.7 \left(\frac{1}{6}\right)^{0.5} (Pr^{0.67}-1)} \quad (4.6.7) \\
  f &= (0.79 \ln Re - 1.64)^2 \quad (4.6.8)
\end{align*}

Where \( k_w \): thermal conductivity of the fluid (water) at \( T_m \) [W/m.K]

\( Nu \): Nusselt number [dimensionless]

\( Re \): Reynolds number [dimensionless]

\( Pr \): Prandtl number [dimensionless]

\( V \): average velocity of the fluid [m/s]

\( \rho_w \): density of water at \( T_m \) [kg/m\(^3\)]

\( c_{pw} \): specific heat of water at \( T_m \) [J/kg.K]

\( \mu_w \): dynamic viscosity of water at \( T_m \) [N.s/m\(^2\)]

\( f \): Moody friction factor [dimensionless]

Similarly, the convective heat transfer coefficient \( h_a \) will be calculated using the following equations for natural convection

\begin{align*}
  h_a &= k_a \frac{Nu}{D_3} \quad (4.6.9) \\
  Pr &= \frac{\mu_a c_{pa}}{k_a} \quad (4.6.10) \\
  Gr &= D_3^3 \frac{\rho_a^2 g \Delta T b}{\mu_a^2} \quad (4.6.11) \\
  Ra &= Gr Pr \quad (4.6.12) \\
  Nu &= \left[ 0.6 + \frac{0.387 Ra^{1/6}}{1+(0.559/Pr)^{9/16}} \right]^{2/3} \quad (4.6.13)
\end{align*}
Where \( k_a \) : thermal conductivity of air at \( T_a \), [W/m.K]

\[ c_{pa} \] : specific heat of air at \( T_a \), [J/kg.K]

\[ \mu_a \] : dynamic viscosity of air at \( T_a \), [N.s/m\(^2\)]

\( b \) : coefficient of expansion for air at \( T_a \), [1/K]

\( Gr \): Grashof number [dimensionless]

\( g \): gravitation = 9.81, [m/s\(^2\)]

\( Ra \): Rayleigh number [dimensionless]

\( \Delta T \): the temperature difference between the ambient and the outer surface, [K]. Since it will be very difficult to determine the outer surface temperature, the temperature difference will be assumed to be 10 K to simplify calculations.
5. Experimental Test and Results

In this chapter, the test procedure and results for optical quality of the parabolic trough field are presented. Furthermore, the identification of the performance model parameters is introduced along with the resulting efficiency curves of the solar field.

5.1. Optical quality test (Photogrammetric test)

As mentioned earlier, photogrammetry method was used to assess the optical quality (surface irregularities) of the parabolic trough collectors. The method involves the use of a set of images, taken from different viewing positions, of the targeted collector that has retro-reflective targets fixed on it. The images were analyzed using the software AICON 3D Studio.

5.1.1. Test setup & procedure

The first step was establishing the test setup as shown in figure 5.1. where retro-reflective targets (non-coded targets) are fixed on the mirror surface. A reference cross is also fixed to establish a reference point for measurements. In addition, a number of coded targets are distributed over the surface to allow for the identification –by the software- of the non-coded targets that are far from the reference point. 244 non-coded targets were fixed on the mirror and another 3 targets on the outer surface of the receiver. The coded target can be directly recognized by the software while the non-coded target requires a coded target in the same image to be recognized and given a unique number.

The next step was the image acquisition (see figure 5.2). Images for the collector were taken using the camera NikonD300-20mm which was preset to suite the illumination condition and the quality of the images required by the software for targets identification. The images were taken from different positions and different elevations in order to cover the entire collector area and to assure high level of
recognition of the non-coded targets by the software. Around 100 images were taken for the shown setup. Samples of the images are presented in appendix A. Finally, the data were analyzed by the Aicon 3D studio software which is described in the next section.

Figure 5.1: Photogrammetry test setup for our system.

Figure 5.2: Image acquisition of the test setup.
5.1.2. Measurements analysis and results

5.1.2.1. Measured surface shape and coordinate system

The initial analysis of the measurements was performed with the software “Aicon 3D studio” version 9.01.02. The software reads and processes the images to establish a 3D coordination system of the parabolic trough by assigning the origin point to the cross reference. Each coded and non-coded target is identified by a unique number and certain coordinates in reference to the origin point.

The 3D coordinate system was established for our measurements. Afterwards, the coordinate system was transformed by placing the origin point on one of non-coded targets that is fixed on the steel structure, and by new definition of the x and y axes using another two points on the steel structure. The new coordinate system is consistent with the one shown in figure 5.3.

Finally, the point of origin of the new coordinate system was transformed to be placed at a point (non-coded target) located on the vertex line of the parabolic shape. The software displays the coordinates of the measured points in 3D view and in tabulated form. Snapshots of the image processing and the resulting coordinate are provided in Appendix A.

Figure 5.3: 3D-Coordinate system for surface analysis.
5.1.2.2. Calculation of slope errors

The 3D-coordinates (in mm) of 244 non-coded targets were used to estimate the local slope errors. The surface of the collector was divided into 25 strips (200mm long) along the y-axis (see figure 5.4). Then the measured slope along the x-axis \((S_x)_m\) of the surface element containing each two adjacent points \((P_i\) and \(P_j\)) was calculated according to equation 5.2.1. It is to be noted that since the adjacent points along the x-axis are not perfectly aligned, the surface element was assumed to have no height deviation along the y-axis. The slope \((S_x)_m\) is illustrated in figure 5.5. The subscript \(m\) here designates measured data while the subscript \(d\) designates design data.

\[
(S_x)_m = \frac{(z_j)_m - (z_i)_m}{(x_j)_m - (x_i)_m} \text{ [rad]} \tag{5.2.1}
\]

Figure 5.4: Division of collector surface in stripes for slope error calculations.

Figure 5.5: Surface element containing adjacent measured points.
The design slope \((S_x)_d\) of the measured point is calculated by equations 5.2.2 and 5.2.3 using the design z-coordinate \((z_i)_d\) and the collector focal length \(f\):

\[
(S_x)_d = \frac{(z_j)_d - (z_i)_d}{(x_j)_m - (x_i)_m} \quad [\text{rad}] \quad (5.2.2)
\]

\[
(z_i)_d = \frac{(x_i)_d^2}{4f} \quad [\text{mm}] \quad (5.2.3)
\]

The slope error \(\Delta S_x\) defined as the deviation of the measured slope from the design slope is

\[
\Delta S_x = (S_x)_d - (S_x)_m \quad [\text{rad}] \quad (5.2.4)
\]

The calculations above were executed using a Matlab code which is shown in Appendix B. A sample of the code’s output is shown in table 5.1. The standard deviation \(\sigma_{slope}\) of the zero-mean Gaussian distribution (see section 4.2.1) of the local slope errors was calculated by

\[
\sigma_{slope} = \sqrt{\frac{\sum_1^n (\Delta S_x)^2}{n}} \quad [\text{rad}] \quad (5.2.5)
\]

where \(n\) is the number of calculated slopes used in the calculations \((n=244)\). The results of the calculations showed a maximum absolute slope error of 24.89 mrad, and a standard deviation \(\sigma_{slope} = 0.0099\) rad = 9.9 mrad. The frequency distribution of the local slope errors is shown in figure 5.6.

Table 5.1: A sample of the slope calculations output (stripe1).

<table>
<thead>
<tr>
<th>(x_m) (mm)</th>
<th>(y_m) (mm)</th>
<th>(z_m) (mm)</th>
<th>(z_d) (mm)</th>
<th>((s_x)_m) (rad)</th>
<th>((s_x)_d) (rad)</th>
<th>(\Delta S_x) (rad)</th>
<th>(\Delta z) (mm)</th>
<th>((\Delta s_x)^2) (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-877.286</td>
<td>9.6948</td>
<td>251.661</td>
<td>246.6767</td>
<td>-0.53387</td>
<td>-0.52506</td>
<td>0.008817</td>
<td>-3.98426</td>
<td>77.74586</td>
</tr>
<tr>
<td>-760.89</td>
<td>133.1091</td>
<td>189.52</td>
<td>185.562</td>
<td>-0.38531</td>
<td>0.013416</td>
<td>13.41585</td>
<td>-3.95795</td>
<td>179.985</td>
</tr>
<tr>
<td>-441.289</td>
<td>146.1586</td>
<td>62.0857</td>
<td>62.41546</td>
<td>-0.24335</td>
<td>-0.00643</td>
<td>-6.43212</td>
<td>0.329764</td>
<td>41.37222</td>
</tr>
<tr>
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<td>158.497</td>
<td>32.8647</td>
<td>32.40112</td>
<td>-0.10159</td>
<td>0.000262</td>
<td>0.261766</td>
<td>-0.46358</td>
<td>0.068521</td>
</tr>
<tr>
<td>0.9791</td>
<td>151.3118</td>
<td>0.3804</td>
<td>0.000307</td>
<td>0.10405</td>
<td>-0.10255</td>
<td>-0.0015</td>
<td>-1.49959</td>
<td>-0.38009</td>
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<td>318.9767</td>
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<td>33.4679</td>
<td>32.61094</td>
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<td>566.5936</td>
<td>129.4658</td>
<td>104.7351</td>
<td>102.8937</td>
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<td>0.431206</td>
<td>-0.01763</td>
<td>-17.6318</td>
<td>-1.84141</td>
</tr>
</tbody>
</table>

59
5.1.2.3. Calculation of receiver displacement Errors

Three non-coded targets where used to estimate the location of the receiver with respect to the vertex of the parabolic shape and to estimate the average deviation of the receiver centerline from the ideal location of the focus which is designed to be at x=0.0 and z=780mm (focal length). The targets were fixed on the outer surface of the receiver glass envelope along the center line of the receiver (as determined by bare eye). Thus, on the z-axis, the measured points were compared to an imaginary points that would be located on the outer surface of the receiver if the receiver was perfectly located along the focus. The outer diameter of the receiver is 65mm. consequently, the z-coordinate of the imaginary points is 812.5mm (=780+65/2). The resulted deviation from the focus in x-direction \(d_x\) and in z-direction \(d_z\) are shown in table 5.2.

Table 5.2: The average deviation of the receiver location from the focus.

<table>
<thead>
<tr>
<th>point no.</th>
<th>x-real (mm)</th>
<th>y-real (mm)</th>
<th>z-real (mm)</th>
<th>x-design (mm)</th>
<th>x-diff (dx) (mm)</th>
<th>z-design (mm)</th>
<th>z-diff (dz) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1036</td>
<td>2.8064</td>
<td>248.8338</td>
<td>804.8985</td>
<td>0</td>
<td>2.8064</td>
<td>812.5</td>
<td>7.6015</td>
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<td>0.7321</td>
<td>1136.562</td>
<td>804.712</td>
<td>0</td>
<td>0.7321</td>
<td>812.5</td>
<td>7.788</td>
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<td>2.0346</td>
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<td>803.719</td>
<td>0</td>
<td>2.0346</td>
<td>812.5</td>
<td>8.781</td>
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<tr>
<td>average</td>
<td>1.8577</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.057</td>
</tr>
</tbody>
</table>

Figure 5.6: Frequency distribution of local slope errors.
The receiver displacement error is defined as the angular deviation of the location of the receiver centerline from the design focus as seen from local points \((P_i)\) on the mirror. The methodology of calculating the local displacement error \(\theta_d\) is illustrated in figure 5.7. The calculations for the local displacement errors \(\theta_d\) and the standard deviation \(\sigma_{\text{displacement}}\) were performed with Excel using the following equations

\[
\theta_d = \tan^{-1} \left( \frac{m}{h} \right) \quad \text{[rad]} \quad (5.2.6)
\]

\[
\sigma_{\text{displacement}} = \sqrt{\frac{\sum_{i=1}^{n} (\theta_d)_i^2}{n}} \quad \text{[rad]} \quad (5.2.7)
\]

\(m\) and \(h\) are defined in figure 5.7 and \(n\) is the number of points taken along the \(x\)-axis to calculate the local slope errors. The local slope errors were calculated for 19 points (point per 10cm) along the collector width. Then, the standard deviation was calculated.

See figure 5.7b

\(f\): focal length

\(\theta_p\): position angle

\(h\): distance from \(P_i\) to the focus

\(\theta_d\): local displacement error

\(h = \frac{(f-g)}{\cos \theta_p}\)

\(\theta_p = \tan \left[ \frac{x}{(f-g)} \right]\)

\(\theta_d = \tan \left( \frac{m}{h} \right)\)

\(g = \frac{x^2}{4f}\)

Figure 5.7a: local receiver displacement error calculations.
Figure 5.7b: local receiver displacement error calculations.

The results show a maximum local error of 7.7 mrad at x = 800 mm and at x = 700 mm. The local errors are listed in Table 5.3. The resulting standard deviation $\sigma_{\text{displacement}} = 0.0053 \text{ rad} = 5.3 \text{ mrad}$.

Table 5.3: Results of receiver displacement errors.

<table>
<thead>
<tr>
<th>x (mm)</th>
<th>g (mm)</th>
<th>$\theta_p$ (rad)</th>
<th>b (rad)</th>
<th>m (mm)</th>
<th>h (mm)</th>
<th>$\theta_d$ (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-900</td>
<td>259.6154</td>
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<td>2.39137</td>
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<td>2.292517</td>
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<td>0.502005</td>
<td>0.842809</td>
<td>5.501417</td>
<td>831.2821</td>
<td>0.00662</td>
</tr>
<tr>
<td>500</td>
<td>80.12821</td>
<td>0.620336</td>
<td>0.724479</td>
<td>6.191623</td>
<td>860.1282</td>
<td>0.00720</td>
</tr>
<tr>
<td>600</td>
<td>115.3846</td>
<td>0.734348</td>
<td>0.610467</td>
<td>6.774825</td>
<td>895.3846</td>
<td>0.00757</td>
</tr>
<tr>
<td>700</td>
<td>157.0513</td>
<td>0.843575</td>
<td>0.50124</td>
<td>7.251132</td>
<td>937.0513</td>
<td>0.00774</td>
</tr>
<tr>
<td>800</td>
<td>205.1282</td>
<td>0.947703</td>
<td>0.397112</td>
<td>7.62481</td>
<td>985.1282</td>
<td>0.00774</td>
</tr>
<tr>
<td>900</td>
<td>259.6154</td>
<td>1.046557</td>
<td>0.298258</td>
<td>7.903185</td>
<td>1039.615</td>
<td>0.00760</td>
</tr>
</tbody>
</table>
5.1.2.4. Calculation of total optical errors and intercept factor

- Total optical errors

In order to calculate the standard deviation of the total errors $\sigma_{\text{tot}}$, the other two optical errors (specular and tracking errors) need to be analyzed. Since we aim at estimating the intercept factor at normal incidence, the tracking errors can be overlooked in this study.

The reflectivity of the mirror that is used to calculate the optical efficiency is the solar-weighted specular reflectivity and averaged over the surface of the mirror. Also, the reflector material (Aluminium) has low diffusive reflectance, consequently, the specular errors are not considered in the calculation of the total errors.

It is to be noted that the purpose here is to estimate the optical errors and calculate the intercept factor to be used in an empirical performance model rather for theoretical performance calculation during the operation of the collector or the design of the collector. Accordingly, equation 4.2.6 is reduced to

$$\sigma_{\text{optical}}^2 = 4\sigma_{\text{slope}}^2 + \sigma_{\text{displacement}}^2$$

(5.2.8)

substituting ($\sigma_{\text{slope}} = 9.9 \text{ millirad}$) and ($\sigma_{\text{displacement}} = 5.3 \text{ millirad}$) in equation 5.2.8, we get $\sigma_{\text{optical}} = 20.5 \text{ millirad}$.

Reference [27] provides an approximation of the RMS width of the sun $\sigma_{\text{tot}}$ for line-focusing collectors to be 2.6 millirad in very clear sky conditions. This value is adopted for our calculations since the effect of different weather conditions are characterized by the empirical performance model of the system (equation 4.1.5).

Recalling equation 4.2.5, with ($\sigma_{\text{optical}} = 20.5 \text{ millirad}$) and ($\sigma_{\text{sun}} = 2.6 \text{ millirad}$), we get $\sigma_{\text{tot}} = 20.6 \text{ millirad}$.
- Intercept factor

We now have the total errors $\sigma_{tot}$ that is required to calculate the intercept factor at normal incidence angle $\gamma_n$ using equation 4.2.1. For parabolic trough with cylindrical receiver, the equation has been evaluated numerically and plotted\cite{28} versus $(\sigma_{tot}C)$ for different rim angles $\Psi$ (figure 5.8). This figure was used to determine the intercept factor of our trough using the characteristics of the PTC-1800 trough ($\Psi = 60^\circ$, $C = 15$ and $\sigma_{tot}C = 309$). The resulting intercept factor $\gamma_n = 0.72$ (see figure 5.9).

![Figure 5.8: Intercept factor vs $(\sigma_{tot}C)$ for different rim angles for a cylindrical receiver (Gaussian approximation).\cite{28}](image)

Accordingly, the optical efficiency of the collector can be calculated by substituting $\gamma_n = 0.72$, $\rho_m = 0.85$, $(\tau\alpha_c)_e = 0.865$ in equation 4.6. The resulting optical efficiency at normal incidence is 0.53 (53%).
Figure 5.9: Intercept factor for the tested trough

5.2. Overall system performance model

The system performance is characterized by equation (4.1.7) which represents an empirical model to estimate the solar field efficiency at any given operating conditions. The parameters $c_1$ through $c_4$ will be determined using measurement data as introduced hereinafter.

5.2.1. Measurements conditions and data

- Measurements conditions

The conditions under which the measurements were taken are not complying with the conditions of the steady-state test. However, the measurement conditions are very similar to that of the quasi-dynamic test except for the collector inlet temperature that is allowed to vary within ±1.0 K which is not possible to achieve in our demonstration plant.
- Measurements data

Unfortunately, it was not possible to take measurements on the system over the course of the thesis period due to the unstable operation caused by continuous tripping of the absorption chiller. Therefore, the identification of the model parameters will be based on measurements taken on 12\textsuperscript{th} July 2010. The series of the measurements is shown in Table 5.4.

Table 5.4: System measurements for empirical parameters identification.

<table>
<thead>
<tr>
<th>No.</th>
<th>Day (year 2010)</th>
<th>Time</th>
<th>HTF inlet temp. (T_{in} \text{[°C]})</th>
<th>HTF outlet temp. (T_{out} \text{[°C]})</th>
<th>ambient temp. (T_a \text{[°C]})</th>
<th>HTF flow rate (V' \text{[l/min]})</th>
<th>global horizontal irradiance (G \text{[W/m}^2)]</th>
<th>wind speed (u \text{[m/s]})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12-Jul</td>
<td>12:34:08</td>
<td>57.18</td>
<td>67.21</td>
<td>40.33</td>
<td>62.95</td>
<td>984.21</td>
<td>3.00</td>
</tr>
<tr>
<td>2</td>
<td>12-Jul</td>
<td>12:34:58</td>
<td>60.23</td>
<td>69.80</td>
<td>39.22</td>
<td>62.95</td>
<td>983.89</td>
<td>1.93</td>
</tr>
<tr>
<td>3</td>
<td>12-Jul</td>
<td>12:38:43</td>
<td>67.15</td>
<td>76.11</td>
<td>38.76</td>
<td>62.95</td>
<td>983.74</td>
<td>2.07</td>
</tr>
<tr>
<td>4</td>
<td>12-Jul</td>
<td>12:39:23</td>
<td>69.75</td>
<td>78.52</td>
<td>39.30</td>
<td>62.95</td>
<td>983.71</td>
<td>0.78</td>
</tr>
<tr>
<td>5</td>
<td>12-Jul</td>
<td>12:40:08</td>
<td>70.98</td>
<td>79.28</td>
<td>39.22</td>
<td>62.95</td>
<td>984.60</td>
<td>2.10</td>
</tr>
<tr>
<td>6</td>
<td>12-Jul</td>
<td>12:42:58</td>
<td>75.91</td>
<td>83.64</td>
<td>38.89</td>
<td>62.95</td>
<td>986.05</td>
<td>1.13</td>
</tr>
<tr>
<td>7</td>
<td>12-Jul</td>
<td>12:43:08</td>
<td>76.48</td>
<td>84.25</td>
<td>39.22</td>
<td>62.95</td>
<td>985.90</td>
<td>0.37</td>
</tr>
<tr>
<td>8</td>
<td>12-Jul</td>
<td>12:44:38</td>
<td>79.04</td>
<td>86.46</td>
<td>38.70</td>
<td>62.96</td>
<td>988.03</td>
<td>1.54</td>
</tr>
<tr>
<td>9</td>
<td>12-Jul</td>
<td>12:47:13</td>
<td>84.26</td>
<td>91.30</td>
<td>39.37</td>
<td>62.95</td>
<td>990.09</td>
<td>0.69</td>
</tr>
<tr>
<td>10</td>
<td>12-Jul</td>
<td>12:47:23</td>
<td>84.61</td>
<td>91.38</td>
<td>39.22</td>
<td>62.96</td>
<td>991.37</td>
<td>1.99</td>
</tr>
<tr>
<td>11</td>
<td>12-Jul</td>
<td>12:49:18</td>
<td>88.16</td>
<td>94.45</td>
<td>38.47</td>
<td>63.16</td>
<td>989.99</td>
<td>2.80</td>
</tr>
<tr>
<td>12</td>
<td>12-Jul</td>
<td>12:49:58</td>
<td>88.48</td>
<td>94.66</td>
<td>37.94</td>
<td>62.96</td>
<td>989.80</td>
<td>2.05</td>
</tr>
<tr>
<td>13</td>
<td>12-Jul</td>
<td>12:51:43</td>
<td>91.97</td>
<td>97.77</td>
<td>38.81</td>
<td>62.95</td>
<td>990.06</td>
<td>1.57</td>
</tr>
<tr>
<td>14</td>
<td>12-Jul</td>
<td>12:54:53</td>
<td>97.77</td>
<td>102.46</td>
<td>37.43</td>
<td>62.96</td>
<td>989.93</td>
<td>1.11</td>
</tr>
<tr>
<td>15</td>
<td>12-Jul</td>
<td>12:54:58</td>
<td>98.20</td>
<td>102.56</td>
<td>37.35</td>
<td>62.96</td>
<td>989.70</td>
<td>1.91</td>
</tr>
</tbody>
</table>

In order to calculate the useful output \(\dot{Q}_{SF}\) using the measurement data (equation 4.1.6), the mass flow is calculated by substituting the measured volume flow rate \(\dot{V}\) in the equation

\[
\dot{m} = \dot{V} \bar{\rho}_w \tag{5.2.1}
\]

Where \(\bar{\rho}_w\) is the average density of the HTF between inlet and outlet.

The solar field efficiency in the model is expressed in term of the incident beam irradiance \(G_b\) while the measured radiation is the global irradiance \(G\). empirical correlations is used to estimate the beam irradiance from the measured global...
irradiance. This will add to the uncertainty of the model, however, this would be acceptable because the purpose here is to illustrate the methodology of the model development rather than having a highly accurate system model taking into account the available measurement instruments and data.

In an average sense beam, diffuse, and hemispherical insolation are correlated with each other. To a good approximation the correlations for instantaneous insolation are independent of incidence angle if the solar radiation is expressed as fraction of extraterrestrial radiation. One such correlation [Erbs et al., 1982] correlates the diffuse irradiance to the global irradiance

\[ G_d/G = \begin{cases} 
1.0 - 0.09k_T & \text{for } k_T \leq 0.22 \\
0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & \text{for } 0.22 \leq k_T \leq 0.8 \\
0.165 & \text{for } k_T \leq 0.8 
\end{cases} \] (5.2.2)

With the hourly clearness index \( k_T \)

\[ k_T = G / [G_0,\text{eff} \cos (\theta_z)] \] (5.2.3)

\[ G_0,\text{eff} = 1361 [1 + 0.033 \cos (360 N/365)] \]

where \( G_0,\text{eff} \) is the effective solar constant.

It must be noted that the data used for global radiation in equation 5.2.3 is the hourly data. The average daily data for \( k_T \) for the system site were obtained from the free online source: Atmospheric Science Data Center (see section 6.2). It was found that \( k_T \) ranges between 0.67 – 0.74 for the system site throughout the years 2000 – 2004 for 12th June during which the measurements were taken. Thus, an average value of \( k_T \) (0.72) will be substituted in equation 5.2.2 to calculate the diffuse irradiance \( G_d \). The obtained value of \( G_d \) will be substituted in equation 4.2 to get the beam irradiance \( G_b \) which will be used to calculate the beam irradiance on the aperture \( G_b \) using equation 4.3.
With the approximation of $G_b$, we have all data required to determine the empirical parameters of the performance model with the model terms calculated as follows (a sample of the calculations is presented in Appendix C):

- $F_{RS}$ → equation 4.4.7
- $K(\theta)$ → equation 4.5.1
- $\theta$ → equation 4.3.11 (using data in table 5.4)
- $\eta_{op,n}$ → equation 4.6 (using data in table 3.1)
- $T_m$ → equation 4.1.8 (using data in table 5.4)
- $T_a$ → table 5.4
- $G_b$ → equations 4.2, 4.3 and 5.2.2 (using data in table 5.4)
- $u$ → table 5.4
- $\dot{Q}_p$ → equation 4.6.1
- $\dot{Q}_{SF}$ → equations 4.1.6 and 5.2.1 (using data in table 5.4)

It should be noted that the angle of incidence calculations assume no tracking errors since it is impossible to evaluate the tracking drive performance and hence the determination of the tracking errors.

5.2.2. Model parameters identification

The mathematical tool that will be used for the identification of the empirical parameters is the Multiple Linear Regression (MLR) method. Linear means that the model has to be written as a sum of terms where the parameters has to be a multiple in front of the terms, so, the equation behind the individual terms can still be non-linear in spite of the description “Linear” of the method\cite{25} which is the case in our model. MLR is an accepted tool by the previously mentioned European standard (EN 12975) for parameters identification. MLR uses a fast, non-iterative matrix method. The advantage of the iterative method is a high flexibility with respect to the input data as well as to the collector model\cite{38}. 
To apply the MLR method on our model, equation 5.2.1 should be rearranged to take the general form

\[ y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 \]  
(5.2.4)

Thus, equation 4.1.7 is rewritten as

\[
F_{RS} K(\theta) \eta_{op,n} - \left\{ \left( \dot{Q}_S + \dot{Q}_p \right) / (A_a G_b) \right\} = c_1(T_m - T_a)/G_b + c_2(T_m - T_a)^2/G_b + c_3 (dT_m/dt)/G_b + c_4 u(T_m - T_a)/ G_b
\]  
(5.2.5)

So, for our model,

\[ y = F_{RS} K(\theta) \eta_{op,n} - \left\{ \left( \dot{Q}_S + \dot{Q}_p \right) / (A_a G_b) \right\}, \]

\[ x_1 = (T_m - T_a)/G_b, \quad x_2 = (T_m - T_a)^2/G_b, \quad x_3 = (dT_m/dt)/G_b, \quad x_4 = u(T_m - T_a)/ G_b \]

\[ b_0 = 0, \quad b_1 = c_1, \quad b_2 = c_2, \quad b_3 = c_3, \quad b_4 = c_4. \]

MLR uses the least square method to define an objective function \( L \) that should be minimized with respect to the parameters (\( b_0 \) through \( b_3 \))

\[
L = \sum_{i=1}^{n} (y_i - y^*_i)^2 \rightarrow \text{min}
\]  
(5.2.7)

Where \( y_i \) is the measured value, \( y^*_i \) is the fitted value (as calculated by the model) and \( n \) is the number of observation (measurements data). The objective function here is the sum of residual (error) squared for the measured data set used in model fitting. The residual is defined as the difference between measured and fitted values. The mean square error (MSE) of the regression is given by [Kratzenberg, 2005]

\[
MSE = \frac{ \sum_{i=1}^{n} (y_i - y^*_i)^2 }{n-k}
\]  
(5.2.8)

Where \( k \) is the number of regression coefficients (\( b_0 \) through \( b_3 \)). For our model \( k=5 \).

5.2.3. Results and efficiency curves

MLR method was applied on the data series in table 5.4 using the data analysis tool in Excel. The parameters resulted from regression are listed in table 5.5. In
addition, the residuals (errors) of the modeled values \( y^* \) are shown in table 5.6. The results show a maximum error of \( y^* \) with respect to \( y \) ((\( y - y^* \))/\( y \)) of 4.8%.

Table 5.5: The results of empirical parameters identification.

<table>
<thead>
<tr>
<th>( c_1 (= b_1) )</th>
<th>( c_2 (= b_2) )</th>
<th>( c_3 (= b_3) )</th>
<th>( c_4 (= b_3) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7336</td>
<td>0.0293</td>
<td>459.0131</td>
<td>0.0163</td>
</tr>
</tbody>
</table>

Table 5.6: The residual (error) of the modeled values \( y^* \).

<table>
<thead>
<tr>
<th>No.</th>
<th>( y )</th>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>( x_3 )</th>
<th>( x_4 )</th>
<th>( y^* )</th>
<th>( y - y^* )</th>
<th>( (y - y^*)/y )</th>
<th>( (y - y^*)^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0940</td>
<td>0.0279</td>
<td>0.6103</td>
<td>6E-05</td>
<td>0.0837</td>
<td>0.0958</td>
<td>-0.0018</td>
<td>-0.0187</td>
<td>3.1E-06</td>
</tr>
<tr>
<td>2</td>
<td>0.1130</td>
<td>0.0329</td>
<td>0.8493</td>
<td>6E-05</td>
<td>0.0637</td>
<td>0.1112</td>
<td>0.0018</td>
<td>0.0162</td>
<td>3.35E-06</td>
</tr>
<tr>
<td>3</td>
<td>0.1376</td>
<td>0.0420</td>
<td>1.3805</td>
<td>6E-05</td>
<td>0.0869</td>
<td>0.1429</td>
<td>-0.0053</td>
<td>-0.0389</td>
<td>2.86E-05</td>
</tr>
<tr>
<td>4</td>
<td>0.1451</td>
<td>0.0445</td>
<td>1.5503</td>
<td>6E-05</td>
<td>0.0348</td>
<td>0.1514</td>
<td>-0.0063</td>
<td>-0.0434</td>
<td>3.97E-05</td>
</tr>
<tr>
<td>5</td>
<td>0.1655</td>
<td>0.0459</td>
<td>1.6463</td>
<td>6E-05</td>
<td>0.0961</td>
<td>0.1575</td>
<td>0.0079</td>
<td>0.0479</td>
<td>6.28E-05</td>
</tr>
<tr>
<td>6</td>
<td>0.1890</td>
<td>0.0522</td>
<td>2.1332</td>
<td>6E-05</td>
<td>0.0592</td>
<td>0.1821</td>
<td>0.0069</td>
<td>0.0363</td>
<td>4.69E-05</td>
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<tr>
<td>7</td>
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<td>0.0525</td>
<td>2.1596</td>
<td>6E-05</td>
<td>0.0197</td>
<td>0.1828</td>
<td>0.0040</td>
<td>0.0214</td>
<td>1.6E-05</td>
</tr>
<tr>
<td>8</td>
<td>0.2017</td>
<td>0.0561</td>
<td>2.4720</td>
<td>6E-05</td>
<td>0.0862</td>
<td>0.1993</td>
<td>0.0024</td>
<td>0.0119</td>
<td>5.78E-06</td>
</tr>
<tr>
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<td>0.2174</td>
<td>0.0616</td>
<td>2.9807</td>
<td>6E-05</td>
<td>0.0426</td>
<td>0.2230</td>
<td>-0.0055</td>
<td>-0.0254</td>
<td>3.05E-05</td>
</tr>
<tr>
<td>10</td>
<td>0.2292</td>
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<td>3.0215</td>
<td>6E-05</td>
<td>0.1236</td>
<td>0.2261</td>
<td>0.0031</td>
<td>0.0137</td>
<td>9.8E-06</td>
</tr>
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<td>3.5520</td>
<td>6E-05</td>
<td>0.1883</td>
<td>0.2519</td>
<td>-0.0053</td>
<td>-0.0216</td>
<td>2.84E-05</td>
</tr>
<tr>
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<td>6E-05</td>
<td>0.1396</td>
<td>0.2561</td>
<td>-0.0041</td>
<td>-0.0162</td>
<td>1.66E-05</td>
</tr>
<tr>
<td>13</td>
<td>0.2672</td>
<td>0.0714</td>
<td>4.0011</td>
<td>6E-05</td>
<td>0.1119</td>
<td>0.2710</td>
<td>-0.0038</td>
<td>-0.0144</td>
<td>1.48E-05</td>
</tr>
<tr>
<td>14</td>
<td>0.3120</td>
<td>0.0799</td>
<td>5.0065</td>
<td>6E-05</td>
<td>0.0886</td>
<td>0.3149</td>
<td>-0.0029</td>
<td>-0.0092</td>
<td>8.32E-06</td>
</tr>
<tr>
<td>15</td>
<td>0.3272</td>
<td>0.0803</td>
<td>5.0609</td>
<td>6E-05</td>
<td>0.1537</td>
<td>0.3183</td>
<td>0.0089</td>
<td>0.0272</td>
<td>7.94E-05</td>
</tr>
</tbody>
</table>

\[ \Sigma (y - y^*)^2 = 0.000394 \]

\[ \text{MSE} = 3.94E-05 \]

In order to assess the validity of the model, 14 sample of measurements - taken on 13th July, 2010- were used to compare the measured efficiency \( \eta_{SF} \) with the modeled efficiency \( \eta^*_{SF} \). The samples and the results are shown in table 5.7 and figure 5.10. The results show a maximum error of \( \eta^*_{SF} \) with respect to \( \eta_{SF} \) ((\( \eta_{SF} - \eta^*_{SF} \))/\( \eta_{SF} \)) of 10.1%. It should be pointed out that the use of outdated measurements for parameter identification and for validation of the model is a source of model uncertainty and will entail errors.
Table 5.7: Measurement samples and results of model validation.

<table>
<thead>
<tr>
<th>Data sample no.</th>
<th>Time</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>$T_{a}$ [°C]</th>
<th>$V'$ [liter/m]</th>
<th>$G$ [W/m²]</th>
<th>$u$ [m/s]</th>
<th>$\eta_{SF}$</th>
<th>$\eta_{SF}^*$</th>
<th>$(\eta_{SF} - \eta_{SF}^*)/\eta_{SF}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10:40:28</td>
<td>48.24</td>
<td>56.30</td>
<td>36.71</td>
<td>62.95</td>
<td>890.69</td>
<td>1.18</td>
<td>0.389</td>
<td>0.383</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>10:41:28</td>
<td>51.16</td>
<td>58.29</td>
<td>37.08</td>
<td>62.95</td>
<td>892.25</td>
<td>0.92</td>
<td>0.343</td>
<td>0.374</td>
<td>-9.0</td>
</tr>
<tr>
<td>3</td>
<td>10:45:13</td>
<td>57.36</td>
<td>64.63</td>
<td>36.50</td>
<td>62.95</td>
<td>906.36</td>
<td>0.87</td>
<td>0.344</td>
<td>0.323</td>
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<td>58.75</td>
<td>66.04</td>
<td>36.32</td>
<td>62.95</td>
<td>910.91</td>
<td>1.16</td>
<td>0.343</td>
<td>0.364</td>
<td>-6.4</td>
</tr>
<tr>
<td>5</td>
<td>10:48:38</td>
<td>63.21</td>
<td>70.00</td>
<td>37.05</td>
<td>62.95</td>
<td>916.64</td>
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</tr>
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<td>6</td>
<td>10:49:23</td>
<td>64.81</td>
<td>72.41</td>
<td>36.98</td>
<td>62.95</td>
<td>921.49</td>
<td>1.00</td>
<td>0.352</td>
<td>0.388</td>
<td>-10.1</td>
</tr>
<tr>
<td>7</td>
<td>10:51:08</td>
<td>67.15</td>
<td>73.61</td>
<td>37.35</td>
<td>62.95</td>
<td>925.16</td>
<td>1.28</td>
<td>0.298</td>
<td>0.308</td>
<td>-3.4</td>
</tr>
<tr>
<td>9</td>
<td>10:52:38</td>
<td>70.47</td>
<td>75.55</td>
<td>36.07</td>
<td>62.95</td>
<td>927.76</td>
<td>2.10</td>
<td>0.234</td>
<td>0.241</td>
<td>-3.0</td>
</tr>
<tr>
<td>10</td>
<td>10:53:18</td>
<td>70.76</td>
<td>76.86</td>
<td>36.37</td>
<td>62.95</td>
<td>927.76</td>
<td>1.53</td>
<td>0.281</td>
<td>0.294</td>
<td>-4.8</td>
</tr>
<tr>
<td>11</td>
<td>10:58:03</td>
<td>79.78</td>
<td>85.45</td>
<td>35.68</td>
<td>62.95</td>
<td>943.93</td>
<td>1.64</td>
<td>0.256</td>
<td>0.243</td>
<td>4.9</td>
</tr>
<tr>
<td>12</td>
<td>10:59:28</td>
<td>81.55</td>
<td>86.62</td>
<td>36.15</td>
<td>62.95</td>
<td>947.55</td>
<td>1.21</td>
<td>0.227</td>
<td>0.205</td>
<td>9.8</td>
</tr>
<tr>
<td>13</td>
<td>11:02:53</td>
<td>85.72</td>
<td>91.46</td>
<td>36.40</td>
<td>62.95</td>
<td>957.70</td>
<td>1.01</td>
<td>0.254</td>
<td>0.254</td>
<td>0.0</td>
</tr>
<tr>
<td>14</td>
<td>11:05:08</td>
<td>89.57</td>
<td>94.58</td>
<td>36.90</td>
<td>62.95</td>
<td>961.55</td>
<td>0.79</td>
<td>0.221</td>
<td>0.231</td>
<td>-4.3</td>
</tr>
</tbody>
</table>

Figure 5.10: Comparison of measured and modeled efficiency for model validation.
According to the performance model (equation 4.1.7), the solar field efficiency during steady state operation \((dT_m/dt = 0)\) is a function of the row shading factor \((F_{RS})\), the angle of incidence \((\theta)\), the wind speed \((u)\), and the reduced temperature difference \((T_m - T_a)/G_b\). Figure 5.11 and 5.12 depict the efficiency curve of the solar field for different values of \(\theta\) and \(u\).

The highest efficiency of the system is realized when the mean HTF temperature is equal to the ambient temperature (no thermal losses). This efficiency represents the optical efficiency at the given angle of incidence, it is relatively low (0.53 at \(\theta=0\)) due to the low intercept factor (0.72) and the low mirror reflectivity (0.85). The efficiency decreases with the increase of the temperature difference \((T_m - T_a)\) or the decrease of the incident beam irradiance \(G_b\). Although the performance model is non-linear, the efficiency curves seem to be linear on the graphs. This can be attributed to the small range of \((T_m - T_a)/G_b\) used in the graphs and the small effect of the parameter \((c_2)\) of the non-linear term in the model compared to the parameter of the linear term \((c_1)\) at low values of \((T_m - T_a)/G_b\).

![Figure 5.11: Solar field efficiency curve at different values of \(\theta\). \((u = 1.0\) m/s)](image-url)
Figure 5.12: Solar field efficiency curve at different values of \( u \). (\( \theta = 0^0 \))

It is obvious that the efficiency has higher sensitivity to the variation of the angle of incidence than that to the variation of wind speed. Noticeable—though small—reductions in efficiency with the increase of the wind speed can be seen in figure 5.12 at high values of \( (T_m - T_a)/G_b \). Based on this observation, the MLR was applied again on the data series with the elimination of the wind speed dependence parameter \( c_4 \). Table 5.8 shows the results of the new regression.

Table 5.8: The empirical parameters for no-wind-dependence regression.

<table>
<thead>
<tr>
<th>( c_1 ) (= ( b_1 ))</th>
<th>( c_2 ) (= ( b_2 ))</th>
<th>( c_3 ) (= ( b_3 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>[W/(m(^2).K)]</td>
<td>[W/(m(^2).K(^2))]</td>
<td>[J/(m(^3).K)]</td>
</tr>
<tr>
<td>1.6868</td>
<td>0.0302</td>
<td>490.5924</td>
</tr>
</tbody>
</table>

It can be seen that the elimination of \( c_4 \) has no major effect on the other three parameters and hence on the modeled efficiency curves. The impact of ignoring wind-dependence losses is visually illustrated in figure 5.13.
Figure 5.13: The efficiency curves modeled with and without the wind-dependence parameter $c_4$. ($\theta = 0^\circ$)

5.2.4. Performance model uncertainty

Some assumptions were made during the development of the performance model and during calculations. These assumptions are sources of uncertainties besides other sources that are found in any system testing. The uncertainty sources for our model are:

- The accuracy of the sensors and instrumentation used for measurements.
- The estimation of the beam irradiance $G_n$ from the measured global irradiance $G$.
- The use of outdated measurement data for parameters identification and model validation.
- The neglect of the tracking system error due to inability to measure it.
Uncertainty analysis cannot be performed given that the true data of the beam irradiance are not available and that the reliability of the outdated measurements should be investigated in advance.

**5.3. Conclusions and recommendations**

A comprehensive mathematical model has been developed and validated for characterizing the performance of the solar field under study based on measurement data collected in July 2010 and the optical quality test results. The model can be used to predict the output and the efficiency of the solar field at a given time of the year under any combination of weather conditions (ambient temperature, wind speed and solar irradiance) and system operating temperature (inlet and outlet temperatures).

The test conditions (under which measurements were taken) are similar to those of quasi-dynamic test of solar collectors as defined by the European standard (EN 12975). The model is capable of predicting the efficiency within the uncertainty of the measurements and the uncertainty associated with the assumptions made throughout the study and the outdated measurement data. A lower level of uncertainty can be achieved by providing the necessary instruments for directly measuring the beam irradiance and by solving the problems related to the operation of the chiller to have measurements up-to-date of the efficiency.

Photogrammetric test has been conducted to evaluate the optical quality of the collectors. The intercept factor at normal incidence was determined to be 0.72 using Rabl & Bendt model [28] which follows a statistical characterization of the sun shape and the optical errors. The photogrammetric test has resulted in a standard deviation of surface slope errors $\sigma_{\text{slope}} = 9.9$ millirad and of receiver displacement errors $\sigma_{\text{displacement}} = 5.3$ millirad. Accordingly, the intercept factor was calculated to be 0.72 resulting in an peak optical efficiency of the solar field at normal incidence of 53%. Other optical test has been conducted in Europe on the
same collector resulted in an intercept factor of 0.83\textsuperscript{[39]} which means that the optical errors of the solar collector in the system are relatively high.

The parameters of the performance model were identified using the mathematical tool MLR. The resulted efficiency curves suggest that the efficiency is sensitive to the variation of the angle of incidence much more than to the variation of wind speed. The curves also depict that efficiencies of (30 – 45\%) are realized for a reduced temperature difference range of (0.04 – 0.06). The efficiency drastically drops (<10\%) at high values of reduced temperature difference (>0.1) and large angle of incidence (>60°).

In general, the model has revealed a low thermal losses and high optical losses. This can be illustrated by taking a point on the efficiency curve with $\theta = 0^\circ$, and a reduced temperature difference of 0.06 ($T_m = 80^\circ C$, $T_a = 35^\circ C$ and $G_b = 750$ W/m$^2$), the overall efficiency is 42\%. Which means that the optical losses account for around 47\% (53\% optical efficiency) while the thermal losses account for around 11\%.

It is recommended that the system being operated at low reduced temperature difference as much as possible bearing in mind the fulfillment of the system temperature requirements whether it is absorption chiller (solar cooling) in summer or domestic water heating in winter. It is also recommend that the parameter identification be executed using most recent data to have a model that effectively represents the current status of the solar field.

Significant improvement of the overall efficiency can be achieved by reducing the optical errors to enhance the optical efficiency. It is to be noted that the optical test results revealed high optical errors, however, these results need to be validated by a well-experienced party in phtogrammetric tests like DLR. According to the validation results, we can state that the low optical efficiency is an outcome of poor optical quality or an outcome of inaccurate test results.
Training local personnel on the advanced test procedures like photogrammetry is highly recommended to create expertise in the solar collectors testing field. It is necessary for the development of the technology in the MENA region which is the aim of the MENA-European cooperation in the renewable energy field.
6. Cost of Electricity Generation by 50 MW Parabolic Trough Plant in Ma’an

In this chapter, the economical and financial aspects of electricity generation by CSP in Jordan are investigated through estimating the cost of electricity generation by a parabolic trough power plant using the simulation tool SAM (System Advisor Model). The proposed plant will have similar characteristics to those of Andasol-1 power plant in Spain which is the first large scale parabolic trough plant in Europe and the first plant with storage system in the world. The net power capacity of the plant is 50MW with 7.5 hours storage capacity.

6.1. Plant site

The operation of CSP plants is economically feasible for areas with an average annual direct normal irradiation (DNI) above 2000 kWh/m².year\textsuperscript{[40]}. From figure 6.1 which represents the solar map of Jordan based on satellite data, it is obvious that the southern and southeastern parts of the country have the highest level of DNI (>2400 kWh/ m².year) and hence the highest potential of economically feasible CSP plants. In addition, electricity transmission system in Jordan is shown in figure 6.2. It can be seen that in the said area, there are two transmission networks: 132KVA and 400KVA, which makes the connection of the new power plants to the existing network an easy and low-cost item compared to the cost of other items in the plant.

Taking into consideration the high level of solar irradiation and the proximity from the national electric grid as well as the availability of meteorological data, the plant site was selected to be in the vicinity of Ma’an airport (around 5 km southwest of Ma’an city) as shown in figure 6.3. The plant is geographically located at latitude 30.15°N and longitude 35.75°E. The elevation of the site ranges between 1065 and 1075m. The terrain is flat as it is located in the vicinity of the airport.
Figure 6.1: solar map of Jordan with average daily sum of direct normal irradiation/m².\[41\]

Figure 6.2: electric power system of Jordan.\[42\]
6.2. **Solar radiation data**

Hourly data of global, diffuse and direct irradiation as well as ambient temperature for the plant site (Maan Airport) were obtained from NERC (National Energy Research Center) where Meteonorm software was used to extract the data. To perform the simulation over the year, SAM software demands the hourly data for other parameters, those parameters are: dew point, relative humidity, wind speed, atmospheric pressure and surface albedo.

Unfortunately, the hourly data were not available for the said parameters, alternatively, the monthly average value of each parameter was taken as the value for all hours of the respective month. The average monthly data were obtained from the free online source: Atmospheric Science Data Center which is
administered by NASA (National Aeronautics and Space Administration). The website provides satellite-based meteorological data averaged over 22 years for any location on earth. The source can be accessed through the link: [http://eosweb.larc.nasa.gov/](http://eosweb.larc.nasa.gov/).

The simulation tool SAM accepts weather data in certain formats such as TMY2 and TMY3 (Typical Meteorological Year 2 & 3). It also offers the ability to create weather data file of TMY3 format by inserting the hourly data for the parameters mentioned before. Thus, this feature was used to create the weather data file for the site. As calculated by the software, the annual DNI in the plant site is 2839 kWh/m² which is a good level of radiation that promises a feasible plant operation.

### 6.3. Power plant

The proposed power plant has a capacity of 50MW and 7.5 hours energy storage. The configuration of Andasol-1 plant will be adopted for our proposed plant. A schematic description of the plant is illustrated in the figure 6.4. In this stand-alone configuration, the plant consists of three main components: the solar field, the storage system and the power block.

![Figure 6.4: Schematic diagram of the parabolic trough plant with storage system.](image)
A heat transfer fluid (HTF) is heated to a temperature level of 393°C as it circulates through the receivers in the solar field. It runs through the steam generator, which consists of multiple heat exchangers, to generate high-pressure steam. The HTF is then pumped back to the solar field at temperature 293°C. The generated steam is then fed into a separate cycle (Rankine cycle) to drive a steam turbine at 100 bar and 370°C. The discharged steam from the turbine is condensed in the air-cooled condenser (ACC) into liquid ready to be heated in the steam generator to complete the cycle.

The thermal energy storage (indirect two-tank system) is charged when the output thermal power of the solar field exceeds the power block requirements. Where the surplus heat is transferred to the molten salt through a heat exchanger. The heated molten salt is stored in the hot salt tank. Discharging salt from the hot tank to reheat the HTF occurs in the same heat exchanger with reversed flow of salt when the solar field does not provide the sufficient power for steam generation.

6.3.1. Solar field

The layout of the proposed plant is shown in figure 6.5. the total area of the proposed plant is 1,950,000m² most of which is occupied by the solar field that has a ground-cover ratio of approximately 0.3. The solar field consists of 624 European trough collectors (ET-150) divided on 156 loop (4 collectors per loop) with a total aperture area of 510,120m². The resulting solar multiple (ratio of the actual aperture area to the area required to deliver the full capacity at the design irradiation) of this configuration is 2.2. The collectors are equipped with continuous single-axis tracking system. Selective characteristics of ET-150 are listed in table 6.1. After initial runs of the software with collectors longitudinal axis oriented N-S and E-W, the results have shown that the yearly output of the plant with N-S is higher than the output with E-W by 15% which can be attributed
to the greater losses resulting from greater incident angles for E-W configuration. Thus, N-S orientation will be adopted in the field.

Figure 6.5: Solar field layout for the proposed plant.

Table 6.1: Characteristics of ET-150.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ET 150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal Length</td>
<td>1.71 m</td>
</tr>
<tr>
<td>Average distance to focus</td>
<td>2.11 m</td>
</tr>
<tr>
<td>HCE Absorber Radius</td>
<td>3.5 cm</td>
</tr>
<tr>
<td>HCE Length</td>
<td>4 m</td>
</tr>
<tr>
<td>Aperture width</td>
<td>5.75 m</td>
</tr>
<tr>
<td>Aperture area</td>
<td>817.5 m²</td>
</tr>
<tr>
<td>Length</td>
<td>150 m</td>
</tr>
<tr>
<td>Number of modules</td>
<td>12</td>
</tr>
<tr>
<td>Mirror reflectivity</td>
<td>0.935</td>
</tr>
<tr>
<td>Absorber absorbtivity</td>
<td>0.96</td>
</tr>
<tr>
<td>Envelop transmissivity</td>
<td>0.963</td>
</tr>
</tbody>
</table>
The collected solar energy is converted into internal energy and transferred to the power cycle by the HTF which is distributed in the solar field through steel pipes with roughness of \(4.75 \times 10^{-5}\) m. The HTF is a hydrocarbon oil. It has a wider liquid temperature range than water, but a lower thermal capacity and higher viscosity. It is a eutectic mixture of two very stable compounds, Biphenyl Oxide and Diphenyl. The melting point of the HTF is 13°C. Thus, a heater is installed to prevent the HTF from freezing, when ambient temperature falls below 13°C.

6.3.2. Power block

The power cycle is a conventional Rankine steam cycle. Because the thermal stability of HTF is only kept up to working temperatures of 400°C, the maximum steam temperature in the power cycle will be nearly 370°C. The steam turbine type is condensing turbine single reheat with six steam extractions.

Unlike Andasol-1 which utilizes cooling towers (wet cooling) for steam condensation, the proposed plant utilizes air-cooled condenser (dry cooling) to reduce the water consumption by the plant. This can be attributed to the high shortage of water in Jordan where most of the conventional power plants use air-cooled condensers. There are three disadvantages of dry cooling when compared to wet cooling: the higher investment cost, the lower cycle efficiency (35% for dry cooling and 37% for wet cooling)\textsuperscript{43}, the higher parasitic losses (7.0 MW for dry cooling and 5.0 MW for wet cooling)\textsuperscript{43} associated with the higher power requirements for the fans of the Air Cooled Condenser (ACC).

Capacity and operation parameters of the power cycle are as follows:

- Nominal Capacity: 50.0 MW.
- Total parasitic losses: 7.0 MW.
- Conversion efficiency: 35%.
- Turbine Inlet Conditions: 100 bar 370°C, reheat: 16.5 bar 370°C.
- Nominal Steam Flow: 59.0 kg/s.
6.3.3. Storage system

As mentioned herein before, the storage system consists of hot and cold salt tanks. The storage media is Nitrate molten salt (60% NaNO₃ + 40% KNO₃) the salt has a high melting point (221°C). The heat capacity \( (C_p) \), thermal conductivity \( (k) \) and viscosity \( (\mu) \) of the salt are given as function of temperature in the equations below:

\[
C_p(T) = 1443 + 0.172 \ T \ [\text{J/kg.K}] \\
k(T) = 0.443 + 0.00019 + T \ [\text{W/m.K}] \\
\mu(T) = 0.001 + (22.714 - 0.12 T + 0.0002281T^2 - 0.0000001474 T^3) \ [\text{Pa s}] \]
\]

The storage is designed to provide the rated power output of the plant for 7.5 hours. The design parameters of the storage system are:

- Cold tank temperature: 292 °C
- Hot tank temperature: 386 °C
- Flow rate: 948 kg/s.
- 38 m height, 15 m diameter.
- Capacity: 1221 MWh, 31,820,00 tons of salt.

6.4. Energy yield simulation

The System Advisor Model (SAM 2010.11.9) software provided by the US National Renewable Energy Laboratory (NREL) was used to estimate the energy yield of the parabolic trough plant with the configuration that has been explained herein before. It was assumed that the plant will be unavailable for 4% of the operating time due to scheduled outages allocated basically for maintenance activities.

The simulation results are shown in figures 6.6 and 6.7. It can be seen from figure 6.6 that the maximum output power is realized in June as it has the maximum solar
irradiation. Figure 6.7 provides a visual and numerical means for following the energy conversion through the complete electricity generation process. In addition, the average daily profile of the net power generated for each month is presented in Appendix E.

![Figure 6.6: Monthly net electric output of the proposed plant.](image)

![Figure 6.7: Annual energy flow through the proposed plant.](image)

The plant is expected to feed the national grid with 213,023 MWh of electric energy per year. This amount of energy is a result of converting 1,448,230 MWh
of incident solar radiation by the proposed plant achieving 14.7% yearly conversion efficiency. The annual capacity factor of the plant can be calculated as:

\[
\text{Capacity factor} = \left( \frac{\text{Annual energy output (MWh)}}{50 \times 8760} \right) \times 100\% = 48.6\%.
\]

Other operational characteristics of the plant are summarized in table 6.2.

Table 6.2: Operational Characteristics of the proposed plant.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plant 1</th>
<th>Plant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total land area (acres)</td>
<td>481.85</td>
<td></td>
</tr>
<tr>
<td>Total incident solar radiation (MWh/year)</td>
<td>1,448,230</td>
<td></td>
</tr>
<tr>
<td>Thermal energy from solar field (MWh/year)</td>
<td>765,868</td>
<td></td>
</tr>
<tr>
<td>Gross electric output (MWh/year)</td>
<td>236,559</td>
<td></td>
</tr>
<tr>
<td>Net electric output (MWh/year)</td>
<td>213,023</td>
<td></td>
</tr>
<tr>
<td>Annual capacity factor</td>
<td>0.486</td>
<td></td>
</tr>
<tr>
<td>Total annual conversion efficiency</td>
<td>14.7</td>
<td></td>
</tr>
<tr>
<td>Annual washing water usage (m(^3))</td>
<td>64275.1</td>
<td></td>
</tr>
<tr>
<td>Annual total water usage (m(^3))</td>
<td>84672.2</td>
<td></td>
</tr>
</tbody>
</table>

Al-Soud and Hrayshat\(^{[43]}\) has estimated the energy output of a 50MW parabolic trough plant without storage (plant 2) in Quweira, south of Jordan using Eurotrough-100 collectors. The annual output of the plant was calculated to be 117,000 MWh having an annual capacity factor of 26.7%. Around double of this capacity factor is achieved by our proposed plant (plant 1) because of the utilization of storage system. A comparison between the two plants is shown in table 6.3.

Table 6.3: comparison of parabolic trough plants in Jordan.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plant 1</th>
<th>Plant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Ma'an</td>
<td>Quweira</td>
</tr>
<tr>
<td>Capacity (MW)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Storage (hours)</td>
<td>7.5</td>
<td>-</td>
</tr>
<tr>
<td>Land use (m(^2))</td>
<td>1,950,000</td>
<td>1,200,000</td>
</tr>
<tr>
<td>Aperture area (m(^2))</td>
<td>510,120</td>
<td>305,200</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Dry</td>
<td>Dry</td>
</tr>
<tr>
<td>Annual energy output (GWh(_e))</td>
<td>213</td>
<td>117</td>
</tr>
</tbody>
</table>
6.5. Economic and financial analysis

The financial analysis of the plant was performed using SAM software. This section introduces the results of the simulation related to the cost of electricity generation and the electricity price for the proposed plant. The simulation was executed for a base case scenario and incentive scenario. Afterwards, sensitivity analysis was conducted by varying some of the financial parameters to assess different financing options and the resulting levelized cost of electricity (LCOE).

The analysis is a 20-year cash flow model for evaluating independent power producer (IPP) power plant project assuming that the electricity produced will be completely fed to the national grid at a price equal to the resulted LCOE (with no price escalation) through a power purchase agreement with the National Electric Power Company (NEPCO), the operator of the national grid.

6.5.1. Plant costs

There are limited resources in the literature that provide cost breakdown for parabolic trough plants worldwide. In addition, it was not possible to get the cost of the plant from local resources (contractors and suppliers) due to the lack of relevant experience. The most detailed cost breakdown available from free resources is presented in Table 6.4 which represents the investment cost of the different subsystems of Andasol 1 plant in Spain.

In order to estimate the capital cost of the proposed plant; the figures in the table were used in conjunction with the following corrections and assumptions:

- Labor cost in Jordan equals to 40% of the labor cost in Europe.
- Additional cost for shipping the mirrors and receivers from Europe to Jordan based on a shipping cost rate of $77/m$^3$ volume.
- Steel structure, storage tanks and concrete have the same material cost assuming the manufacturing will be done locally.
- Additional cost for shipping all other items like pumps, heat exchangers … etc is based on a shipping cost of 15% of the estimated equipment cost.
- $6,000,000 added to the power block cost to account for the additional investment required for dry cooling.
- Contingency cost is 5% of the total direct cost.
- The indirect costs (project development, management, procurement … etc) is 15% of the total direct cost.
- The land price is estimated to be ($0.5/m²).
- Annual fixed cost represents the cost of water use is ($1.4/m³, $118,541 total).
- Annual operation and maintenance cost (labor & material) is expressed in fixed rate as $50.0/kW.

Table 6.4: Estimated investment cost of Andasol-like power plant.[44]
Accordingly, the capital and annual running cost inputs for the software are listed in table 6.5. Also, the share of each item in the total capital cost is shown in figure 6.8.

Table 6.5: Capital and annual costs for the proposed plant.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (Million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct capital cost</strong></td>
<td></td>
</tr>
<tr>
<td>Site improvement</td>
<td>8.480</td>
</tr>
<tr>
<td>Solar field</td>
<td>134.251</td>
</tr>
<tr>
<td>HTF System</td>
<td>32.385</td>
</tr>
<tr>
<td>Storage</td>
<td>40.740</td>
</tr>
<tr>
<td>Power plant</td>
<td>44.984</td>
</tr>
<tr>
<td>Balance of plant</td>
<td>20.700</td>
</tr>
<tr>
<td>Contingency</td>
<td>14.077</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>295.618</strong></td>
</tr>
<tr>
<td><strong>Indirect capital cost</strong></td>
<td></td>
</tr>
<tr>
<td>Engineering, Procurement and management</td>
<td>44.343</td>
</tr>
<tr>
<td>Land</td>
<td>0.975</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>45.318</strong></td>
</tr>
<tr>
<td><strong>Total capital cost</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>340.935</strong></td>
</tr>
</tbody>
</table>

**Annual costs**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual fixed cost (water)</td>
<td>0.119</td>
</tr>
<tr>
<td>O&amp;M (labor and material)</td>
<td>2.500</td>
</tr>
<tr>
<td><strong>Total annual cost</strong></td>
<td><strong>2.619</strong></td>
</tr>
</tbody>
</table>

*others include engineering, management, land, and contingency.

Figure 6.8: Share of the plant items in the total capital cost.
6.5.2. Financial parameters

6.5.2.1. Base case scenario

The base case scenario represents the anticipated financial terms for the investment in normal conditions with no incentives provided by the government. Table 6.6 lists those terms along with other assumptions required to perform the financial analysis.

Table 6.6: Financial parameters for the base case scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant lifetime (investment period)</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>Inflation rate (IR)</td>
<td>5.00%</td>
<td>This is the value of the inflation rate in Jordan for 2010. [6]</td>
</tr>
<tr>
<td>Real discount rate (RDR)</td>
<td>6.00%</td>
<td></td>
</tr>
<tr>
<td>Nominal discount rate (NDR)</td>
<td>12.35%</td>
<td>NDR account for the inflation rate according to the following formula: NDR = (1+RDR)(1+IR) - 1</td>
</tr>
<tr>
<td>Net salvage value</td>
<td>10.00%</td>
<td>conservative assumption for the value of the plant at the end of the lifetime</td>
</tr>
<tr>
<td>Income tax rate</td>
<td>15.00%</td>
<td>% of the taxable income which equals to the operating income minus the debt interest payment</td>
</tr>
<tr>
<td>Insurance</td>
<td>0.30%</td>
<td>% of the total capital cost</td>
</tr>
<tr>
<td>Debt fraction</td>
<td>60.00%</td>
<td>% of the total capital cost to be borrowed</td>
</tr>
<tr>
<td>Loan term</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>Loan rate</td>
<td>6.00%</td>
<td>interest rate for commercial loan</td>
</tr>
<tr>
<td>Minimum required Internal Rate of Return (IRR)</td>
<td>12.00%</td>
<td>The minimum required rate of return on the equity for the investors.</td>
</tr>
<tr>
<td>Plant availability</td>
<td>96.00%</td>
<td>the plant is assumed to be out of operation for forced and scheduled maintenance activities for 4% of the operating hours</td>
</tr>
</tbody>
</table>

6.5.2.2. Incentive scenario

The incentive scenario accounts for financial incentives provided by the government as shown in table 6.7. It is assumed that the government will provide reduced income tax for the whole lifetime of the plant. In addition, lower loan
interest rate will be applied by providing soft loan from international financing bodies (such as World Bank and Kreditanstalt fur Wiederaufbau (KfW)) through the government to promote investment in renewable energy projects. The other financial variables will remain the same as in the base case scenario.

Table 6.7: Financial parameters for the incentive scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant lifetime (investment period)</td>
<td>20 years</td>
<td>This is the value of the inflation rate in Jordan for 2010. [6]</td>
</tr>
<tr>
<td>Inflation rate (IR)</td>
<td>5.00%</td>
<td></td>
</tr>
<tr>
<td>Real discount rate (RDR)</td>
<td>6.00%</td>
<td></td>
</tr>
<tr>
<td>Nominal discount rate (NDR)</td>
<td>12.35%</td>
<td>NDR account for the inflation rate according to the following formula: NDR = (1 + RDR) (1 + IR) - 1</td>
</tr>
<tr>
<td>Net salvage value</td>
<td>10.00%</td>
<td>conservative assumption for the value of the plant at the end of the lifetime</td>
</tr>
<tr>
<td>Income tax rate</td>
<td>7.50%</td>
<td>50% income tax exemption</td>
</tr>
<tr>
<td>Insurance</td>
<td>0.30%</td>
<td>% of the total capital cost</td>
</tr>
<tr>
<td>Debt fraction</td>
<td>60.00%</td>
<td>% of the total capital cost to be borrowed</td>
</tr>
<tr>
<td>Loan term</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>Loan rate</td>
<td>3.00%</td>
<td>low interest rate for soft loan</td>
</tr>
<tr>
<td>Minimum required Internal Rate of Return (IRR)</td>
<td>12.00%</td>
<td>The minimum required rate of return on the equity for the investors.</td>
</tr>
<tr>
<td>Plant availability</td>
<td>96.00%</td>
<td>the plant is assumed to be out of operation for forced and scheduled maintenance activities for 4% of the operating hours</td>
</tr>
</tbody>
</table>

6.5.3. Financial Simulation Results

The cashflows of the two scenarios are shown in figures 6.9 and 6.10. The primary metric of the financial performance is the levelized cost of electricity (LCOE) which represents the selling price of energy. LCOE and other financial indices are listed in table 6.8.
Figure 6.9: After-tax cashflow for the base case scenario.

Figure 6.10: After-tax cashflow for the incentive scenario.

Table 6.8: Financial indices for the plant.

<table>
<thead>
<tr>
<th></th>
<th>Base case scenario</th>
<th>Incentive scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levelized cost of energy (LCOE) (¢/kWh)</td>
<td>20.96</td>
<td>17.89</td>
</tr>
<tr>
<td>After tax net present value (NPV) (US $)</td>
<td>6,476,315.53</td>
<td>6,585,258.48</td>
</tr>
<tr>
<td>Min. debt service coverage ratio (DSCR)</td>
<td>2.01</td>
<td>2.13</td>
</tr>
</tbody>
</table>
In both cases there is a very high initial negative cash flow representing the investment for the plant and a high positive cash flow in the last year of operation obtained by the operating income and the realization of the salvage value. Both cash flow diagrams also show the steadily positive, but decreasing cash flows from year 1 to year 19: They decrease as the operating costs are increasing due to the effect of inflation electricity price is assumed to be constant over the plant lifetime (no price escalation).

It is obvious that a reduction of LCOE by 14.6% is possible by the incentives stated here before which are very likely to be provided by the government given the investment promotion laws in Jordan and the cooperation channels with the European Union and the World Bank.

Al-Soud and Hrayshat\textsuperscript{[43]} has estimated the LCOE for the 50MW parabolic trough plant mentioned before (plant 2) to be 25.4 ¢/kWh for a base case scenario which has the same financing parameters as in our base case except for the debt fraction which is 70% for plant 2. The lower LCOE for our proposed plant results from the utilization of storage system in the operation of the plant.

In 2010, the cost of electricity in Jordan as published by NEPCO -the national grid operator- was 68.27 Jordanian Fils (JF)/kWh (9.64 ¢/kWh)\textsuperscript{[46]} which is higher than the cost in 2009 by 25%. The cost of electricity (LCOE) from the proposed plant is higher than the current cost of electricity by 117% for the base case scenario and by 86% for the incentive scenario. The higher cost of electricity generated by the proposed plant can be attributed to the high investment cost compared to the investment cost of the conventional fossil-fired power plants. Nevertheless, there is an anticipated reduction of CSP plant investment cost according to many studies that investigated different scenarios. This reduction will be a result of increasing demands on the CSP technology and an outcome of the continuous learning process within the industry.
Other potential of investment cost reduction could be achieved by financing such projects with grants from the developed countries that are pursuing the fulfillment of their commitments to reducing their CO₂ emissions through the implementation of renewable energy and energy efficiency projects in the developing countries.

6.5.4. Sensitivity Analysis

Sensitivity analysis was performed to assess how the LCEO may change with the variations of different input parameters. The analysis is important for specifying the inputs that have the most effect on the LCEO. The analysis was conducted for two types of inputs: the investment cost and financial parameters. Figures (6.11 – 6.14) illustrate the results of the analysis for both cases where each input parameter has been varied by ±10%.

Figure 6.11: Sensitivity of LCOE (base case) to investment cost.

Figure 6.12: Sensitivity of LCOE (base case) to financial parameters.
Among the investment cost items, the LCOE is mostly sensitive to solar field cost which has the highest share in the total investment cost. With 10% reduction in the solar field cost, the LCOE is reduced by 4.3% (from 20.96 to 20.05 ¢/kWh for the base case and from 17.89 to 17.12 ¢/kWh in the incentive case). There is a potential future reduction in the solar field cost by the ongoing technology improvement and the anticipated increase of demands.

On the other hand, the debt fraction has the largest impact on the LCOE among the financial parameters. With 10% increase in the debt fraction, the LCOE is reduced by 2.8% for the base case (from 20.96 to 20.36 ¢/kWh) and by 3.9% for the incentive case (from 17.89 to 17.18 ¢/kWh).
Using the optimization option in the software, it was found that the optimum debt fraction that results in the lowest LCOE is 85.2% for the base case (LCOE = 17.89 ¢/kWh) and 84.3% for the incentive case (LCOE = 15.02 ¢/kWh).

Furthermore, the simulation was run with zero interest rate on the debt fraction assuming the project is financed by grant, the resulted LCOE is 17.56 ¢/kWh for the base case and 16.28 ¢/kWh for the incentive case.

6.6. Conclusions

The energy output and LCOE from a 50MW (with 7.5 hours storage) parabolic trough plant in Ma’an, Jordan were evaluated for base-case and incentive scenarios using the simulation tool SAM.

The annual energy output from the plant was estimated to be 221,899 MWh achieving an yearly conversion efficiency of 14.7%. The financial simulation resulted in an LCOE of 20.96 ¢/kWh which is still high when compared to the current cost of electricity in Jordan (9.64 ¢/kWh) which is being generated mostly by fossil fuel. However, taking into consideration the volatile prices of fossil fuel, parabolic trough plants can highly contribute to the energy security in Jordan where the fossil fuel resources are extremely limited.

A remarkable reduction in the LCOE (14.6%) of the proposed plant is achievable by tax exemption along with lower interest rate on the debt fraction. The tax exemptions assumed in this study represent normal exemptions provided by the government according to the investment promotion laws. However, more economically feasible parabolic trough plants can be realized by providing further financial incentives (e.g. zero income tax). It is to be pointed out that such plants have environmental benefits (such as CO$_2$ emission reduction) - not included in this study- that add to the feasibility of the plants.
A significant reduction of LCOE is possible by securing grants for financing such plants. With the incentives stated before along with grant funding, the LCOE goes down to 16.28 ¢/kWh which is higher than the current cost of electricity by 69%. Grant funding is available through the cooperation between Jordan and some developed countries that provide funds to promote development projects in the renewable energy field such as the United States, Germany and Japan.

The LCOE is highly sensitive to the solar field cost (10% less cost of solar field $\Rightarrow$ 4.3% less LCOE) and debt fraction (10% less cost of solar field $\Rightarrow$ 2.8% less LCOE). Thus, attention must be given to the optimization of those items when carrying out feasibility studies for CSP plants. Possible option would be investigating the opportunities of local manufacturing for some items of the solar field which will cause a considerable reduction in the solar field cost.

The investment and operating costs of CSP plants in Jordan are lower than in Europe. In addition, the solar radiation in Jordan is higher than in Europe. These factors yield a lower LCOE in Jordan (and other MENA countries) which makes the region attractive to implement such plants and achieve the target of the European initiatives that aim at importing electricity generated by renewable resources from the MENA region.
References


Appendix A: Test images samples & 3D Aicon output

A.1. Samples of images used for photogrammetric test

Figure A.1.1: Images for photogrametric test (sample 1)

Figure A.1.2: Images for photogrametric test (sample 2)
A.2. Snapshots of the 3D-Aicon software processing and output

Figure A.2.1: Image processing by 3D-Aicon software.

Figure A.2.2: Recognition of surface points and camera positions.
Figure A.2.3: Numbering of coded and non-coded targets.

Figure A.2.4: Coordinates of the non-coded targets in 3D view and tabulated form.
Appendix B: Matlab code for slope errors calculations

%calculations of surface slope errors
function [errors] = SlopeError(surf,n)
%surf is the input matrix for the 3D coordinates in mm of the measured
%surface points (n) imported from excel file "3D coordinates.xls", with
%measured coordinates x in column1, y in column2 and z in column1.
%the surface is divided into 200mm transversal strips along the length %of
%the collector from st1-st25. and the design z-coordinate %z=x^2/4*780 is
%added to column4 (design focal length = 780mm)
j = ones(1,25);
for i = 1:n
    if surf(i,2) >= 0 && surf(i,2) < 200
        str1(j(1,1),1) = surf(i,1); str1(j(1,1),2) = surf(i,2);
        str1(j(1,1),3) = surf(i,3);
        str1(j(1,1),4) = (str1(j(1,1),1)^2)/(4*780); j(1,1) = j(1,1)+1;
    end
    if surf(i,2) >= 200 && surf(i,2) < 400
        str2(j(1,2),1) = surf(i,1); str2(j(1,2),2) = surf(i,2);
        str2(j(1,2),3) = surf(i,3);
        str2(j(1,2),4) = (str2(j(1,2),1)^2)/(4*780); j(1,2) = j(1,2)+1;
    end
end
%the division continues with other strips up to 25, the code for %strips 3
%through 24 follows the same concept but it is not shown to %avoid lengthy
%presentation
if surf(i,2) >= 4800 && surf(i,2) < 5000
    str25(j(1,25),1) = surf(i,1); str25(j(1,25),2) = surf(i,2);
    str25(j(1,25),3) = surf(i,3);
    str25(j(1,25),4) = (str25(j(1,25),1)^2)/(4*780); j(1,25) = j(1,25)+1;
end
end
j = j-1;
%sorting of measured points in each strip based on the x coordinate
str1 = sortrows(str1,1); str2 = sortrows(str2,1); str3 = sortrows(str3,1);
str4 = sortrows(str4,1); str5 = sortrows(str5,1); str6 = sortrows(str6,1);
str7 = sortrows(str7,1); str8 = sortrows(str8,1); str9 = sortrows(str9,1);
str10 = sortrows(str10,1); str11 = sortrows(str11,1); str12 = sortrows(str12,1);
str13 = sortrows(str13,1); str14 = sortrows(str14,1); str15 = sortrows(str15,1);
str16 = sortrows(str16,1); str17 = sortrows(str17,1); str18 = sortrows(str18,1);
str19 = sortrows(str19,1); str20 = sortrows(str20,1); str21 = sortrows(str21,1);
str22 = sortrows(str22,1); str23 = sortrows(str23,1); str24 = sortrows(str24,1);
str25 = sortrows(str25,1);
%for each strip, calculation of measured slope (Sx)_m in column5, design
%slope (Sx)_d in column6, slope error ΔSx in rad in column7 and in %milliard in
%column8
for i = 1:j(1,1)-1
    str1(i,5) = (str1(i+1,3)-str1(i,3))/(str1(i+1,1)-str1(i,1));
    str1(i,6) = (str1(i+1,4)-str1(i,4))/(str1(i+1,1)-str1(i,1));
    str1(i,7) = str1(i,6)-str1(i,5); str1(i,8) = str1(i,7)*1000;
end
for i = 1:j(1,2)-1
    str2(i,5) = (str2(i+1,3)-str2(i,3))/(str2(i+1,1)-str2(i,1));
    str2(i,6) = (str2(i+1,4)-str2(i,4))/(str2(i+1,1)-str2(i,1));
end

str2(i,7) = str2(i,6) - str2(i,5); str2(i,8) = str2(i,7) * 1000;
end
% the calculations continue with other strips up to 25, the code for % strips 3 through 24 follows the same concept but it is not shown to % avoid lengthy presentation
for i = 1:j(1,25) - 1
    str25(i,5) = (str25(i+1,3) - str25(i,3)) / (str25(i+1,1) - str25(i,1));
    str25(i,6) = (str25(i+1,4) - str25(i,4)) / (str25(i+1,1) - str25(i,1));
    str25(i,7) = str25(i,6) - str25(i,5); str25(i,8) = str25(i,7) * 1000;
end
% combining the strips into full surface matrix (results)
m = 1;
for i = m:j(1,1)
    for k = 1:8
        result(i,k) = str1(i,k); k = k + 1;
    end
    i = i + 1;
end
m = 1;
for i = i:i+j(1,2) - 1
    for k = 1:8
        result(i,k) = str2(m,k); k = k + 1;
    end
    i = i + 1;
    m = m + 1;
end
m = 1;
% combining the strips continue with other strips up to 25, the code % for strips 3 through 24 follows the same concept but it is not shown %to avoid lengthy presentation
for i = i:i+j(1,25) - 1
    for k = 1:8
        result(i,k) = str25(m,k); k = k + 1;
    end
    i = i + 1;
    m = m + 1;
end
% calculations of the height (z-coordinate) deviation in column 9 and the % the square of the slope error in column 10 of the results matrix
for i = 1:n - 1
    result(i,9) = result(i,4) - result(i,3);
    result(i,10) = result(i,8)^2;
end
% the function returns the matrix errors that contains the local slope % error and the square of the local slope error as well as the height % deviation errors = result;
Appendix C: Sample calculation of performance model terms.

A sample calculation is presented here to illustrate the application of the equations used to identify the different terms of the performance model. The performance data used in this illustration are those shown in the first row of table 5.4, i.e. the measurements taken on 12\textsuperscript{th} July 2010 at 12:34:08pm. The measured data are:

C.1. Problem statement

A parabolic trough solar field installed on the rooftop of a hotel in the dead sea area (longitude = 35.586\textdegree E, latitude = 31.714\textdegree N) using water as heat transfer fluid. The field consists of fourteen collectors distributed among three rows as shown in figure 3.3 with an aperture area of 9.162m\textsuperscript{2} for each collector (width=1.8m, length=5.09m). The solar field is oriented at 71\textdegree counterclockwise from north as shown in the stated figure. The following performance data were measured on 12\textsuperscript{th} July 2010 at 12:34:08pm.

\begin{align*}
T_{in} &= 57.185 \degree C, \quad T_{out} = 67.215 \degree C, \quad T_a = 40.33 \degree C, \quad \dot{V} = 62.952 \text{ l/min}, \quad G = 984.21 \text{ W/m}^2, \quad u = 3.00 \text{ m/s}.
\end{align*}

Given the measured data and figure 3.3, find all terms in the performance model below which will be used along with other measurement data to identify the parameters $c_1$ through $c_4$.

\begin{align*}
F_{RS} K(\theta) \eta_{op,n} &= \left( \frac{\dot{Q}_{SF} + \dot{Q}_p}{A_a G_b} \right) = \\
&= c_1(T_m - T_a)/G_b + c_2(T_m - T_a)^2/G_b + c_3 (dT_m/dt)/G_b + c_4 u(T_m - T_a)/G_b \tag{5.2.5}
\end{align*}

C.2. Solution

1- Angle of incidence $\theta$
   - Day number $N$ (July 12) = 193,
   - Local Clock Time $LCT$ (12:34:08pm) = 12+34/60+8/3600 = 12.569 hours
   - Equation Of Time $EOT = 0.258 \cos x - 7.416 \sin x - 3.648 \cos 2x - 9.228 \sin 2x$
\( x = \frac{360 (N-1)}{365.242} = \frac{360 (193-1)}{365.242} = 189.24^\circ \)

\( EOT = -5.45 \text{ minutes} \)

- Longitude correction \( LC = \frac{(30 - 35.586)\times 15}{15} = -0.3724 \text{ hours} \)
- Solar time \( t_s = LCT + \frac{(EOT/60)}{LC} - DLS = 12.569 - 5.45/60 + 0.3724 - 1 = 11.85 \text{ hours} \)

- Hour angle \( \omega = 15(t_s - 12) = 15(11.85 - 12) = -2.243^\circ \)
- Latitude angle \( \phi = 31.714^\circ \) (given)
- Declination angle \( \delta = \sin^{-1}(0.39795 \cos [0.98563(N-173)]) \)
  \( = 22.00^\circ \)
- Solar altitude angle \( \alpha = \sin^{-1}(\sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega) \)
  \( = 80.08^\circ \)
- Solar zenith angle \( \theta_z = 90 - \alpha = 90 - 80.08 = 9.92^\circ \)
- Solar azimuth angle \( \beta \)
  \[ \beta' = \cos^{-1}\left(\frac{\sin \delta \cos \phi - \cos \delta \sin \phi \cos \omega}{\cos \alpha}\right) = 167.8^\circ \]
  \( \omega = -2.243^\circ < 0, \quad \Rightarrow \beta = \beta' = 167.8^\circ \)
- Aperture azimuth angle \( \Omega = 71^\circ \) (given in figure 3.3)
- Tracking angle \( \rho = \tan^{-1}\left(\sin (\beta - \Omega) / \tan \alpha\right) = 9.84^\circ \)
- Angle of incidence \( \theta = \cos^{-1}\left(\frac{1 - \cos^2 (\alpha) \cos^2 (\beta - \Omega)}{1^2}\right) = 1.174^\circ \)

2- Incidence angle modifier \( K(\theta) \)
\[
K(\theta) = 1 - 5.782 \times 10^{-3} \theta + 1.485 \times 10^{-4} \theta^2 - 2.955 \times 10^{-6} \theta^3
\]
\[
= 1 - 5.782 \times 10^{-3} (1.174) + 1.485 \times 10^{-4} (1.174^2) - 2.955 \times 10^{-6} (1.174^3)
\]
\[
= 0.99341
\]

3- Optical efficiency at normal incidence \( \eta_{op, n} = \rho_m (\tau_{oc}) \gamma_n \)
\[
= (0.85) (0.865) (0.72) = 0.529
\]

4- Field shading factor \( F_{RS} \)
- solar profile angle \( \alpha_p = \tan^{-1} \left[ \frac{\tan \alpha \cdot \cos (90 - \Omega)}{\cos (\beta - 180)} \right] \)
  \[ = \tan^{-1} \left[ \frac{\tan 80.08 \cdot \cos (90 - 71)}{\cos (167.8 - 180)} \right] \]
  \[ = 79.76^\circ \]
- Effective width \( W_e = \min \left[ \max(0; S \cdot \sin \alpha_p / W); 1 \right] \).

For row 1, \( S = 6.5m \):
\[ W_{e1} = \min \left[ \max(0; 6.5 \sin 79.76 / 1.8); 1 \right] \]
\[ = 1.8m \]

For row 2, \( S = 4.0m \):
\[ W_{e2} = \min \left[ \max(0; 4.0 \sin 79.76 / 1.8); 1 \right] \]
\[ = 1.8m \]

For row 3, no shading because there is no other row blocking the sun: \( W_{e3} = 1.8m \).
\[ W_t = 3 \times 1.8 = 5.4m. \]
\[ \Rightarrow F_{RS} = (W_{e})_t / W_t = 1.0 \]

5- Useful output \( \dot{Q}_{SF} \)
- mass flow rate \( \dot{m} = \dot{V} \rho_w \).

volume flow rate \( \dot{V} = (62.952 \text{ l/min})(0.001 \text{ m}^3/\text{liter})/(60 \text{ s/min}) = 1.049 \times 10^{-3} \text{ m}^3/\text{s} \)

average HTF density \( \bar{\rho}_w = (\rho_w @ T_{in} + \rho_w @ T_{in}) / 2 \)
\[ \rho_w @ 57.185 = 985.13 \text{ kg/m}^3, \rho_w @ 67.215 = 979.5 \text{ kg/m}^3 \] (Appendix D)
\[ \Rightarrow \bar{\rho}_w = 982.3 \text{ kg/m}^3 \]
\[ \Rightarrow \dot{m} = \dot{V} \bar{\rho}_w = (1.049 \times 10^{-3}) (982.3) = 1.03 \text{ kg/s} \]
- Useful output \( \dot{Q}_{SF} = \dot{m} \bar{c} (T_{out} - T_{in}) \)

average HTF specific heat \( \bar{c} = (C_p @ T_{in} + C_p @ T_{in}) / 2 \)
\[ C_p @ 57.185 = 4.185 \text{ kJ/kg.K}, C_p @ 67.215 = 4.189 \text{ kJ/kg.K} \] (Appendix D)
\[ \Rightarrow \bar{c} = 4.187 \text{ kJ/kg.K} \]
\[ \Rightarrow \dot{Q}_{SF} = (1.03) (4.187) (67.215 - 57.185) = 43.289 \text{ kW} = 43,289 \text{ W} \]

6- Piping heat losses \( \dot{Q}_p \)
\[ \dot{Q}_p = U_p A_o (T_m - T_a) \]
- HTF mean temperature \( T_m = (T_{out} + T_{in}) / 2 = (67.215 + 57.185) / 2 = 62.2 \text{ °C} \)
- Pipes outer surface area \( A_o = \pi D_3 L_p \)
  Pipe outer diameter (with insulation) \( D_3 = 0.2083m \), total pipe length \( L_p = 33 \text{ m} \)

C3
\[ A_o = 21.573m^2 \]

Overall heat transfer coefficient:
\[ U_p = \frac{1}{D_2 h_m + \frac{\ln \left( \frac{D_2}{D_1} \right)}{2 k_p} + \frac{\ln \left( \frac{D_2}{D_i} \right)}{2 k_i} + \frac{1}{h_a}} \]

Pipe inner diameter \( D_1 = 0.0409m \), pipe outer diameter \( D_2 = 0.0483m \)

The thermal conductivity of carbon steel ranges from 55 W/m.K at 0.0°C to 45 W/m.K at 200°C\(^{[13]}\) while the thermal conductivity for Rockwool insulation ranges from 0.037 W/m.K at 50°C to 0.088 W/m.K at 300°C\(^{[12]}\). So, by interpolation, thermal pipe conductivity \( k_p @ 62.2^oC = 51.9 \) W/m.K, insulation thermal conductivity \( k_i @ 62.2^oC = 0.0395 \) W/m.K

- Heat transfer coefficient inside the pipe \( h_m \)

Reynolds number \( Re = D_1 V \rho_w / \mu_w \)

Flow velocity in the pipes \( V = 0.78m/s \), water density \( \rho_w @62.2^oC = 981.8 \) kg/m\(^3\)

Dynamic viscosity of water \( \mu_w = \rho_w v_w \)

Kinematic viscosity \( v_w @62.2^oC = 4.6 \times 10^{-7} \) m\(^2\)/s (Appendix D)

\[ \Rightarrow \mu_w @62.2^oC = (981.8) (4.66 \times 10^{-7}) = 4.5 \times 10^{-4} \) kg/m.s

\[ \Rightarrow Re = (0.0409) (0.78) (981.8) / 4.5 \times 10^{-4} = 69,603 \]

Prandtl number \( Pr \) of water @ 62.2°C = 2.93 (Appendix D)

Moody friction factor \( f = (0.79 \ln Re -1.64)^2 = (0.79 \ln 69,603 -1.64)^2 = 0.0195 \)

Nusselt number \( Nu = \frac{(f/8)(Re-1000)Pr}{1 + 12.7 (f/8)^{0.5} (Pr^{0.67} -1)} = 294.4 \)

- Heat transfer coefficient at the insulation outer surface \( h_a \)

Grashof number \( Gr = D_2^3 \rho_a g \Delta T b / \mu_a^2 \)

Air density \( \rho_a @40.33^oC = 1.127 \) kg/m\(^3\)
coefficient of expansion for air $b@40.33^\circ C = 0.033 \, 1/K$

thermal conductivity of air $k_a@40.33^\circ C = 0.0271 \, W/m.K$ (Appendix D)

$\Delta T = 10 \, K$ (assumption)

dynamic viscosity $\mu_a@40.33^\circ C = 1.905 \times 10^{-5} \, kg/m.s$ (Appendix D)

$\Rightarrow Gr = (0.2083)^3 (1.127)^2 (9.81) (10) (0.0033)/(1.905 \times 10^{-5})^2$

$= 9.58 \times 10^6$

Rayleigh number $Ra = Gr \, Pr = (9.58 \times 10^6) (0.709) = 6.79 \times 10^6$

Nusselt number $Nu = [0.6 + \frac{0.387 \, Ra^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}]^2$

$= 25.2$

$\Rightarrow$ heat transfer coefficient $h_a = k_a \frac{Nu}{D_3} = (0.0271) (25.2) / 0.2083$

$= 3.28 \, W/m^2.K$

$\Rightarrow U_p = 0.24 \, W/m^2.K$

$\Rightarrow \dot{Q}_p = U_p \, A_o (T_m - T_a) = (0.24) (21.573) (62.2 - 40.33) = 113.46 \, W$

7- Incident beam irradiance $G_b$

Diffuse irradiance $G_d$

$G_d/G = 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4$

For clearness index $k_T = 0.72$ (5-years average for the day of measurements)

$G_d = 984.21 \{0.9511 - 0.1604(0.72) + 4.388(0.72^2) - 16.638(0.72^3) + 12.336(0.72^4)\}$

$= 212.01 \, W/m^2$

Beam irradiance $G_n = [G - G_d] \cos \theta_z = [984.21 - 212.01]/\cos 9.88$

$= 783.9 \, W/m^2$

Incident beam irradiance $G_b = G_n \cos \theta = 783.7 \, W/m^2$

8- $(T_m - T_a)/G_b = (62.2 - 40.33) / 783.7 = 0.0279 \, m^2.K/W$

9- $(T_m - T_a)^2/G_b = (62.2 - 40.33)^2 / 783.7 = 0.61 \, m^2.K^2/W$

10- $u (T_m - T_a)/G_b = (3.0)(0.0279) = 0.0837 \, m^2.K/W$

11- $(dT_m/dt)/G_b$
Using the mean temperature for a measurement taken at 12:33:43
\[ \frac{dT_m}{dt} = \frac{\Delta T_m}{dt} = \frac{62.2 - 60.99}{25} = 0.048 \text{ K/s} \]
\[ \Rightarrow \left( \frac{dT_m}{dt} \right)/G_b = \frac{0.0326}{783.7} = 6.17 \times 10^{-5} \text{ m}^2.\text{K/J} \]

12- Aperture area \( A_a = (9.162)(14) = 128.268 \text{ m}^2 \)

Finally, by substituting all terms in equation 5.5.2
\[
(0.99341)(0.529) - \left\{ \frac{(43,289 + 113.64)}{(128.268)(783.7)} \right\} = 0.0279 c_1 + 0.61 c_2 + 6.17 \times 10^{-5} c_3 + 0.0837 c_4
\]

\[ \Rightarrow 0.0947 = 0.0279 c_1 + 0.61 c_2 + 6.17 \times 10^{-5} c_3 + 0.0837 c_4 \]
Appendix D: Thermophysical Properties of air and water

Table D.1: Thermophysical properties of air at atmospheric pressure (101.3 kPa).[^13]

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>$\rho$ (kg/m$^3$)</th>
<th>$c_p$ (J/kg·K)</th>
<th>$\nu$ (m$^2$/s)</th>
<th>$k$ (W/m·K)</th>
<th>$\alpha$ (m$^2$/s)</th>
<th>$Pr$</th>
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$T$ : temperature  
$\rho$ : density  
$c_p$ : specific heat  
$\mu$ : dynamic viscosity  
$\nu$ : kinematic viscosity  
$k$ : thermal conductivity  
$\alpha$ : thermal diffusivity  
$Pr$ : Prandtl number

[^13]: Reference [13]
Table D.2: Thermophysical properties of water. [13]

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<th>K</th>
<th>°C</th>
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$T$: temperature  
$\rho$: density  
$c_p$: specific heat  
$\beta$: coefficient of expansion  
$Pr$: Prandtl number

κ: thermal conductivity  
ν: kinematic viscosity  
α: thermal diffusivity
Appendix E: Average daily profile of electric power generated Ma’an plant

Figure E.1: Average daily profile of the generated electric power by the power plant in Ma’an for the months January, February & March.

Figure E.2: Average daily profile of the generated electric power by the power plant in Ma’an for the months April, May & June.
Figure E.3: Average daily profile of the generated electric power by the power plant in Ma’an for the months July, August & September.

Figure E.4: Average daily profile of the generated electric power by the power plant in Ma’an for the months October, November & December.