Master Thesis

ANALYSIS AND EVALUATION TOOLS DEVELOPMENT OF PHOTOVOLTAIC MODULES AND SYSTEM PERFORMANCE UNDER JORDANIAN AND GERMAN CLIMATIC CONDITIONS

By
Laith Sa’d Basha

Submitted to
Faculty of Engineering at Cairo University
and
Faculty of Electrical Engineering and Computer Science at University of Kassel
in partial fulfillment of the requirements for M.Sc. degree in Renewable Energy and Energy Efficiency for the MENA region

Faculty of Engineering

Giza, Egypt
Cairo University

Kassel, Germany
Kassel University

March, 2012
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Approved by the Examining Committee

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<td>Electrical power and machines department, Faculty of Engineering Cairo University</td>
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Faculty of Engineering
Giza, Egypt
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Kassel University

March, 2012
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<tr>
<td>$A$</td>
<td>Absorption coefficient</td>
</tr>
<tr>
<td>$A'$</td>
<td>Isentropy index</td>
</tr>
<tr>
<td>$alt$</td>
<td>Altitude angle</td>
</tr>
<tr>
<td>$AM$</td>
<td>Air mass</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat capacity [J/ kg.K]</td>
</tr>
<tr>
<td>$EQT$</td>
<td>Equation of time</td>
</tr>
<tr>
<td>$f$</td>
<td>Geometrical factor</td>
</tr>
<tr>
<td>$FF$</td>
<td>Fill Factor</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravity 9.81[m/s²]</td>
</tr>
<tr>
<td>$G$</td>
<td>Global irradiation [W/m²]</td>
</tr>
<tr>
<td>$G_b$</td>
<td>Direct horizontal beam [W/m²]</td>
</tr>
<tr>
<td>$G_{in}$</td>
<td>Direct inclined beam [W/m²]</td>
</tr>
<tr>
<td>$G_d$</td>
<td>Diffused irradiance [W/m²]</td>
</tr>
<tr>
<td>$G_{di}$</td>
<td>Diffused inclined irradiance [W/m²]</td>
</tr>
<tr>
<td>$G_i$</td>
<td>Global inclined irradiation [W/m²]</td>
</tr>
<tr>
<td>$G_o$</td>
<td>Extraterrestrial radiation and equal 1367 [W/m²]</td>
</tr>
<tr>
<td>$Gr$</td>
<td>Grashof number</td>
</tr>
<tr>
<td>$Gr_r$</td>
<td>Reflected irradiance from ground (and surrounding)</td>
</tr>
<tr>
<td>$Gr_{in}$</td>
<td>Reflected inclined irradiance from ground (and surrounding)</td>
</tr>
<tr>
<td>$h_{ci}$</td>
<td>Inside(back side) surface Convection coefficient [W/m².K]</td>
</tr>
<tr>
<td>$h_{co}$</td>
<td>Outside(front side) surface Convection coefficient [W/m².K]</td>
</tr>
<tr>
<td>$h_{ri}$</td>
<td>Inside(back side) surface Radiation coefficient [W/m².K]</td>
</tr>
<tr>
<td>$h_{ro}$</td>
<td>Outside(front side) surface Radiation coefficient [W/m².K]</td>
</tr>
<tr>
<td>$I/(h_{ci}+h_{ri})$</td>
<td>Internal heat transfer resistance (convection + radiation) [m²K/W]</td>
</tr>
<tr>
<td>$I/(h_{co}+h_{ro})$</td>
<td>External heat transfer resistance (convection + radiation) [m²K/W]</td>
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<td>$I_{MP}$</td>
<td>Current at maximum power point</td>
</tr>
<tr>
<td>$I_{ph}$</td>
<td>Photo current</td>
</tr>
<tr>
<td>$I_{SC}$</td>
<td>Short circuit current</td>
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<tr>
<td>$m$</td>
<td>Mass flow [Kg/s]</td>
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<tr>
<td>$n$</td>
<td>Refractive index</td>
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<tr>
<td>$n_{eq}$</td>
<td>Equivalent refractive index</td>
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<tr>
<td>$NOD$</td>
<td>Number of the day</td>
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<tr>
<td>$Nu$</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>$Nu_{i,fr}$</td>
<td>Nusselt number for free convection in the PV module back side surface</td>
</tr>
<tr>
<td>$Nu_{i,fo}$</td>
<td>Nusselt number for forced convection in the PV module back side surface</td>
</tr>
<tr>
<td>$Nu_{o,fr}$</td>
<td>Nusselt number for free convection in the PV module front side surface</td>
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<tr>
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<td>Nusselt number for forced convection in the PV module front side surface</td>
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<tr>
<td>$P$</td>
<td>Power [W]</td>
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<td>$P_{MP}$</td>
<td>Maximum power point</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl Number</td>
</tr>
<tr>
<td>$PV_{ef}$</td>
<td>Occupancy rate “gaps to PV cells in the module”</td>
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\( \dot{Q} \): Thermal energy “heat gaining by the PV module” [W]

\( q_{\text{cond}} \): Heat conduction [Joule]

\( q_{\text{conv}} \): Heat convection [Joule]

\( q_{\text{rad}} \): Heat radiation [Joule]

\( R \): Reflection coefficient

\( r \): Correlation coefficient

\( R_a \): Rayleigh Number

\( R_e \): Reynolds number

\( R_{\text{it}} \): Internal (back side surface) total heat transfer resistance [m²K/W]

\( R_{\text{to}} \): External(front side surface) total heat transfer resistance [m²K/W]

\( R_{xi} \): Internal (back side surface) conduction heat transfer resistance [m²K/W] = \( \sum \frac{\Delta x}{\lambda} \)

\( R_{xo} \): External(front side surface) conduction heat transfer resistance [m²K/W] = \( \sum \frac{\Delta x}{\lambda} \)

\( T \): Transmittance

\( T_\infty \): Absolute temperature of surrounding [°K, °C]

\( T_{\text{ambi}} \): Inside ambient temperature [°C]

\( T_{\text{ambo}} \): Outside ambient temperature [°C]

\( T_{\text{cell}} \): PV cells temperature [°C]

\( T_{\text{modi}} \): Inside (back side surface) module temperature [°C]

\( T_{\text{modo}} \): Outside (front side surface) module temperature [°C]

\( T_s \): Absolute temperature of surface [°K, °C]

\( V_{\text{MP}} \): Voltage at maximum power point

\( V_{\text{OC}} \): Open circuit voltage [V]

\( w_i \): Wind speed at the back side of PV module [m/s]

\( w_o \): Wind speed in front side of PV module [m/s]
List of Greek letters

\( \alpha_f \) : Front surface absorption coefficient
\( \alpha_{PMP} \) : Temperature coefficient for power at Maximum power point [%]
\( \alpha_{inv,T} \) : Temperature effects on inverter
\( \beta \) : Volumetric thermal expansion coefficient [1/K]
\( \beta \) : Tilt angle
\( \Delta x \) : Thickness [m]
\( \delta \) : Declination angle
\( \varepsilon \) : Emissivity
\( \eta_{PV} \) : PV module STC efficiency
\( \eta_{MPPT} \) : Inverter efficiency at Maximum power point tracking
\( \phi \) : Location latitude
\( \gamma \) : Elevation angle (90-\( \beta \))
\( \lambda \) : Thermal conductivity, conduction coefficient [W/m.K]
\( \nu \) : Kinematic viscosity [m\(^2\)/s]
\( \rho \) : Material density [kg/m\(^3\)]
\( \rho_g \) : Ground average reflectance coefficient
\( \sigma \) : Stefan–Boltzmann constant = 5.669 \times 10^{-8} \text{ W/(m}^2\text{K}^4)\)
\( \tau \) : Material transmission coefficient
\( \theta_{AOI} \) : Angle of incidence
\( \theta_{Az} \) : Surface azimuth angle
\( \theta_z \) : Zenith angle
\( \nu \) : Phase velocity [m/s\(^2\)]
\( \omega \) : Hour angle
## List of Abbreviations

<table>
<thead>
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<tbody>
<tr>
<td>AC</td>
<td>Alternative current</td>
</tr>
<tr>
<td>a-Si</td>
<td>Amorphous silicon</td>
</tr>
<tr>
<td>ARC</td>
<td>Anti Reflection coating</td>
</tr>
<tr>
<td>BAPV</td>
<td>Building Added Photovoltaic</td>
</tr>
<tr>
<td>BIPV</td>
<td>Building Integrated Photovoltaic</td>
</tr>
<tr>
<td>BOS</td>
<td>Balance Of System</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium Telluride</td>
</tr>
<tr>
<td>CEC</td>
<td>California Energy Commission</td>
</tr>
<tr>
<td>CIS</td>
<td>Copper indium Selenium</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>EPIA</td>
<td>European Photovoltaic Industry Association</td>
</tr>
<tr>
<td>EVA</td>
<td>Ethylene vinyl acetate</td>
</tr>
<tr>
<td>G\text{ISET}</td>
<td>ISET sensor irradiation measurement</td>
</tr>
<tr>
<td>G\text{Pyr}</td>
<td>Pyranometer irradiation measurement</td>
</tr>
<tr>
<td>IWES</td>
<td>Institute for Wind Energy and Energy System Technology, (Fraunhofer-IWES)</td>
</tr>
<tr>
<td>MBE[%]</td>
<td>Mean Bias Error</td>
</tr>
<tr>
<td>MDA</td>
<td>Ma’an Development Area</td>
</tr>
<tr>
<td>MENA</td>
<td>Middle east and North Africa</td>
</tr>
<tr>
<td>\mu-Si</td>
<td>Micromorphous silicon</td>
</tr>
<tr>
<td>Mono-cr</td>
<td>Monocrystalline</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum power point tracking</td>
</tr>
<tr>
<td>NERC</td>
<td>National energy research center</td>
</tr>
<tr>
<td>NOCT</td>
<td>Normal Operating cell temperature</td>
</tr>
<tr>
<td>Poly-cr</td>
<td>Polycrystalline Photovoltaic</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>RMSE[%]</td>
<td>Relative Root Mean Square Error</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Condition</td>
</tr>
<tr>
<td>SOPHIA</td>
<td>Solar Photovoltaic European Research Infrastructure</td>
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<tr>
<td>WEO 2009</td>
<td>World Energy Outlook, 2009</td>
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Finally, I would to thank my parents and siblings for their moral support and prays and letting me become who I am today.
Abstract

Photovoltaic (PV) is growing at a rapid pace in the last decade, and it achieved a considerable attention as one of the low carbon most promising renewable energy alternatives. The Photovoltaic’s performance depends mainly on the incident irradiation, ambient temperature and thermal characteristic of the PV technology.

The aim is to develop an evaluation tool for analyzing the performance of the different photovoltaic technologies. This thesis was performed for two different sites, Kassel in Germany and Ma’an in Jordan. For the Kassel site, a comparison between two different irradiation measurement sensors (Pyranometer and ISET sensor) was performed, then an estimation of electrical and thermal characteristics for the two photovoltaic technologies (polycrystalline Silicon and micromorphous silicon μ-Si) has been investigated by the simulation model. Moreover, the outputs of the simulation were evaluated by using a real measured data for the module and system level.

The evaluation of the output power for the module and system levels show less deviation by using ISET sensor as the base of irradiation measurement, while it was deviated more when measuring the irradiation via pyranometer. Therefore ISET sensor was more accurate than pyranometer for irradiation measurement.

On the other hand, for the Ma’an site, estimation of electrical and thermal characteristics for the two photovoltaic technologies (polycrystalline Silicon and Cadmium Telluride CdTe) has been determined by the simulation model. The estimated output power shows that the highest energy yield was occurred at the optimum tilt angle (32°). Generally, in the both sites the results show that, thin film technology achieves a higher specific energy yield than polycrystalline technology.
Chapter 1

Introduction
1. Introduction
Photovoltaic power generation has been receiving considerable attention as one of the most promising energy generation alternatives. It can hold the world electricity consumptions. Photovoltaic (PV) industry has been continuously growing at a rapid pace over the recent years. Silicon crystalline PV modules are widely used in the world. New PV technologies with cheaper manufacturing cost compared to traditional silicon crystalline based modules are available in the international market these days such as; amorphous silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Selenium (CIS). In addition, new standards and testing schemes are developed to be comparable with the new or improved technologies.

Photovoltaic can be recognized as one of the most promising renewable energy sources. Germany is the technology leader in photovoltaic field where research and studies are performed to optimize the PV performance for different technologies to achieve the maximum power and energy production under different conditions. Fraunhofer (IWES) institute, which is located in Kassel-Germany, is one of the leaders in photovoltaic researches and it has the PV testing facilities for such a research.

On the other hand, Jordan is located within the world solar belt and has more than 300 sunny days per year[1]. The lack of conventional resources forces Jordan to utilize abundant renewable energy resources such as solar energy. Studies related to sun irradiation in Ma'an site in Jordan introduce that it is blessed with a high insulation during the year, the generated electricity could reach more than 10 GWh/year from 5MW PV grid connected power plant[2]. Companies started to invest and test many PV technologies to study large-scale projects such as Shams Ma’an project with a 100MWp initial capacity and the project target is to expand the capacity to 500MWp in the future[3].

Due to increasing in the electricity price; Domestic PV systems could be used and implemented with a low system cost when compared to the previous years. Because of the noticeable drop in the PV system cost, it could compete the utility electricity price especially in the region with a high irradiation such as the solar belt regions. However, PV installations are mainly ground mounted; in Germany Building Integrated Photovoltaic (BIPV) and roof top installations have a big role in PV projects and people benefit from these projects through reducing the energy bill. Many countries started to issue a special legislation to encourage investing in PV projects.

Two PV modules with the same rated power – even with the same technology- will not provide the same output power and energy yield. Also, the different thermal characteristics play an important role in module efficiency as well as the output power; this is because the PV module is influenced by a variety of environmental factors and solar cell physics. Hence, testing and modelling the PV module/system in the outdoor environment with specifying the influences of all significant factors, are very important to check the system performance and to facilitate
efficient troubleshooting for photovoltaic module/system through considering hourly, daily and monthly or annual basis \cite{4}. This is performed through the European project (SOPHIA) which defines the relevant aspects and deficits of the module and system performances in order to benchmark a standardized test procedure data base.

Photovoltaic output power depends on many factors; such as sun position, weather conditions, module temperature, thermal characteristics, module material composition and mounting structure.

Real time power generation should be investigated precisely for grid performance, because a high penetration of PV production could create instability in the grid \cite{5}. It is very important to measure the produced PV systems peak power to protect the grid and power needed at high consumption. The costs of the generated electricity from photovoltaic’s decrease year by year and it is expected to be cheaper than conventional recourses, and this leads the customers to install their PV systems instead of using the expensive conventional electricity from the utility \cite{6}. In future, real time power especially from domestic systems will be more important to take into consideration because higher penetration of PV systems will affect the grid performance. Furthermore, it is the base of controlling energy management systems for the smart homes.

The uncertainty of the photovoltaic performance models is still too high; the early existing PV performance models mainly deal with the ideal PV module characteristics rather than the dynamic situation under the surrounding conditions \cite{7}. Also, researches are mainly conducted for evaluating PV module performance rather than system performance. In Jordan there are a lack of studies concerning the dynamic operation of PV modules and systems.

The objective is to develop an evaluation tool for analyzing the performance of different photovoltaic technologies; electrical and thermal performance photovoltaic model based on the PV module characteristics is simulated, under consideration of the different irradiation sensor measurement and different PV modules technologies. Module level and system level are simulated regarding the compatible information and surrounding boundary conditions.

The study is performed by considering the maximum efficiency of the PV module and the effect of module temperature on the output power as well as energy yield, the utilized tools for the study is Matlab Simulink and it can be used for different PV module/system mounting structures such as ground mounting, Building Integrated Photovoltaic (BIPV) and Building Added Photovoltaic (BAPV). In this thesis the evaluations and measurements are based on ground mounted structures. The simulation is performed under physical, thermal and electrical characteristics of the PV modules. Moreover, the degradation is considered in the simulation for the PV modules under test.
Two locations are considered; Kassel in Germany and Ma’an in Jordan based on available meteorological data. In relation to Kassel site the model is evaluated based on two different PV Technologies; polycrystalline Silicon and micromorphous silicon μ-Si. Also, with introducing isolation material at the back cover of the PV module to study the effects of the low ventilation at the backside of the module, which is the branch of the Building Integrated Photovoltaic (BIPV). DC and AC output power and energy yield at 30° south orientation are predicted and evaluated with the available measured data of the PV test filed in Fraunhofer-IWES.

In relation to Ma’an, two PV technologies are considered; polycrystalline Silicon and Cadmium telluride CdTe technologies. DC and AC output power and energy yield for different south orientation are predicted. Also an investigation for the two different brands of polycrystalline technology with the same output power is performed to compare the different performances. The available meteorological data belongs to Ma’an Development Area (MDA)\(^1\). The PV modules which are under study, belong to the PV test field of (Kawar Group company\(^2\)), they are now in the measuring stage to specify the most efficient PV technology in the site.

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1 MDA: Ma’an Development Area , [www.mda.jo]

2 Kawar Group: is a Jordanian company, they own a PV test field in Ma’an (www.Kawar.com)
Chapter 2

Photovoltaic Overview
2. Photovoltaic Overview

In this chapter, an introduction about the main PV electrical characteristic is explained, different technologies specifications with the main performance factor are investigated. At the end of this chapter a brief economical and market survey is introduced.

2.1 Photovoltaic characteristics

Photovoltaic systems are mainly grouped in two categories; Stand-alone system (also called off-grid) and grid connected system (also called on-grid). Stand alone systems can be integrated with another energy source such as Wind energy or a diesel generator which is known as hybrid system. The storage is the main difference between these categories, where the produced electrical energy is stored in batteries in off-grid system and the public grid utility is the storage tank for the excessive produced energy from on-grid systems.

On-grid systems are installed more often nowadays, some countries offer incentives to encourage people to invest in Photovoltaic and to reduce green house gas emissions. Feed-in-tariff was introduced in European countries such as Germany and Greece. “Net metering” mechanism was introduced in USA, and it is now under parliament discussion in Jordan.

Photovoltaic systems can provide electricity for home appliances, villages, water pumping, desalination and many other applications. Figure 2.1 explains briefly the different photovoltaic system applications:

![Photovoltaic systems applications diagram]

Figure 2.1: Photovoltaic systems applications[8]
- **Irradiation effect**

Photovoltaic output power is affected by incident irradiation. PV module short circuit current $(I_{sc})$ is linearly proportional to the irradiation, while open circuit voltage $(V_{oc})$ increases exponentially to the maximum value with increasing the incident irradiation, and it varies slightly with the light intensity $[^9]$. Figure 2.2 describes the relation between Photovoltaic voltage and current with the incident irradiation.

![Figure 2.2: Effects of the incident irradiation on module voltage and current $[^9]$](image)

- **Temperature effect**

Module temperature is highly affected by ambient temperature. Short circuit current increases slightly when the PV module temperature increases more than the Standard Test Condition (STC) temperature, which is 25°C. However, open circuit voltage is enormously affected when the module temperature exceeds 25°C. In other words the increasing current is proportionally lower than the decreasing voltage. Therefore, the output power of the PV module is reduced $[^9]$. Figure 2.3 explains the relation between module temperature with voltage and current.

![Figure 2.3: Effect of ambient temperature on module voltage and current $[^9]$](image)
- **Maximum power point (P\textsubscript{MPP})**
  Maximum electrical power of the PV module is equal to the current at maximum power point (I\textsubscript{MP}) multiplied by the voltage at maximum power point (V\textsubscript{MP}), which is the maximum possible power at Standard Test Condition (STC). Referring to Figure 2.4, the “knee” of the I-V curve represents the maximum power point (P\textsubscript{MPP}) of the PV module/system. At this point the maximum electrical power is generated at STC\textsuperscript{[10]}. The usable electrical output power depends on the PV module efficiency which is related to the module technology and manufacture.

- **Fill factor (FF)**
  The fill factor is an important parameter for PV cell/module; it represents the area of the largest rectangle, which fits in the I-V curve. The importance of FF is linked with the magnitude of the output power. The higher the FF the higher output power. Figure 2.5 illustrates the fill factor which is the ratio between the two rectangular areas and is given by the following formula. The ideal FF value is 1 which means that the two rectangles are identical\textsuperscript{[10]}.

$$FF = \frac{I_{MP} \cdot V_{MP}}{I_{SC} \cdot V_{OC}}$$
• **Module efficiency ($\eta_{PV}$):**
The PV cell/module efficiency is the ability to convert sunlight to electricity. The efficiency is necessary for space constraints such as a roof mounted system. Mathematically, it determines the output power of the module per unit area. The maximum efficiency of the PV module is given by:

$$\eta_{PV_{max}} = \frac{V_{MP} \cdot I_{MP}}{G \cdot A} \cdot 100\%$$

Where $G$ is global radiation and considered to be 1000 W/m$^2$ at (STC) and $A$ is the Area of the PV module [11].

**2.2 Photovoltaic module technologies**
The single junction technology is grouped into two main types; silicon crystalline and thin film technologies. Currently, multi-junction technology is under research and processing, to enhance the PV modules efficiency and to improve the response sensitivity of the sun light spectrum in order to cover the entire incident irradiation wavelength. Figure 2.6 shows the main parts of the PV module structure, they are as follows:

- **Front surface**: mainly is a glass cover, and it must have a high transmission and low reflection capability for the concerned sun light wavelength. Low iron glass is commonly used because of its “low cost, strong, stable, highly transparent, and impermeable to water and gases and has good self-cleaning properties” [11] [Appendix B].
- **Encapsulant**: is used to provide a strong bond between the solar cells in the module, it should be stable at different operating temperatures and should be transparent with low thermal resistance. EVA (ethyl vinyl acetate) is commonly used with a very thin layer at the front and back surface of the assembled cells [11].

![Figure 2.6: PV module layers][11]
- **PV cells**: is the part which is responsible for producing power.
- **Back surface**: is the back sheet for the PV module, it can be made from Tedlar (thin polymer sheet) material or glass for building façade. It must have low thermal resistance \[^{[11]}\].

The following is a summary of some of the available PV technologies in the market.

### 2.2.1 Crystalline technology

Crystalline technology is the most efficient PV modules available in the market. In general, silicon based PV cells are more efficient and longer lasting than non-silicon based cells. On the other hand, the efficiency decreases at higher operating temperature \[^{[12]}\].

#### 2.2.1.1 Monocrystalline Technology

Monocrystalline is the oldest, most efficient PV cells technology which is made from silicon wafers after complex fabrication process \[^{[12]}\].

Monocrystalline PV cells are designed in many shapes: round shapes, semi-round or square bars, with a thickness between 0.2mm to 0.3mm \[^{[12]}\]. Round cells are cheaper than semi-round or square cells since less material is wasted in the production. They are rarely used because they do not utilize the module space. However, in BIPV or solar home systems where partial transparency is desired, round cells are a perfectly viable alternative \[^{[8]}\]. Figure 2.7 shows the monocrystalline PV module and cell layered structure.

![Monocrystalline PV module and cell layered structure](image)

**Figure 2.7: monocrystalline PV module and cell layered structure \[^{[13]}\]**

The main properties of monocrystalline PV module are \[^{[8]}\]:

- Efficiency: 15% to 18% (Czochralski silicon).
- Form: round, semi round or square shape.
- Thickness: 0.2mm to 0.3mm.
- Color: dark blue to black (with ARC), grey (Without ARC).
2.2.1.2 Polycrystalline
Polycrystalline PV modules are cheaper per unit area than monocrystalline; the module structure is similar to the monocrystalline \cite{12}. To increase the overall module efficiency, larger square cells should be used. By using larger cells the module cost will be lower, because less number of cells are used \cite{8}. Figure 2.8 shows a polycrystalline cell and module.

![Polycrystalline cell and module](image)

Figure 2.8: Polycrystalline cell and module \cite{8}

The main properties of polycrystalline PV module are \cite{8}:
- Efficiency: 13% to 16%.
- Form: Square.
- Thickness: 0.24mm to 0.3mm.
- Color: blue (with ARC), silver, grey, brown, gold and green (without ARC).

2.2.2 Thin film Technology
Thin film technology represents the second PV generation; due to less production materials and less energy consumption, it’s cheaper than crystalline technology. Amorphous silicon, copper Indium Silinum (CIS) and Cadmium Telluride (CdTe) are used as semiconductor materials. Because of the high light absorption of these materials, layer thicknesses of less than 0.001mm are theoretically sufficient for converting incident irradiation \cite{8}. Figure 2.9 shows a comparison between the Crystalline and thin film technologies. It can be seen that thin film technology has the lower cell thickness, semiconductor consumption and primary energy consumption.
Thin-film cells are not limited to standard wafer sizes, as in the case of crystalline cells. Theoretically, the substrate can be cut to any size and coated with semiconductor material. However, because only cells of the same size can be connected in series for internal wiring, for practical purposes only rectangular formats are common. “The raw module” is the term which is used for thin film technology\textsuperscript{[8]}

Despite the relatively low efficiency per unit area, thin film technology has many advantages when compared to crystalline technology\textsuperscript{[8]}:

- Better utilization of diffuse and low light intensity.
- Less sensitive to higher operating temperature
- Less sensitive to shading because of long narrow strip design, while a shaded cell on crystalline module will affect the whole module.
- Energy yield at certain condition is higher than crystalline technology.

2.2.2.1 Amorphous Silicon technology (a-Si)

In this case, silicon is deposited in a very thin layer on to a backing substrate such as; metal, glass or even plastic. Figure 2.10 shows layered structure of an amorphous cell. This technology is not preferred to utilize for roof installation due to its low efficiency per unit area which leads to consume a larger area than utilizing crystalline silicon\textsuperscript{[8]}.

Another disadvantage of a-Si PV cells is light-induced degradation (known as the Staebler-Wronski effect), which reduces the module efficiency during the first 6-12 months of operation before leveling off at a stable value of the nominal output power\textsuperscript{[8]}.

Figure 2.9: Comparison of cell thickness, material consumption and energy expenditure for thin-film cells (left) and crystalline silicon cells (right)\textsuperscript{[8]}
The main properties for amorphous silicon PV module are [8]:
- Efficiency: 5% to 7% module efficiency (stabilized condition).
- Thickness: 1mm to 3mm substrate material, with approximately 0.001mm (1μm) coating, of which approximately 0.3μm amorphous silicon.
- Color: reddish brown to blue or blue-violet.

2.2.2.2 Copper indium Selenium technology (CIS) [8]
Currently, Copper Indium Selenium or diselenide technology is the most efficient thin film technology. CIS compound is often also alloyed with gallium (CIGS) and/or sulphur, and it is not susceptible to light-induced degradation like amorphous silicon. Figure 2.11 shows the layered structure for CIS module. The other advantages of CIS are:
- Low cost processing method and using less than 1/200 active material vs. crystalline silicon.
- Has a wide spectrum response for the sun light.
- Has the highest module efficiency among thin film technology.

The main properties for CIS PV module are [8]:
- Efficiency: 9% to 11% module efficiency.
- Thickness: 2mm to 4mm substrate material (non-hardened glass) with 3μm to 4μm coating, of which approximately 1μm to 2μm CIS.
- Color: dark grey to black.
2.2.2.3 Cadmium Telluride technology CdTe
The main advantage of this technology is the lowest production cost among thin film technologies. The back contact is a weak point in CdTe cells since it is responsible for ageing. Modern high-grade CdTe modules do not suffer any initial degradation such as Amorphous technology. Figure 2.12 shows the layered structure of CdTe PV module [8].

![Figure 2.12: CdTe module and layered structure of a CdTe cell Source [8]](image)

The main properties for CdTe PV modules are [8]:
- Efficiency: 7% to 8.5% module efficiency.
- Thickness: 3mm substrate material (non-hardened glass) with 0.005mm coating.
- Color: reflective dark green to black.

2.2.2.4 Micromorphous tandem Technology
Micromorphous silicon module technology combines microcrystalline and amorphous silicon in tandem structure to enhance the performance of the module; they are assembled in the top and bottom of photovoltaic cell. Microcrystalline cells have similar optical properties as the crystalline cells. Also, micromorphous cell has the ability to response to a broad band of the solar spectrum wave length, and the efficiency could reach to 9.1%. The light-induced degradation is very slight comparing with amorphous cells [8].

Figure 2.13 shows layered structure and spectrum response for a certain micromorphous PV module.

![Figure 2.13: Micromorphous layered structured and its spectrum response [14]](image)
Researches pay attention to modify or merge multilayer junction to cover the entire solar spectrum. The greatest energy of the solar irradiation exists in the visible light wave length (between 400nm and 800nm). Spectral response describes the wavelength range in which a photovoltaic cell works most efficiently and the efficiency influences under different irradiance conditions [8].

The following figure shows the mismatching between PV cells response and the solar radiation energy. It is concluded that, although crystalline solar cells have the maximum single junction efficiency (13-18%), are not particularly sensitive to long wavelength solar radiation. Amorphous silicon cells can absorb short wavelength light optimally. In contrast, CdTe and CIS have better response of absorbing the medium wavelength, but the main constraint of using these technologies are the low modules efficiencies (5-7%). Currently, many modern cells are multi junction structures to combine multiple compounds, to response for a wider spectrum and to harness a much larger portion of the available energy than what would be possible with a single type of solar cell such as silicon thin film tandem junction PV cells [8].

![Figure 2.14: Spectral sensitivity of different solar cell types][15]

### 2.3 Performance factors

Photovoltaic module is affected by many factors during conversion; these factors are occurred mainly by climatic conditions, which affect the effective incident irradiation, and also from the fabrication and electrical specification of the PV modules. In this section a summary of the main factors, which are considered in the simulation, are introduced.

- **Optical loss**
  The effective irradiation is the total irradiation which reaches the PV cells. It is responsible on generating power. Incident irradiation faces obstructions before reaching the PV cells. It is reflected and absorbed from glass cover, EVA and ARC layers. This leads to decrease the
expected output power. However, the main losses are caused by the interference between the air and the glass cover\textsuperscript{[16]}.

On the other hand, incident irradiation on the PV module falls in different angles and projections, and the optical losses become higher as the irradiation incident angle is higher; this depends on the season, location and mounting structure of the PV module\textsuperscript{[16]}. More details are explained in chapter 4.

- **Thermal effect**
  Thermal response of the PV module is the main factor which affects the electrical power output. The PV module receives the incident irradiation; a portion of it is converted to electricity in proportional with the module efficiency. The rest of the incident irradiation heats the PV module and increases its operating temperature in relation to the PV material heat capacity\textsuperscript{[17]}. As it is explained in section 2.1, PV module voltage is reduced extremely compared to the increasing of the current at higher operating temperature, so the generated power is reduced.

  In the same time, a portion of the absorbed heat is dissipated into surrounding; this is occurred through conduction, convection and the radiation exchange heat transfer between the module and the surrounding\textsuperscript{[17]}. In the simulation model, heat transfer effect on the PV module is determined dynamically. The explanation and calculation are discussed in chapter 4.

- **Degradation**
  Degradation (or aging) of the PV module has a key role for decreasing the output power among its life time, and it differs from technology to another. It is important factor for the investors whom interested in Photovoltaic field. In this section degradation from PV performance point of view is considered based on the previous researches on this field\textsuperscript{[18]}.

  Degradation generally is caused by UV absorption near the top of silicon surface for crystalline silicon based technology, many other factors such as lamination disintegration of backing material, bubbling at solder spots, and fissures in backing material, module delamination, solder-joint degradation, hot spots, encapsulant, discoloration, mechanical damage and cell degradation. NREL\textsuperscript{3} Laboratory grouped the degradation into 5 categories\textsuperscript{[19]}:

  1) Degradation of packaging materials.
  2) Loss of adhesion.
  3) Degradation of cell/module interconnects.
  4) Degradation caused by moisture intrusion.
  5) Degradation of the semiconductor device.

\textsuperscript{3} NREL: National Renewable Energy Laboratory. [www.nrel.gov]
EVA and back sheet layers obscurations are the main reason for the PV module degradation. EVA represents the encapsulation for the front and back of the PV cells, protects the cells from the moisture. However, it is impossible to protect it among the lifetime, because EVA material is degraded by ultraviolet (UV) radiation, and it becomes less elastic during its life time. Then the moisture can reach the PV cells even with a very small amount, and during the years electrical connections will be trapped by the moisture leading to increase the internal resistance which affects the output voltage. On the other hand, and if the UV radiation reaches the PV cells, it causes an incremental decrease in the output current\textsuperscript{[20]}.

Regarding many studies of PV cells, it is concluded that the degradation differs from technology to another and from region to another depending on the climatic and weather conditions. Table 2.1 shows different studies performed by different institutes and centers in different areas in the world. The Australian Cooperative Research Center studies the crystalline and thin film technologies during 19 months. This study concludes that the crystalline technologies degrade with an average of 2\% per year during the period of study, while amorphous silicon and CIS shows a significantly higher degradation\textsuperscript{[18]}.

Another study was performed in Lugano (Switzerland) for 10kWp crystalline silicon PV system, which shows degradation rate of 0.53\% per year which is achieved during the 20 years of the study\textsuperscript{[18]}.

Also, a study was performed in Negev desert (for 60 polycrystalline silicon PV modules during three years in 1992. The result was a degradation rate of 1.3\% per year. Nevef desert is almost in the same latitude of Ma’an city in Jordan\textsuperscript{[18]}.

In general silicon crystalline modules have a linear degradation rate with around (0.3\%-1\% per year) during the module life time. On the other hand thin film technology degrades rapidly during the first 12-18 months of operation before leveling off at a stable value (the main effect known as the Staebler-wronski effect)\textsuperscript{[18]}. In relation to thin film PV modules manufacture nowadays introduce the module specification after the first degradation in order to overcome the conflict between the nominal value for the first year and the next years.

In the simulation, degradation is assumed to be 3.5\% for the modules under study in Kassel, this assumption is with respect to the module age (3 years), based on the modules age and the test field criteria. However, it is considered 1.3\% per year in Ma’an case. This value is based on the study performed in Negev desert and based on the module age.
### Table 2.1: Summary of some studies on PV module field degradation around the world

<table>
<thead>
<tr>
<th>Number in Section</th>
<th>Location</th>
<th>Test duration</th>
<th>Module Tech.</th>
<th>Degradation rate (%/year)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1[15]</td>
<td>Perth (Australia)</td>
<td>16-19 months</td>
<td>c-Si</td>
<td>0.5-2.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperate climate</td>
<td></td>
<td>p-Si</td>
<td>1.0-2.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>a-Si</td>
<td>18.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CIS</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>2[22]</td>
<td>Mesa, Arizona (USA)</td>
<td>2-4-4 years</td>
<td>c-Si</td>
<td>0.4</td>
<td>Initial scattering of the performance is high</td>
</tr>
<tr>
<td></td>
<td>Desert climate</td>
<td>2-4-2.7 years</td>
<td>p-Si</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.7-6.7 years</td>
<td>a-Si</td>
<td>1.16 (6-7 year) to 3.52 (2.7 year)</td>
<td></td>
</tr>
<tr>
<td>3[20]</td>
<td>Trinidad, California (USA)</td>
<td>11 years</td>
<td>c-Si</td>
<td>0.4</td>
<td>Variability in maximum power increase significantly over time</td>
</tr>
<tr>
<td></td>
<td>Cool coastal climate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4[18]</td>
<td>Hamamatsu (Japan)</td>
<td>10 years</td>
<td>c-Si</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperate climate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5[23]</td>
<td>Golden, Colorado (USA)</td>
<td>8 years</td>
<td>c-Si</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mountain continental climate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6[24]</td>
<td>Ispra (Italy)</td>
<td>22 years</td>
<td>p-Si</td>
<td>0.3 (Silicone)</td>
<td>Two technologies were evaluated for the encapsulant, namely silicone and EVA</td>
</tr>
<tr>
<td></td>
<td>Temperate climate</td>
<td></td>
<td></td>
<td>0.67 (EVA)</td>
<td></td>
</tr>
<tr>
<td>7[28]</td>
<td>Lugano (Switzerland)</td>
<td>20 years</td>
<td>c-Si</td>
<td>0.53</td>
<td>Power variability has increased significantly</td>
</tr>
<tr>
<td></td>
<td>Temperate climate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8[26]</td>
<td>Negev desert (Israel)</td>
<td>3-4 years</td>
<td>p-Si</td>
<td>1.3</td>
<td>Tests were performed under concentrated light using mirrors (2:56 ratio)</td>
</tr>
<tr>
<td></td>
<td>Desert climate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- c-Si: Crystalline silicon; p-Si: polycrystalline silicon; a-Si: amorphous silicon.

Many factors regarding a balance of system (BOS) should be considered, these factors affect the PV system and mounting structure. Figure 2.15 shows the main losses which affects the conversion process. These losses are clouds, pollution, soiling and atmospheric particles and shading. Also, PV material spectral mismatch, module optical losses, connection mismatching of PV module, deviation from data sheet and cables losses.
The following are examples for performance factors that affect the system and mounting structures.

- **Wind**
The PV module temperature is affected by the wind speed and direction as well as the solar irradiation and ambient temperature. The wind speed has an important effect on cooling the PV module through convection heat transfer, even the wind speed is very low, but it increases the convection heat transfer which decreases the module temperature based on the mounting structure for the PV module or system\(^{[13]}\). Also, the wind speed effect on the mounting structure should be considered, because it affects the mechanical behavior of the PV system.

- **Snow**
In higher altitude areas, the PV modules are strongly affected by snow during the winter season; the snow melting on the photovoltaic systems depends on the module temperature and irradiation; because the heat capacity of the photovoltaic is low, therefore its temperature follows quickly the outside temperature. Horizontal module has greater exposure to the snow than the inclined module. By increasing the slope of the PV module, the effect of the snow will be lower\(^{[13]}\). In relation to the solar irradiation data which are used in the simulation, it can be noticed that the snow affects the irradiation measurements in the winter season.

- **Dust and Dirt**
Dirt and dust can be noticed clearly at the lower edges of the module. This effect is noticed more often in the summer, especially in the dry areas. In countries with little rainfall, a greater loss due to soiling is expected, so that periodical mechanical cleaning should be considered especially in the summer season\(^{[13]}\). In the simulation, dust effect is not accounted, so this can causes a deviation between predicted and measured values.
2.4 Photovoltaic Economics and market

2.4.1 Photovoltaic economics

The economics of the photovoltaic takes more consideration in the system level more than module level; PV system consists of the PV modules and Balance of System (BOS), which means the complimentary electronic, electrical, mechanical devices and the required safety. The PV modules as well as PV system prices have a rapid decrease in comparison with 5 years ago and the main reason for this rapid decrease is the research and development in combination with the market development [21].

Based on EPIA\textsuperscript{4} study and by considering the system performance ratio of 80% (Performance ratio “is the relation between the actual and theoretical energy output of the PV plant” [22]), the levelized cost of energy (€/kWh) for PV electricity generation cost for different regions in Europe depends on the annual irradiation. For example the specific energy yield in the Scandinavian countries is between 700-800 kWh/kWp and the PV electricity generation cost is around 0.25 €/kWh. However, in south of Europe, such as Spain and Italy, the specific energy yield is around 1500 kWh/kWp and the PV electricity generation cost is around 0.13 €/kWh. These values are expected to decrease in the coming years with expected range of (0.14 - 0.07) €/kWh for the large scale PV systems in most of Europe by 2020 [21].

In relation to PV technology prices, the prices are decreasing year by year. Figure 2.16 shows the annual price reduction for different PV module technologies and the expectation of the module price until the year 2015 [21].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{module_pricing.png}
\caption{Module Pricing, driven by efficiency [23]}
\end{figure}

\footnotesize{\textsuperscript{4} EPIA: European Photovoltaic Industry Association}

\newpage

22
It can be seen that the reduction in the prices among the different PV modules are linear. Also, thin film technology is the cheapest technology. Multicrystalline technology which is highly used, is expected to be less than 1.25$/Wp by 2013.

### 2.4.2 Photovoltaic Market

In the last decade Photovoltaic market grows rapidly and proves its improvement. The total installed capacity in the world in 2000 was 1.5 gigawatts peak (GWp) and in 2010 it was around 40 GWp which is 27 times more than the beginning of this decade with a yearly growth rate of 40%. On the other hand, the total installed capacity is recorded as 7.2 GWp in 2009, while it is recorded 16.6 GWp in 2010. This is a very high rate to encourage the industry to develop and invest in this field. As an example, Germany stated a national target with installing 51 GWp by the year 2020, in 2010 Germany installed 7.4 GWp and the total capacity of the grid connected systems are more than 17GWp[^24].

Figure 2.17 shows the global cumulative installed capacity from 2000 to 2010.

![Figure 2.17: Global cumulative installed capacity](image)

[^24]: Given their annual market size and cumulative installed capacity, Japan and China are presented separately from the rest of the APEC region in the reference document.

“Three main zones developing markets for PV in contrasting ways. The EU leads the way, followed by the Asia-Pacific (APEC) region, following the pace of economic development and wealth. Also, Japan and China, the APEC region includes South Korea, Australia, Taiwan and Thailand[^5]. North America appears is the third region, with Canada developing steadily alongside the USA, a huge market with tremendous potential for growth outside these three regions, the Middle East and North Africa (MENA) region represents untapped potential for the
medium term. PV also shows great potential in South America and Africa, where electricity demands will grow significantly in the coming years”[24].

2.4.3 Market forecasts until 2015

Based on EPIA study. Figure 2.18 illustrates two future different scenarios for PV market growth rate, Policy-driven⁶ and moderate scenarios⁷, the policy driven scenario shows more optimistic and accurate expectation than the moderate one, and this can be proved by considering the market growth over the last decade[24].

![Figure 2.18: expected annual PV market growth][24]

It can be noticed that the Policy-driven scenario expects around 196GW of PV installed capacity while the moderate one expects the installed PV capacity to be around 131GW, in both cases it is expected to reach 100GW within 3 to 4 years[24]. On the other hand, it is also expected to rebalance the global PV installation; Figure 2.19 shows the future cumulative installed capacity in the world.

---

⁶ Policy-Driven scenario: “This scenario assumes the continuation or introduction of support mechanisms, namely feed in tariffs, accompanied by a strong political will to consider PV as a major power source in the coming years. This must be complemented by a removal of non-necessary administrative barriers and the streamlining of grid connection procedures”[24].

⁷ Moderate scenario: “This scenario assumes a “business-as-usual” market behavior with no major reinforcement of existing support mechanisms, but takes into account a reasonable continuation of current Feed in tariffs aligned with PV systems prices”[24].
As it can be seen, in years 2010 and 2011 there is no sign of any change, but when considering the coming years and based on the rapid improvement in PV market in China, Japan and North America, major growth will occur in the mentioned regions specially with the lower manufacturing prices than in Europe [24].
Chapter 3

Approach
3 Approach

3.1 Technique

The efficient PV simulation model should be applicable in various circumstances. It can be used to design a certain PV system and predict the real time output power, which is an essential point for the grid performance, also to determine the hourly, daily, monthly and yearly energy yield. It can also be used for monitoring the PV module/system behavior under different environmental conditions in order to diagnose any problem during the operation\(^4\).

The previously existing PV performance models mainly deal with the ideal PV module characteristics. With respect to the outcome of the SOPHIA Project; the uncertainty of the performance model of the PV module and System are still too high\(^7\). To improve the uncertainty the simulated model takes into account many aspects such as the effects of optical loss on the incident irradiation, PV module heat capacity, dynamic module temperature (the module temperature follows the previous module temperature sequentially in order to achieve the real time output power). This simulated model is based on these aspects in order to determine accurate results of the predicted output power and energy yield. On the other hand, the most of available researches are mainly conducted for evaluating PV module performance rather than system performance.

Photovoltaic degradation is also considered in the model, the effect of the degradation is considered in order to obtain compatible results with the measured value, as well as to obtain close results for the PV system regarding its age.

Briefly, the simulated model is objected to develop an evaluation tool for analyzing the performance of different photovoltaic technologies. The simulated performance photovoltaic model is based on the thermal and electrical characteristics of the PV module. Different irradiation sensor measurements have been used.

Two approaches are simulated and evaluated, the module and system levels. For module level, the simulation is based on the input power (irradiation) with the related losses. The output power of the simulation is based on thermal dissipated power and DC output power. On the other hand, system level simulation is based on a mathematical inverter model in order to predict the AC power.

The study is performed by considering the maximum efficiency of the PV module and the effect of module temperature on the output power as well as energy yield. The utilized tools for the study is the Matlab Simulink and it can be used for different PV module/system mounting structure such as ground mounting, BIPV and BAPV.
Two locations are considered; Kassel in Germany and Ma’an in Jordan based on available meteorological data. For Kassel site, the model is evaluated based on two different PV Technologies; polycrystalline Silicon and micromorphous silicon μ-Si. Also, with introducing isolation material at the back cover of the PV module to study the effects of the low ventilation at the backside of the module, which is the branch of the Building Integrated Photovoltaic (BIPV). DC and AC output power and energy yield at 30° south orientation are predicted and evaluated with the available measured data of the PV test field in Fraunhofer-IWES. For Ma’an site, two PV technologies are considered; polycrystalline Silicon and Cadmium telluride (CdTe) technologies are studied. DC and AC output power and energy yield for different south orientation are predicted. Also an investigation for two different brands of polycrystalline technology with the same output power is performed to compare the different performances.

In order to validate and check the simulation model, three evaluation tools are considered to compare predicted results with the real measurements in Kassel site. Root-Mean-Square Error (RMSE), mean bias error (MBE) which are commonly used for estimating the differences between the real measured values and simulated (predicted) values. Relative RMSE gives information on the general scatter of the simulated values versus measured values. Relative MBE gives information on a general offset of the simulated results. The negative value of the relative MBE means that the prediction is under estimation and the positive value means that the prediction is over estimation.\[25\]

\[
RMSE[\%] = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_{pred} - x_{meas})^2}
\]

\[
MBE[\%] = \frac{1}{n} \sum_{i=1}^{n} (x_{pred} - x_{meas})
\]

Also, correlation Co-efficient ($r$) is considered, it gives an indication of how strengthen of the linear relation between measured ($x$) and simulated values ($y$). Correlation Co-efficient is always between -1.0 and +1.0. If the correlation is positive, the relation is positive. If it is negative, the relation is negative. A correlation greater than 0.8 is generally described strong, whereas a correlation less than 0.5 is generally described weak. It is given by the following equation\[26\].

\[
r = \frac{n \sum xy - (\sum x) * (\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2} \sqrt{n(\sum y^2) - (\sum y)^2}}
\]

The evaluation is based on tilt angle 30° south orientation for the irradiation measurement and PV module/ system structure.
3.2 Site specifications

Two sites are chosen to perform the study, Kassel in Germany and Ma’an in Jordan.

3.2.1 Kassel

Kassel is located in the middle of Germany; it’s located at latitude 9.46° and longitude 51.3°. Altitude of Kassel is around 190-230m over the sea level. “The coordinates are available in Fraunhofer –IWES facility”.

The average daily global horizontal irradiation is around 3 kWh/m².day \(^{[27]}\). Kassel receives a high amount of diffused irradiation because of the clouds and long winter season than in Middle East region. Many houses install PV systems and integrate them with the public utility grid. They are benefiting from Feed-In-tariff mechanism for selling the excess electrical energy generated by PV system to the utility. The following figure shows the yearly incident irradiation in Kassel.

![Yearly global horizontal radiation in Kassel](image)

Figure 3.1: yearly global horizontal radiation in Kassel \(^{[27]}\)

Kassel has many institutes and companies concern in renewable energy, many studies were performed and evaluated, and this encourages researching and studying the solar projects regarding the technologies and international criterion. Institute for Wind Energy and Energy System Technologies (Fraunhofer-IWES) is one of the leaders in solar energy field, where this thesis is supervised.
3.2.2 Ma’an
Ma’an is located in the southern part of Jordan, at latitude 30.2° and longitude 35.4°. Altitude of Ma’an is around 1000m over the sea level, “these coordinates are provided within the meteorological data file”.

Ma’an (look to the boundary condition, section 4.4) was chosen because it is one of the best sites in Jordan, it is located within the “solar belt” and it’s considered in Desertec project as an area with a very good solar irradiation\(^{[28]}\). Ma’an is one of the highest solar irradiation areas in Jordan and it has low values of diffuse irradiation. The annual average daily global irradiance is around 6 kWh/m\(^2\).day, and it has wide flat lands which is suitable for a large scale PV plants\(^{[1]}\)

Many investors these days concern for performing large scale PV projects in Ma’an, and around 5 small systems are tested to find out the suitable technology for the area’s weather condition\(^{[3]}\). The following map shows the global horizontal insulation bands in Jordan

![Distribution of daily average solar radiation in Jordan]\(^{[1]}\)

3.3 Photovoltaic under study
Many technologies are chosen to perform this thesis; these technologies are simulated and evaluated in relation to module level and system level. DC power and energy are determined for modules level, and AC power and energy are considered for system level.

For module level, each module under test is simulated through its electrical specifications and dimensions from the data sheet (Table 3.1). In relation to the system level, the PV modules under test are modeled as a PV array; each PV array is designed regarding the PV modules peak power, which depends mainly on the incident irradiation. Also, the design is based on the maximum DC input power of the inverter, the modeled inverter is fabricated by SMA company, with rated power of 1200W [Appendix C], the PV module temperature is considered also in the system level part.
In Kassel, micromorphous silicon and polycrystalline are studied. They are simulated on the basis of the presence and absence of a thermal isolation at the back cover of the PV module; the isolation is referred to the BIPV approach; because in this case the ventilation at the back side is very low. These modules are evaluated in relation to the available data which is measured by Fraunhofer (IWES) institute, the evaluation results are explained in chapter 5. The simulation is based on 30° south orientation, and on time resolution of 15 seconds. The irradiation data is based on the pyranometer and ISET sensor measurements. The simulation is based on monthly meteorological data which is collected at 15 seconds time resolution. Then the data is collected together to perform a yearly predicted data; because of the large repetition iteration, which the computer operating system cannot cover.

1. Micromorphous silicon technology (85Wp)
   The module peak power is 85Wp; the simulation and evaluation are conducted on the basis of the presence and absence of isolation layer at the back cover of the PV module. The system composes of 12 modules with capacity of 1020Wp; the array consists of 4 strings, and each string has 3 modules in series.

2. Polycrystalline silicon technology (162Wp)
   The module peak power is 162Wp; the simulation and evaluation are conducted on the basis of the presence and absence of isolation layer at the back cover of the PV module. The system consists of 1 string with 7 modules in series; the system peak power is 1134Wp. Figure 3.3 shows the PV test field which is located in Fraunhofer (IWES) facilities.

![Figure 3.3: PV test field infrastructure in IWES (left: Polycrystalline. center and right: Micromorphous)](image)

On the other hand, three modules are considered in Ma’an, these modules are owned by a private test field of a private company. In order to test the performance of the modules; PV power, energy yield and specific energy are determined at different tilt angles. The irradiation measurement is based on rotating shadow band radiometer instrument (RSR) with time resolution of 10 minutes. The meteorological data belongs to Ma’an Development Area (MDA) [29]. Cadmium telluride (CdTe) and Polycrystalline PV modules are considered.
1. Cadmium Telluride technology (70Wp)
The module peak power is 70Wp; the simulation is based on the module and system level, the system composes of 5 strings, each string has 3 modules in series, the system peak power is 1050Wp.

2. Polycrystalline silicon technology (230Wp)
Two different brands with the same peak power are tested and compared together. The module peak power is 230Wp; the simulation is based on the module and system level. The system consists of 1 string with 5 modules in series, the system peak power is 1150Wp. Figure 3.4 shows the PV test field which is implemented in Ma’an.

![Figure 3.4: PV test field infrastructure in Ma’an](image)

Table 6.1 shows the main characteristics of the PV modules under test, these characteristics are considered in relation to the module data sheets.

<table>
<thead>
<tr>
<th></th>
<th>Kassel- Germany</th>
<th>Ma’an-Jordan</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module</td>
<td>Ploy-cr</td>
<td>µ-sc</td>
</tr>
<tr>
<td>Power [Wp]</td>
<td>162</td>
<td>85</td>
</tr>
<tr>
<td>V_{MP} [A]</td>
<td>22.7</td>
<td>49</td>
</tr>
<tr>
<td>I_{MP} [V]</td>
<td>7.14</td>
<td>1.74</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>12.4</td>
<td>8.1</td>
</tr>
<tr>
<td>( \alpha_{P_{MP}} ) [%/°C]</td>
<td>-0.485</td>
<td>-0.24</td>
</tr>
<tr>
<td>( \alpha_{V_{MP}} ) [%/°C]</td>
<td>-0.104 V/ °C</td>
<td>-0.3</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>1318</td>
<td>1129</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>994</td>
<td>934</td>
</tr>
<tr>
<td>Array (SxP)</td>
<td>7x1</td>
<td>4x3</td>
</tr>
<tr>
<td>PV system size [Wp]</td>
<td>1134</td>
<td>1020</td>
</tr>
<tr>
<td>cover factor</td>
<td>0.95</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 3.1: Specification of PV module under test

* The modules data are confidential. For Kassel site; it belongs to the PV test field of Fraunhofer-IWES. For Ma’an site, it belongs to PV test field which is owned by Kawar Group Company. The data is given under the permission of IWES (Kassel-Germany) and Kawar group (Ma’an-Jordan)
Chapter 4

Methodology
4 Methodology
The simulated PV model is composed mainly of the incident irradiation, electrical and thermal characteristics of the PV module, associated with the environmental effects. Also, Balance of System (BOS) under the effects of ambient temperature and inverter loading.

In this chapter, the performed methodology of the simulation is explained significantly, the input and output power with the dynamic thermal behaviour of the photovoltaic are categorized under module (array) level and BOS. The mentioned performance factors in the previous chapter are essential in order to provide a closer picture of the real behaviour of the PV module, as well as decreasing the uncertainty.

4.1 Module level model
Concerning the module level, the simulation model composes of the input and output power from the PV module (array) with the consideration of dynamical thermal effects. The following sections are the methodology used in the model.

4.1.1 Input power
In this section the meteorology concerning the effect of the sun position on the incident irradiation is determined. Furthermore, the calculation of converting the horizontal incident irradiation into any inclined plane is obtained. Also, the calculation of the effective irradiation which reaches to the PV cells, is investigated with respect to the optical loss.

4.1.1.1 Meteorology
Meteorological data concerning Photovoltaics evaluation tools are divided into, solar data, wind data and climatic data such as humidity and atmospheric pressure. The data used in the simulation are bounded regarding the boundary conditions.

• Sun position angles
The optical properties is an important parameter for evaluating the effective irradiation for the PV system, angle of incidence ($\theta_{AOI}$) and zenith angle ($\theta_Z$) are the main concerning angles which affect the optical loss. In order to analyse the mentioned angles, other relevant angles have to be considered such as declination angle($\delta$), hour angle ($\omega$), PV tilt angle ($\beta$), location latitude ($\Phi$) and PV azimuth angle($\theta_{Az}$)$^{[13]}$. 
In this model a site specification should be used such as latitude, reference longitude, actual longitude, altitude, PV azimuth angle (ref, North=0), and tilt angle $\beta$.

The starting point is to calculate the Declination angle, equation of time, local time and hour angle.

- **Declination angle ($\delta$):** is the angular position of the sun with respect to the plane of the equator. It is varied between -23.45° to 23.45 ° in relation to the assigned day among the year $^{[30]}$. To calculate ($\delta$), number of the day among the year ($NOD$) should be taken into account. 1st January is the day number (1) should be determined where:

$$\delta = 23.45 \times \sin \left( \frac{360}{365} \times (284 + NOD) \right)$$

- **Equation of time (EQT):** is the difference between true solar time and mean solar time $^{[31]}$ and given by:

$$EQT = (0.123 \times \cos \left( \frac{360}{365} \times (88 + NOD) \right) - (0.167 \times \sin \left( \frac{720}{365} \times (10 + NOD) \right))$$

- **Local Solar time (LST):** is the exact time at a certain longitude of the observer.

$$LST = time_h + EQT + \frac{(lon_{act} - lon_{ref})}{15}$$

$$time_h = hour + \frac{minutes}{60} + \frac{seconds}{3600}$$

Where $lon_{ref}$ is the reference longitude and $lon_{act}$ is the actual longitude $^{[11]}$. 
**Hour angle (ω):** is a measure of the time of any day with respect to the solar noon. Solar noon is the time when the sun is in the highest point in the sky\(^ {11}\).

\[
ω = (12 - LST) \times 15
\]

Where \(LST\) is the local solar time.

**Zenith angle (θz):** is the angle between the perpendicular projection of the surface and the sun beam. It is given by:

\[
θz = \cos^{-1}(\cos(Φ) \times \cos(δ) \times \cos(ω)) + \sin(Φ) \times \sin(δ))
\]

Where \(Φ\) is the latitude at a certain location and \(δ\) is the declination angle\(^ {30}\).

**Angle of Incidence (θ\(_{AOI}\)):** Angle of incident is the angle between the perpendicular on the surface and the sun beam, and it is given by:

\[
θ_{AOI} = \cos^{-1}((\sin(δ) \times \sin(Φ) \times \cos(β)) + (\sin(δ) \times \cos(Φ) \times \sin(β) \times \cos(θ_{AZ})) + (\cos(δ) \times \cos(Φ) \times \cos(β) \times \cos(ω)) - (\cos(δ) \times \sin(Φ) \times \sin(β) \times \cos(θ_{AZ}) \times \cos(ω)))
\]

Where \(θ_{AZ}\) and \(β\) is the surface azimuth angle and the tilt angle of the photovoltaic module. The reference of surface azimuth angle is the north. \((θ_{AZ}=180^\circ)\) at south facing PV module.

The following figures show the angles of incidence and zenith angles for the horizontal surface and 30° south orientation for Kassel and Ma’an sites, these figures are obtained from the simulation model. The angle of incident and Zenith angle are equals at the horizontal surface.

![Figure 4.2: Variation of angle of incidence (θ\(_{AOI}\)) and zenith angles (θ\(_z\)) for 30° South orientations and horizontal surface for Ma’an and Kassel cities.](image-url)
Airmass

Airmass is the mass ratio between the atmospheric mass through which the beam irradiation passes, and the atmospheric mass at which the irradiation passes when the sun is at the zenith. The air mass equal to 1 at the sea level when the sun is at the zenith \[^{[30]}\].

When the solar irradiation passes through the atmosphere, it collides with dust, aerosols and gases such as ozone (O\(_3\)), carbon dioxide (CO\(_2\)) and water vapour (H\(_2\)O). During this collision a part of photons energy is absorbed by these particles. The solar irradiation is attenuated in relation to the path length of the irradiation, the shortest path occurs when the sun is at the highest point in the sky (the zenith). At this point the power density of the irradiation equal\(^8\) to 1353 W/m\(^2\) and it's defined as solar constant. The motion of the sun among the years affects the total irradiation reaches a certain point at the earth\(^{[32]}\).

Figure 4.3 describes the solar spectrum for the sun irradiation, the yellow line is the extraterrestrial irradiation and is referred to AM0. The red line is the terrestrial irradiation level after passing through the atmosphere. It is equal 1.5 at the solar zenith angle 48.2°.

Airmass is the amount of atmosphere at which the irradiation passes before reaching a certain point at the sea level. Airmass coefficient (AM) defines the direct optical path length through the Earth's atmosphere. It is expressed as a ratio relative to the path length vertically upwards (relative air mass). Airmass coefficient is used to characterize the solar spectrum through the atmosphere. It is given by the following formula:

\[
AM_{rel} = \frac{1}{\cos(\theta z)}
\]

\(^{8}\) In many references solar constant is considered 1367[W/m\(^2\)]
Air mass coefficient is commonly used to characterize the performance of Photovoltaic cells under standardized conditions and it is expressed as “AM1.5”. During the sunrise and sunset, the zenith angle becomes higher; this causes a higher air mass value. The higher airmass coefficient the lower direct irradiation and the higher diffused irradiation, because of the absorption and collision \[32\]. Figure 4.4 shows a various air mass values for different zenith angles.

![Figure 4.4: Various Airmass\[33\]](image)

At the higher altitude areas, air mass and spectral contents of sunlight change; airmass at a certain altitude is given by the following formula:

$$Airmass_{actual} = \frac{e^{0.0001184\cdot alt}}{cos(\theta z) + 0.5057 \cdot (96.08 - \theta z)^{-1.634}}$$

Where \(alt\) is the altitude of the location (the height above the sea level)\[30\]. Air mass is introduced in the simulation, but without considering its value; and this is because the irradiation measurement is performed at ground or roof level, so the effect of the airmass is included already in the measurement.

4.1.1.2 Irradiation

The solar irradiation is the input power of the PV system, the incident irradiation on the photovoltaic cell/module is the starting point for measuring the effective irradiation that reach the PV cells as well as for the power generation measurement.

Global irradiation at any surface \(G\) is equal to the summation of the direct normal beam \(Gb\), diffused beam \(Gd\) and the reflected irradiation from the surroundings and mainly from the ground \(Gr\)- Albeldo.
\[ G = G_b + G_d + G_r \text{ [W/m}^2\text{]} \]

Figure 4.5 describes the three parts of irradiation which reaches the earth surface.

![Figure 4.5: Incident solar irradiation](image)

Generally, solar applications are tilted to a certain angle regarding many factors such as area latitude, optimum tilt angle in relation to the maximum energy yield and regarding the area terrain. But most of irradiation measurements are based on horizontal surface. It is necessary to determine the incident irradiation at inclined surface from the horizontal measurement. The calculation is quite straightforward as the previous equation, but the elements should be converted to an assigned inclination angle by depending on the sun position angles.

\[ G_i = G_{bi} + G_{di} + G_{ri} \text{ [W/m}^2\text{]} \]

- **Direct inclined component**(*\(G_{bi}\)*):
The direct beam on an inclined surface is calculated by the following equation:

\[ G_{bi} = G_b \times R_b \]

\[ R_b = \frac{\cos(\theta_{AOI})}{\cos(\theta_z)} = \frac{\cos(\theta_{AOI})}{\sin(\alpha_s)} \]

Where \(G_b\) is the direct irradiation, \(R_b\) is a geometric factor (the ratio between the tilted and horizontal solar beam irradiation), \(\theta_z\) is the Zenith angle and \(\alpha_s\) is the solar elevation\[35\].

- **Diffused inclined component**(*\(G_{di}\)*):
Diffused irradiation measurement depends on the location of the PV system; it can be calculated through different validated models such as Jordan model which is the ideal and simplest one, Also, Klucher, Reindl and Hay models\[35\]. It can be calculated with one of the following models.
1. Hay model:
Hay model assumes that the sky diffused irradiation originates from two sources: the Sun’s disc and the rest of the sky with isotropic diffused irradiation. The two components are described by anisotropy index $(A')^{[36]}$.

\[
G_{di} = G_d \cdot \left(0.5 \cdot (1 - A') \cdot (1 + \cos \beta) + \left( A' \cdot \frac{\cos(\theta_{ADI})}{\cos (\theta_z)} \right) \right)
\]

\[
A' = \frac{G_b}{G_o}
\]

Where $A'$ is the anisotropy index, $\beta$ is the tilt angle, $G_o$ is the extraterrestrial radiation and equal $1367 \text{ w/m}^2$.

2. Reindl model:
Reindl model accounts for the horizon brightening and employs the same definition of the anisotropy index $A'$ as described in Hay model $^{[37]}$.

\[
G_{di} = G_d \cdot \left(0.5 \cdot (1 - A') \cdot (1 + f \cdot \sin^3(\frac{\beta}{2})) \cdot (1 + \cos \beta) + \left( A' \cdot \frac{\cos(\theta_{ADI})}{\cos (\theta_z)} \right) \right)
\]

\[
f = \frac{G_b}{G}
\]

Where $f$ is the modulating function and $G$ is the global radiation in W/m$^2$.

Three researches were investigated $^{[35][36][37]}$ and compared in order to be used in the simulation. Riendl and Hay model were performed the best deviation; they show a good accuracy with the relative Root Mean Square error (RMSE) and relative mean bias error (MBE). In the simulation, Reindl model is used to calculate the inclined diffused irradiation.

- **Reflected Component (Gri):**
The ground reflected irradiance on an inclined surface is calculated from the equation:

\[
Gri = 0.5 \cdot \rho_g \cdot G(1 - \cos \beta)
\]

Where $\rho_g$ is the ground average reflectance coefficient (Ground Albeldo factor), it is assumed as 0.2 for an unknown surface $^{[35]}$. 

40
Many technologies are used to measure the incident solar irradiation; this depends on the type of measurement, evaluation criteria and cost. The following are the different sensors that used in the simulation:

- **Pyranometer (horizontal or tilted):** It measures global and diffused irradiation. The time response of the pyranometer is based on its thermal characteristics. The measured band width of the incident irradiation is around (280 to 4000 nm) which covers almost the total wavelengths of the incident sun light\textsuperscript{[38]}

- **Rotating Shadowband Radiometer Instrumentation (RSR):** It measures direct, diffused and global radiation, also ambient temperature. It depends on high stability Photovoltaic silicon photodiode head unit. Its response is faster than pyranometer but with less precision\textsuperscript{[34]}. Photodiode sensor measures global and diffused sunlight. Direct sunlight is calculated by Irradiance's computer program in the Campbell Scientific data logger\textsuperscript{[39]}, the final data is corrected to be in the same characteristics of the pyranometer measurement\textsuperscript{9}.

- **PV cell sensor:** It measures total horizontal and tilted radiation and considering spectral response based on sensor technology; It responses to a certain bandwidth of indecent irradiation spectrum. It gives a compatible measurement for evaluating a PV system with the same sensor technology, and it can be a reference for other technologies but with a certain amount of deviation in relation to the spectral response; so it is preferable to use sensor with the same PV technology such as: monocrystalline, amorphous crystalline, polycrystalline cadmium telluride (CdTe) or copper indium diselenide (CIS) which increases the accuracy. The optical loss is already considered in these types of sensor\textsuperscript{[40]} In the simulation crystalline silicon cell sensor is used for irradiation measurement (ISET sensor).Figure 4.6 shows the mentioned solar irradiation sensors.

\textsuperscript{9} This information is regarding my contact with Dr. Edward Kern from irradiance company, in 30, Jan, 2012

Figure 4.6: Pyranometer, Rotating Shadowband Radiometer Instrumentation and silicon cell sensors
• Other factors

Ambient temperature
Ambient temperature is an important factor for simulation, because the PV module temperature depends directly on the internal and external heat transfer coefficients which are affected mainly by the ambient temperature and irradiance. Many sensors can be used to measure the ambient temperature and PV module surface temperature such as thermometer, PT100, PT 1000 and thermocouples.

Wind measurement
The wind speed and direction are measured by using many systems such as cup anemometer and wind vane. In the simulation, wind speed is considered regardless the wind direction. Figure 4.7 shows examples for wind measurement tools, irradiation and ambient temperature measurement sensor.

![Figure 4.7: Wind measurement system and ambient temperature measurements](image)

4.1.2 Optical loss
A major proportion of the yearly irradiation is in the weak light range (long wave length). The PV module output power is usually lower than the expected. The main reasons of this deviation are the climatic condition such as ambient temperature, irradiation and PV module material losses such as reflection and transmission loss. In terms of direct irradiation, it is exposed to the reflection loss which mainly depends on the angle of incident ($\theta_{AOI}$) and refractive indices ($n$) of the PV module materials $^{[41]}$.

Table 4.1 shows the refractive index and thickness for a certain silicon PV module of different layers.
### Table 4.1: Refractive indices and thickness for PV modules layers

The calculation is performed by using Snell’s law, which is the sinus ratio between the beam angles in two different medias. Also, it is equivalent to the phase velocity ($v$) ratio or to the inverse ratio of refraction indices ($n$) and it is given by:

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

Figure 4.8 explains the effect of the refraction index on each layer of the PV module:

![Figure 4.8](image)

Regarding to the previous formula refraction angle for each layer of the PV cell is calculated as follows:

- **Glass**: $\sin \theta_{\text{glass}} = \sin \theta_{\text{AOI}} \cdot \frac{n_{\text{AOI}}}{n_{\text{glass}}}$
- **EVA**: $\sin \theta_{\text{EVA}} = \sin \theta_{\text{glass}} \cdot \frac{n_{\text{glass}}}{n_{\text{EVA}}}$
- **AR coating**: $\sin \theta_{\text{AR}} = \sin \theta_{\text{EVA}} \cdot \frac{n_{\text{EVA}}}{n_{\text{AR}}}$
• Silicon cell: \[ \sin \theta_{\text{Si}} = \sin \theta_{AOL} \cdot \frac{n_{AR}}{n_{Si}} \]

For simplifying reflection loss, an equivalent refractive index for silicon module front layers is assumed based on many researches. Table 4.2 explained the equivalent refractive indices \( n_{eq} \) for different silicon crystalline module structure. This table based on the study “Non-destructive optical characterization of photovoltaic modules by an integrating sphere. Part I: Mono-Si modules”\(^{[43]}\).

Regarding the values in the following table, equivalent refractive index is assumed \( n_{eq} = 3 \) in the simulation and by taking into account that EVA and ARC layer are very thin layer. In other words the front side layer is assumed as a one layer of low iron glass. The specifications are shown in Appendix B.

<table>
<thead>
<tr>
<th>Category</th>
<th>Front structure</th>
<th>( n_{eq} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Flat-glass/ text-Si</td>
<td>3.0</td>
</tr>
<tr>
<td>B</td>
<td>Flat-glass/ARC/ text-Si</td>
<td>2.5</td>
</tr>
<tr>
<td>C</td>
<td>Flat-glass/ ARC/flat-Si</td>
<td>2.5</td>
</tr>
<tr>
<td>D</td>
<td>Text-glass/ text-Si</td>
<td>3.0</td>
</tr>
<tr>
<td>E</td>
<td>Text-glass/ ARC/flat-Si</td>
<td>3.0</td>
</tr>
<tr>
<td>F</td>
<td>Text-glass/ARC/ text-Si</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Table 4.2: Equivalent refractive indices for different PV module layer**\(^{[43]}\)

The equivalent refractive angle is given by:

\[ \sin \theta_{\text{Si}} = \sin \theta_{AOL} \cdot \frac{1}{n_{eq}} \]

\[ \sin \theta_{\text{Si}} = \frac{\sin \theta_{AOL}}{3} \]

By calculating the refractive angle based on the equivalent refractive index of the PV module front layers, reflection coefficient and transmittance are calculated. Figure 4.9 shows the assumption which is used in the simulation for calculating the effective irradiance. The occupancy rate\(^{10} 0.95\) is considered for silicon PV cells, while it is considered 0.98 for thin film technology.

\(^{10}\) Occupancy rate: is the area consumed by the PV cells layout on the PV module
The reflection coefficient composes of two components, Perpendicular and Parallel components. The perpendicular reflection component ($R \perp$) is the relation between the square sinus of equivalent refractive angle and incidence angle:

$$R \perp = \frac{\sin^2(\theta_{sci} - \theta_{AOI})}{\sin^2(\theta_{sci} + \theta_{AOI})}$$

Perpendicular reflection component ($R||$) is the relation between the square tangents of equivalent refractive angle and incidence angle:

$$R|| = \frac{\tan^2(\theta_{sci} - \theta_{AOI})}{\tan^2(\theta_{sci} + \theta_{AOI})}$$

The average reflection is given by:

$$R_{avg} = \frac{1}{2} (R \perp \ast R||)$$

The transmittance is the factor which affects the direct irradiation before reaching the PV cells; as it is seen in the following equation, the transmitted irradiation is determined after considering the reflection and absorption (A) coefficient. Absorption is considered as losses with 2% from the indecent irradiation for the selected glass type. Figure 4.10 shows the relation between the transmittance and the angle of incidence for a certain medium. It can be seen, that when the angle of incidence increases more than 60° degrees, the transmittance drops rapidly.\[41\]
\( T = (1 - R_{avg}) \times (1 - A) \)

\[ G_{\text{glass}} = G_{bi} \times T \]

\[ G_{\text{cell}} = (G_{\text{glass}} \times \tau) + G_{di} + G_{ri} \]

Where:

- \( G_{\text{glass}} \): total irradiation directly before the PV module.
- \( G_{\text{cell}} \): total irradiation which hits the PV cells and generate power.
- \( T \): Transmittance
- \( \tau \): Transmission coefficient

The irradiation \((G_{\text{cell}})\) is the effective irradiation which reaches the PV cells in the PV module.

### 4.1.3 Thermal power

As the module is exposed to the sunlight, it generates electricity as well as it gains heat. Typically, standard PV modules convert not more than 20% of the incident irradiation to electricity, the rest is absorbed by the PV module material and a portion of the absorbed heats is dissipated.

#### 4.1.3.1 Absorption

Absorption depends on the many factors such as Reflection from top surface, operating point of solar cells, Absorption of light through the gap between PV cells, absorption of long waves (infra-red) spectrum, conductivity of PV module materials and Packing density of solar cells\(^{[11]}\). This absorbed heat is responsible on raising the module temperature, when the module temperature increases the efficiency of the module decreases. Figure 4.11 shows the heat flow through the PV module.

\(^{[11]}\) The calculation procedures used in thermal part are based on [VDI- Wärmeatlas]\(^{[46]}\)
In order to determine the PV module operating temperature, the module thermal energy should be calculated. A part of this thermal energy is absorbed and the rest is dissipated through conduction, convection and radiation heat transfer.

\[
\dot{Q} = (Area \times Gi) - Pel + (\alpha_f \times Gi) + ((1 - PV_{cf}) \times \alpha_f \times Gi)
\]

Where:
\(\dot{Q}\): is the heat gained by the PV module [W].
\(Area\): PV module area \([m^2]\).
\(Gi\): Total inclined irradiation \([W/m^2]\).
\(Pel\): Electrical output power \([W]\).
\(\alpha_f\): Front side surface absorption coefficient.
\(PV_{cf}\): Occupancy rate “gaps to PV cells in the module”.

PV cell temperature is determined by the formula:

\[
\Delta T_{cell} = \frac{\dot{Q} - \left( Area \times (h_{ro} + h_{co}) \times (T_{mod_o} - T_{ambi}) \right) + \left( (h_{ri} + h_{ci}) \times (T_{mod_i} - T_{ambi}) \right)}{(m \times Cp)}
\]

\(\dot{m} = Area \times \rho \times \Delta x\)

Where:
\(h_{ci}\): Inside(back side) surface convection coefficient\([W/m^2.K]\).
\(h_{co}\): Outside(front side) surface convection coefficient\([W/m^2.K]\).
\(h_{ri}\): Inside(back side) surface radiation coefficient\([W/m^2.K]\).
\(h_{ro}\): Outside(front side) surface radiation coefficient\([W/m^2.K]\).
\(T_{ambi}\): Inside ambient temperature \([^\circ C]\).
\(T_{ambi}\): Outside ambient temperature \([^\circ C]\).
$T_{modi}$: Inside (back side surface) module temperature [°C].
$T_{modo}$: Outside (front side surface) module temperature [°C].
$m$: Mass flow rate [Kg/s].
$C_p$: Specific heat capacity [J/ kg·°C].
$\rho$: Material density [kg/m³], the values are listed in table 4.4.
$\Delta x$: Thickness [m].

In the simulation, it is assumed that the PV cell temperature is equal to the module surface temperature. Also, it is assumed that the surface and back temperature are equals. The simulation is performed based on the assumption at which the electrical generated power is constant during the time interval for each iteration.

Because of the natural and environmental conditions, the gained heat is dissipated, which leads to decrease the module temperature and to increase the output power. The following section explains the dissipated thermal heat.

4.1.3.2 Dissipation
The absorbed heat is the energy gained from the incident irradiation minus the generated DC power. After the absorption, a rest of the heat is dissipated through the PV module layer to the surrounding. The PV module has a relatively low thermal capacity in order to dissipate the heat through the encapsulation to the module surface (steady state heat flow) [17]. Then the heat flows out because of the convection and radiation heat transfer mechanism. The balance model of energy conversion in the PV module is described in the following Figure.

![Energy flow in the PV module](image)

Figure 4.12: Energy flow in the PV module [17]

In the simulation; Photovoltaic modules are considered as a flat plate with one dimensional heat flow. Thermal power during PV module operation is consist of absorption and dissipation. Figure 4.13 describes the heat flow in the PV module.
The PV module structure under study consists of three main layers:

1. Front layer which is assumed as a low iron glass cover.
2. Photovoltaics cells.
3. Back sheet is considered as Tedler cover with or without isolation material.

The simulation model is based on the following balance model equation:

\[
G_{irradiation} = P_{electrical} + P_{absorption} + P_{dissipation}
\]

In order to determine the dynamic module temperature; heat transfer coefficients should be calculated. Figure 4.14 illustrates the structure which is considered in the simulation, where the symbols \( h_i \) and \( h_o \) represents the inside (internal) and outside (external) convection and radiation heat transfer coefficients. Generally they depend on the heat flux of the PV module \( q \), and the temperature difference between the operating module temperature \( T_s \) and surrounding temperature \( T_\infty \).

\[
h = \frac{q}{\Delta T_{s\infty}}
\]
The dissipated energy \( q_{loss} \) is determined by the following equation \(^{17}\).

\[
q_{loss} = q_{convection} + q_{radiation}
\]

The calculation of the thermal dissipation of the PV module depends on many factors:

- Front surface convection heat transfer coefficient \( (h_{co}) \).
- Back surface convection heat transfer coefficient \( (h_{ci}) \).
- Front surface radiation heat transfer coefficient \( (h_{ro}) \).
- Back surface radiation heat transfer coefficient \( (h_{ri}) \).
- Front surface conduction heat transfer resistances \( (R_{xo}) \).
- Back surface conduction heat transfer resistances \( (R_{xi}) \).

Figure 4.15 illustrates the total heat transfer resistance of the front and the back cover of the PV cells, in order to calculate the dissipated heat, conduction heat transfer resistances should be determined. The simulation is based on the assumption, that the PV cell temperature is equal to the surface module temperature.
The following is the methodology which is used in the simulation:

Convection heat transfer is divided into two parts; free convection and forced convection. The following flowchart explains the convection heat transfer through different categories of the PV modules. In this thesis natural and forced convections are considered regardless the channel convection. To figure out the convection heat coefficients \((h_{ci} \text{ and } h_{co})\) Nusselt number should be determined.

Figure 4.16: Convection heat transfer flow chart \([46]\)
Convection heat dissipation

- Free convection

Free convection is divided into three categories based on the tilt angle. This is very important for predicting the PV module temperature of ground mounted systems and BIPV. The calculation procedures which are considered in this simulation are summarized as follows.

**First category**: Vertical mounted such as BIPV facade (tilt angle equal 90 degree).

**For PV module front side surface**: 

\[ R_{ao} = P_{ro} \times G_{ro} \]

\[ G_{ro} = \left| \frac{g \times l^3}{\nu^2} \times \beta \times |T_{modo} - T_{ambo}| \right| \]

Where:
- \( R_{ao} \): Outside (PV front surface) Rayleigh number.
- \( P_{ro} \): Outside (PV front surface) Prandtl number.
- \( G_{ro} \): Outside (PV front surface) Grashof number.
- \( g \): Gravity; 9.81 [m/s\(^2\)].
- \( l \): characteristic length for PV module [m].
- \( \nu \): Kinematic viscosity [m\(^2\)/s].
- \( \beta \): Volumetric thermal expansion coefficient [1/K].

For laminar flow, Rayleigh number is \((R_{ao} > 0.1, R_{ao} < 10^{12})\):

\[ P'_{ro} = \left( 1 + \left( \frac{0.492}{P_{ro}} \right)^{9/16} \right)^{16/9} \]

\[ Nu_{o.fr} = \left( 0.825 + 0.387 \times (R_{ao} \times P'_{ro})^{1/6} \right)^2 \]

For turbulent flow, Rayleigh number is \((R_{ao} \geq 10^{12})\), then:

\[ Nu_{o.fr} = 0.14 + (R_{ao})^{1/3} \]

Where \( P'_{ro} \) and \( Nu_{o.fr} \) are the new value for Prandtl number and free convection Nusselt number at PV module front surface.
For PV module back side surface:

\[ R_{ai} = P_{ri} \times G_{ri} \]

\[ G_{ri} = \left| \frac{g \times l^3}{\nu^2} \times \beta \times |T_{modi} - T_{ambi}| \right| \]

For laminar flow, Rayleigh number is \((R_{ai} > 0.1, R_{ai} < 10^{12})\):

\[ P'_{ri} = \left( 1 + \left( \frac{0.492}{P_{ri}} \right)^{16 \over 9} \right)^{16 \over 9} \]

\[ Nui_{fr} = (0.825 + 0.387 \times (R_{ai} \times P'_{ri})^{1/2})^2 \]

For turbulent flow, Rayleigh number is \((R_{ai} \geq 10^{12})\):

\[ Nui_{fr} = 0.14 + (R_{ai})^{1/3} \]

Where \(Nui_{fr}\) is the free convection Nusselt number at the PV module back surface.

**Second category:** Tilt angle is between 15° and 90° (15° ≤ tilt angle < 90°):

For PV module front side surface:

\[ R_{ao} = P_{ro} \times G_{ro} \]

\[ G_{ro} = \left| \frac{g \times l^3}{\nu^2} \times \beta \times |T_{modo} - T_{ambo}| \right| \]

\[ \gamma = 90 - \beta \]

\[ R_{sc} = 10^{(8.9 - 0.00178 \times \gamma)^{1.82}} \]

\[ R_{a,fr} = R_{ao} \times \cos \gamma \]

Where \(\gamma\) is the complement of the tilt angle.
For laminar flow, if \((R_{ao} < R_{ac})\):

\[
P'_r o = \left( 1 + \left( \frac{0.492}{P'_{ro}} \right)^{\frac{9}{16}} \right)^{\frac{16}{9}}
\]

\[
Nuo_{fr} = \left( 0.825 + 0.387 \times \left( R_{ar} \times P'_r o \right)^{\frac{1}{6}} \right)^2
\]

For turbulent flow, if \((R_{ao} > R_{ac})\):

\[
Nuo_{fr} = 0.56 \times (R_{ar} \times \cos \gamma)^{\frac{1}{4}} + 0.13 \times (R_{ao}^{\frac{1}{3}} - R_{ac}^{\frac{1}{3}})
\]

**For PV module back side surface:**

\[
R_{ai} = P_{ri} \times G_{ri}
\]

\[
G_{ri} = \left| \frac{g \times l^3}{\nu^2} \times \beta \times |T_{mod} - T_{amb}| \right|
\]

\[
R_{ar} = R_{ai} \times \cos \gamma
\]

For laminar flow, Rayleigh number is \((0.1 < R_{ai} < 10^{12})\), then:

\[
P'_{ri} = \left( 1 + \left( \frac{0.492}{P'_{ri}} \right)^{\frac{9}{16}} \right)^{\frac{16}{9}}
\]

\[
Nui_{fr} = \left( 0.825 + 0.387 \times \left( R_{ar} \times P'_{ri} \right)^{\frac{1}{6}} \right)^2
\]

For turbulent flow, Rayleigh number is \((R_{ai} \geq 10^{12})\), then:

\[
Nui_{fr} = 0.14 + \left( R_{ai} \right)^{\frac{1}{3}}
\]
**Third category**: Horizontal or almost horizontal mounted structure with a tilt angle between 0° and 15° (0°<tilt angle≤15°)

Here, characteristic length is used rather than the PV module length; it is given by the following equation. Briefly it is the ratio between the surface area of the PV module and the perimeter.

\[
l_c = \frac{l \times b}{2 \times (l + b)}
\]

Where \( l \) is the module length and \( b \) is the module width.

\[
R_{ao} = P_{ro} * G_{ro}
\]

\[
G_{ro} = \frac{g * l c^3}{\nu^2} * \beta * |T_{modo} - T_{amb}|
\]

**For PV module front side surface:**
The calculation procedures are similar to the calculation procedure of the tilted front side surface, but with using the characteristic length \((l_c)\).

**For PV module back side surface:**
The calculation depends on the comparison between characteristic length and the length multiplied by the cosines of the tilt angle complement \((\gamma)\):

For \( l_c < l * \cos (\gamma) \); then Nusselt number equal (1), and for \( l_c > l * \cos (\gamma) \) then:

\[
R_{ai} = P_{ri} * G_{ri}
\]

\[
G_{ri} = \frac{g * l c^3}{\nu^2} * \beta * |T_{modi} - T_{ambi}|
\]

\[
P'_{ri} = \left( 1 + \left( \frac{0.492}{P_{ri}} \right)^{\frac{9}{16}} \right)^{-\frac{16}{9}}
\]

For laminar flow, \((1000 < R_{ai} \times P'_{ri} \leq 10^{10})\), then:

\[
Nui_{fr} = 0.6 * (R_{ai} * P_{ri})^{\frac{1}{3}}
\]
For turbulent flow, \( R_{ai} \cdot P'_{ri} \leq 1000, R_{ai} \cdot P'_{ri} > 10^{10} \), then:

\[
Nui_{fr} = 0.571 \times (G_{ri} \cdot P_{r'it}^2)^{\left(\frac{1}{5}\right)}
\]

**Forced convection**

For forced convection, wind speed is the main factor in the calculation. Wind direction is postponed for future research; the following is the procedure which is used in the simulation to determine the forced convection heat transfer coefficients.

**For PV module front side surface:**

\[
R_{eo} = \frac{w_{o} \cdot b}{v}
\]

Where:
- \( R_{eo} \): Reynold number
- \( w_o \): Wind speed at PV module front side \([\text{m/s}]\)
- \( b \): PV module width \([\text{m}]\)
- \( v \): Kinematic viscosity

For laminar flow

\[
Nuo_{fo} = 0.664 \times R_{eo}^{1/2} \times P_{ro}^{1/3}
\]

For turbulent flow

\[
Nuo_{fo} = \frac{0.037 \times R_{eo}^{0.8} \times P_{ro}}{1 + 2.443 \times R_{eo}^{-0.1} \times (P_{ro}^{2/3} - 1)}
\]

Where \( Nuo_{fo} \) is the Nusselt number for forced convection at the PV module front surface.

**For PV module back side surface:**

\[
R_{ei} = \frac{w_{i} \cdot b}{v}
\]

Where \( w_i \) is the wind speed at the back side of PV module

For laminar flow:

\[
Nui_{fo} = 0.664 \times R_{ei}^{1/2} \times P_{ri}^{1/3}
\]

Where \( Nui_{fo} \) is the Nusselt number for forced convection in the PV module back side surface.
For turbulent flow:

\[
N_{ui, fo} = \frac{0.037 \cdot R_{el}^{0.8} \cdot P_{ri}}{1 + 2.443 \cdot R_{el}^{-0.1} \cdot (P_{ri}^{2/3} - 1)}
\]

After calculating the Nusselt numbers for the free and forced convection; convection heat coefficients are computed by:

\[
h_{co} = 3 \sqrt{Nu_{ofr}^{1/3} + Nu_{fo}^{1/3}} \cdot \frac{\lambda}{b} \quad [\text{W/m}^2\cdot\text{K}]
\]

\[
h_{ci} = 3 \sqrt{Nu_{ifr}^{1/3} + Nu_{io}^{1/3}} \cdot \frac{\lambda}{b} \quad [\text{W/m}^2\cdot\text{K}]
\]

Table 4.3 lists the values for volumetric thermal expansion coefficient (β), thermal conductivity (λ), kinematic viscosity (ν) and Prandtl number (Pr) for the air. These values are interpolated at the film which is the median temperature between the ambient and the module temperature.

<table>
<thead>
<tr>
<th>T</th>
<th>β</th>
<th>λ</th>
<th>ν</th>
<th>Pr</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>[1000/K]</td>
<td>[mW/(m.K)]</td>
<td>[10^-7m^2/s]</td>
<td>[]</td>
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<td>0.0000237</td>
<td>0.7011</td>
</tr>
</tbody>
</table>

Table 4.3: Air physical specification \[46\]

\[
T_{avi} = \left| T_{ambi} + \frac{T_{modi} - T_{ambi}}{2} \right|
\]

Where:

- \(T_{ambi}\): Outside (front surface) film temperature;
- \(T_{avi}\): Inside (back surface) film temperature;
**Radiation heat dissipation**

Radiation heat coefficients are calculated by using the following equations:

Outside (front side) surface Radiation coefficient ($h_{ro}$):

$$h_{ro} = 0.5 * \varepsilon * \sigma * \left( (1 - \cos \beta) * \left( T_{modo}^2 + T_{ambo}^2 \right) * (T_{modo} + T_{ambo}) \right) + \left( 1 + \cos \beta \right) * \left( T_{modo}^2 + (0.552 * T_{ambo}^{1.5})^2 \right) * (T_{modo} + (0.552 * T_{ambo}^{1.5}))$$

Inside (back side) surface Radiation coefficient ($h_{ri}$):

$$h_{ri} = 0.5 * \varepsilon * \sigma * \left( (1 + \cos \beta) * \left( T_{modi}^2 + T_{ambi}^2 \right) * (T_{modi} + T_{ambi}) \right) + \left( 1 + \cos \beta \right) * \left( T_{modi}^2 + (0.552 * T_{ambi}^{1.5})^2 \right) * (T_{modi} + (0.552 * T_{ambi}^{1.5}))$$

After calculating the heat transfer coefficients, the total resistances are calculated in order to determine the new value of the module temperature; this temperature will be the driving force for the new heat transfer coefficient values. The following formulas explain how to figure out the new value of the module temperature, by considering the boundary condition ($T_{cell} = T_{module}$).

$$R_{xo} = \frac{\Delta X_o}{\lambda}$$

$$R_{xi} = \frac{\Delta X_i}{\lambda}$$

$$R_{ti} = \frac{1}{(h_{ci} + h_{ri})} * R_{xi}$$

$$T_{modo} = T_{cell} - \left( \frac{R_{xo}}{R_{to}} * (T_{cell} - T_{ambo}) \right)$$

$$T_{modi} = T_{cell} - \left( \frac{R_{xi}}{R_{ti}} * (T_{cell} - T_{ambi}) \right)$$

Where:

- $R_{xo}$: External (front surface) conduction heat transfer resistance [m²K/W].
- $R_{xi}$: Internal (back surface) conduction heat transfer resistance [m²K/W].
- $R_{to}$: Total internal heat transfer resistance [m²K/W].
- $R_{ti}$: Total external heat transfer resistance [m²K/W].
- $\Delta X$: Thickness.
- $1/(h_{co} + h_{ro})$: External (front surface) total heat transfer resistance [m²K/W].
- $1/(h_{ci} + h_{ri})$: Internal (back surface) total heat transfer resistance [m²K/W].
In relation to the above equations, the specifications of the used PV module materials in the simulation are shown in the following table.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [m]</th>
<th>Conductivity $\lambda$ [W/m.K]</th>
<th>Density $\rho$ [kg/m$^3$]</th>
<th>Specific heat capacity $C_p$ [J/kg*K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>0.0032$^a$</td>
<td>0.8$^a$</td>
<td>2500$^a$</td>
<td>500$^a$</td>
</tr>
<tr>
<td>ARC</td>
<td>100*10$^{-9}b$</td>
<td>32$^b$</td>
<td>2400$^b$</td>
<td>691$^b$</td>
</tr>
<tr>
<td>EVA</td>
<td>0.0005$^{ab}$</td>
<td>0.35$^{ab}$</td>
<td>960$^b$</td>
<td>2090$^b$</td>
</tr>
<tr>
<td>PV cell</td>
<td>255*10$^{-6}b$</td>
<td>148$^b$</td>
<td>2330$^b$</td>
<td>667$^b$</td>
</tr>
<tr>
<td>Tedler</td>
<td>0.00015$^a$</td>
<td>0.2$^b$</td>
<td>1200$^b$</td>
<td>1250$^b$</td>
</tr>
<tr>
<td>Polystyrol</td>
<td>0.05$^c$</td>
<td>0.033$^c$</td>
<td>33$^c$</td>
<td>1500$^c$</td>
</tr>
</tbody>
</table>

Table 4.4: Physical specification of PV materials

### 4.1.4 Electrical DC output power

Electrical output power depends on the efficiency of the PV module. The efficiency at Standard Test Condition (STC) is used to determine the nominal power of the PV module.

Standard Test Condition (STC) defines the solar irradiation which is equal to 1000 W/m$^2$ at operating cell temperature 25°C together with the spectrum of corresponding AM1.5$^{[48]}$. In many cases with non-optimal orientation such as BIPV, BAPV and systems with high tilt angle, the mentioned circumstances are rarely achieved. Also, STC gives the researchers and the operators just a narrow view about the daily PV performance, so power prediction could be extremely higher or lower than expected due to the surrounding factors such as the effect of module temperature on the efficiency.

Normal Operating cell temperature-NOCT condition is the case when the PV module operates under the standard operating condition- SOC (Global solar irradiation as 800 W/m$^2$, ambient temperature 20°C and wind speed of 1 m/s) together with the solar spectrum of corresponding AM1.5$^{[49]}$.

Therefore instead of STC condition, EN 61853-1 has been introduced to describe the correlation between different solar irradiation and operating temperature.

**Photovoltaic (PV) modules performance testing and Energy rating EN 61853.**

This standard test condition is written to be applicable to all PV technologies and it includes four sectors:

- EN 61853-1 describes PV module performance in term of power ratings (watts) over a range of Irradiance and temperature.
- EN 61853-2 describes performance effect of angle of incidence, estimating module temperature from irradiance and the impact of spectral response measurement of energy production.
• EN 61853-3 describes PV module energy ratings (watt-hours).
• EN 61853-4 describes the standard time periods and weather conditions that can be utilized for calculating energy rating.

EN 61853-1 states a guideline for evaluating the PV module performance over the possible module temperature range and Irradiance under a certain air mass (AM1.5) rather than considering the past standard test conditions. The purpose of the mentioned standard is to define a testing and rating system, which provides the PV module power (watts) at a maximum power operation for a set of conditions, by providing the characterization parameter for the module under various values of irradiance and temperature [48]. This part is under discussion and accreditation.

The power delivery of PV module is a direct function of module temperature and irradiance level. PV cell/module performance is linear with temperature of crystalline material, but not longer with general relation for thin film material [48].

As the measurements need to be taken exactly, the specified irradiance and temperature in such a standard should be taken into account. It provides the investor or/and grid operator with a very close picture for the real time output power from the Photovoltaics.

The following table shows the standard condition for the PV module performance regarding (EN 61853-1); this table will appear in the data sheet of the PV modules in the coming years.

<table>
<thead>
<tr>
<th>Irradiance W/m²</th>
<th>Spectrum</th>
<th>Module Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>AM1.5</td>
<td>15°C</td>
</tr>
<tr>
<td>1000</td>
<td>AM1.5</td>
<td>25°C</td>
</tr>
<tr>
<td>800</td>
<td>AM1.5</td>
<td>50°C</td>
</tr>
<tr>
<td>600</td>
<td>AM1.5</td>
<td>75°C</td>
</tr>
<tr>
<td>400</td>
<td>AM1.5</td>
<td>&lt;STC&gt;</td>
</tr>
<tr>
<td>200</td>
<td>AM1.5</td>
<td>NA</td>
</tr>
<tr>
<td>100</td>
<td>AM1.5</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 4.5: PV module efficiency regarding different irradiance and temperature table [48]

The generated electrical power from the PV module is not more than 20% of the gained energy. In the simulation the electrical output power depends on the module maximum efficiency and the module operating temperature; the mentioned standard (EN61853-1) is not used because no data are available, but it can be in the near future. The output power of the PV module is calculated through considering the cable loss (assumed 0.5%) and the degradation effect. The following equation is used in the simulation.

\[
P_{el_{DC}} = 0.995 \times \eta_{pv} \times \left(1 - \left(\alpha_{MP} \times (T_{cell} - T_{stc})\right)\right) \times (Gi \times Area) \times (1 - degradation)
\]
Where
\( \eta_{pv} \): PV module STC efficiency.
\( \alpha_{P_{MP}} \): Temperature coefficient for power at Maximum power point[\%].
\( T_{cell} \): PV cell operating temperature [\( ^\circ C \)].
\( T_{stc} \): 25 [\( ^\circ C \)].
\( G_i \): Total inclined irradiation [W/m2].

As it is written in the equation; PV cell operating temperature is an important factor for calculating the output electrical power. Cell temperature calculation is discussed in the previous section.

### 4.2 Balance of System (BOS) model
The balance of system defines the system level aspect. It is specified by the PV array, inverter, and the accounted losses, the systems under study are designed to be around (1-1.15) kWp, to be compatible with the selected inverter (sunny boy, 1200W)

#### 4.2.1 Inverter
To investigate the AC output power, inverter is introduced to determine the output AC power and AC energy yield. “European Standard provides a procedure for the measurement of the accuracy of the maximum power point tracking (MPPT) of inverters, which are used in grid-connected systems. Both the static and dynamic MPPT efficiency is considered The static MPPT efficiency describes the accuracy of an inverter to regulate on the maximum power point on a given static characteristic curve of a PV generator” [50]. The weighted European (Maximum Power Point Tracking) MPPT efficiency is:

\[
\eta_{MPPT} = 0.03\eta_{MPPT@5\%} + 0.06\eta_{MPPT@10\%} + 0.13\eta_{MPPT@20\%} + 0.10\eta_{MPPT@30\%} + 0.48\eta_{MPPT@50\%} + 0.20\eta_{MPPT@100\%}
\]

The weighted CEC MPPT efficiency (California Energy Commission) is:

\[
\eta_{MPPT} = 0.04\eta_{MPPT@10\%} + 0.05\eta_{MPPT@20\%} + 0.12\eta_{MPPT@30\%} + 0.21\eta_{MPPT@50\%} + 0.53\eta_{MPPT@75\%} + 0.05\eta_{MPPT@100\%}
\]

Where \( \eta_{MPPT} \) is inverter efficiency.

In the simulation, the efficiency of the inverter is based on the input voltage at maximum power point (\( V_{MP} \)) with the effects of inverter loading and ambient temperature. The maximum efficiency of the selected inverter is 92.1\%. The electrical capacity of the selected inverter is 1200W and it belongs to SMA company [Appendix C].
Table 4.6 describes the procedures which are used in the simulation; it shows the interpolation between the PV system voltages at maximum power point \( V_{MP} \) and the effect of the temperature to determine the inverter efficiency in relation to inverter loading. The following formula shows the calculated system voltage (DC) with the effect of the module temperature.

\[
V_{sys-MP} = (n_{series} \times V_{MP}) - \left( (T_{cell} - T_{stc}) \times \alpha_{V_{MP}} \times n_{series} \right)
\]

Where:
- \( V_{sys-MP} \): PV system DC voltage at maximum power point [V]
- \( n_{series} \): Number of modules in series
- \( T_{cell} \): PV cell operating temperature [°C].
- \( \alpha_{V_{MP}} \): Temperature coefficient for power at Maximum power point [%].

![Image](image.png)

Table 4.6: Inverter efficiency with respect to the inverter loading “sunnyboy 1200W” [Appendix C]

The inverter operation is temperature dependent. The inverter is composed of semiconductor components which are sensitive to the temperature, so at a high operating temperature the inverter derates to protect these components from overheating. When the temperature of the semiconductor components increase to a certain threshold level, the inverter shifts its operation to a lower operation point. This causes a step reduction in the output AC power, in extreme case the inverter switches off\(^{[51]}\).

Table 4.7 describes the procedures which are used in the simulation regarding the ambient temperature effects on the inverter operation. It is seen that when the ambient temperature reaches more than 39 °C the inverter starts to derate with respect to the operating voltage level.
PV system designers should take into account an important point concerning the inverter size, regarding the international standard IEC 62548, the PV system is sized between 80%-110% of the inverter rated power, based on the incident irradiation which drives the PV system generated electrical power \[^{[52]}\]. Generally, in relation to the low solar irradiation areas such as middle and northern Europe, PV system is sized of about 10% more than the inverter rated power, while in a high irradiation areas such as Middle East and Africa, PV system is sized 10-20% less than the inverter rated power.

The PV systems under test are designed between (90%-95%) of the inverter rated power even in Kassel site (low irradiation area); and this is because, the measured effective incident irradiation in summer which is measured by ISET sensor, reaches more than 1200W/m\(^2\) many times during the year of study, and this causes a higher DC power output of the PV system, and may it affects the inverter operation. Hence, to be in a safe and high performance mode, the systems are designed less than what is expected.

The systems under test and evaluation are subjected to pass through SMA inverter 1200W to determine the AC power and yield, a mathematical inverter model is simulated based on the following equation and by assuming a cable loss of 0.5%, the degradation effect is considered in module level part.

\[
Pe_{AC} = (0.995 \times Pe_{DC} \times \eta_{MPPT} \times \alpha_{inv,T})
\]

\(\eta_{MPPT}\): Inverter efficiency at maximum power point tracking.
\(\alpha_{inv,T}\): Temperature coefficient on inverter.
4.3 Simulation model

The simulation model is based on the real time power balance concept of the PV operation. The incident irradiation, ambient temperature and wind speed are the inputs of the simulation model. The incident irradiation is affected by weather, mounting structure and PV elements. However, the output power includes the converted electrical energy in the solar cells and the gained heat, this heat is dissipated to the environment from the front and back cover of the PV module through heat transfer mechanism. On the other hand, the rest of the heat is absorbed and increases the module temperature of the PV cells. Figure 4.17 shows the relation between input and output power.

![Figure 4.17: Real time power balance for PV module](image)

Simulation model is based on two main milestones; module level and system level. In relation to the module level, three main points are investigated and simulated starting from the input power (irradiation) and ending by and the thermal power and electrical output power. Figure 4.18 is the block diagram for the simulation model.

![Figure 4.18: Simulation model block diagram](image)

Power input model includes the determination of zenith angle ($\theta z$) and angle of incidence ($\theta_{AOI}$) which are the main factors to convert the horizontal irradiation into a certain tilted irradiation. Angle of incidence is also used for calculating the optical loss which affects the incident
irradiation for Pyranometer case, while in the case of ISET sensor the optical loss is already considered because its structure is similar to the PV module structure. So the effect of the front cover of the PV module is considered in the measurement.

For Kassel site, the simulation is performed by using a meteorological data which is based on 15 seconds time resolution for the year 2009. On the other hand, for Ma’an site, the simulation is performed by using meteorological data which is based on 10 minutes time resolution for the year 2011.

By converting the incident irradiation into a certain inclined angle, electrical DC power output is calculated by depending on the effect of the operating temperature on the module efficiency. In other words, Power output calculation based on the temperature difference between the module and the standard test condition temperature (25°C), because the module temperature is the driving factor of the decay in the PV module efficiency as well as the magnitude of the output power.

The rest of irradiation is absorbed by the PV module materials and then it is converted to thermal energy. This energy heats the PV module, and a portion of this heat is dissipated through the heat transfer mechanism (conduction convection, radiation). The absorbed part of this heat increases the PV module temperature; the module temperature is obtained through a loop function and by depending on the heat capacity of the PV module, together with the physical characteristics of the PV module. At the end of each loop, a new module temperature is obtained. The new module temperature affects the magnitude of the output power. The thermal power model is based on the assumption that the electrical output power is constant during each time step of the simulation.

In relation to the system level, electrical aspects are considered rather than building system and this is why the system temperature is based on the module temperature. AC power and Energy yield are determined through simulating a mathematical model for a 1.2kW inverter, and by taking into consideration the inverter loading and the effect of the ambient temperature on the inverter operation. This inverter model can be used also for a inverters with larger capacity.

Initial conditions are assumed for the heat transfer coefficients and for the initial module temperature. Degradation is considered 3.5% and 1.3% for Kassel and Ma’an modules respectively. The simulation model is attached in Appendix D.

4.4 Boundary conditions
Boundary conditions in this thesis are divided into two categories; the first one is the surrounding circumstances of performing this thesis, and the second one is concerning the simulation model itself, hereafter the boundary conditions which are considered:

Boundary conditions regarding the thesis surrounding circumstance.
• Thesis period is just six month, therefore in order to take all the aspects into consideration, more than this period is needed. Hence, many assumptions are assumed.
• Delay in test PV field implementation in Jordan side (Amman city) forced me to modify the research evaluation tools into the following criteria:

- Evaluation of the simulation is performed just for the available measured data in (Fraunhofer – IWES) facilities, Kassel.

- In Jordan; Ma’an is selected instead of Amman because the proposed PV test filed which was considered in Amman at the beginning of this thesis is still under construction.

• Meteorological and measured data in Kassel is based on the year 2009, and it is measured in Frouhhofer-IWES PV test field. Due to the snow effects some records are not considered in the simulation and measurement.

• In Ma’an, the meteorological data is based on the year 2011. The solar data which is measured by the rotating shadow band radiometer instrument is corrected to pyranometer measuring format. There is a loss in wind speed data from 11/9/2011 to 8/11/2011. The data belongs to MDA company.

**Boundary conditions regarding the simulation model.**

• The boundaries of the measured global irradiation are 0-1500W/m², and it is between 0-800w/m² for the diffused irradiation\(^{[53]}\).

• PV modules are assumed to be three equivalent layers; front surface (Low iron glass), PV cells layer and back layer. Eva and ARC layers have very small effects which are not considered.

• Equivalent refractive index \(n_{eq}\) is assumed to be 3 for the front layer of all the PV modules under test.

• One dimensional heat transfer is considered in the calculation.

• Conduction heat transfer resistances \((R_{x1}, R_{x0})\) are assumed to be constant and independent from temperature.

• Temperature model based on constant electrical power during the time interval between each measurement, this causes a deviation in the temperature model.

• PV Module temperature is assumed to be equal the PV cells temperature \((T_{cell} = T_{surface})\).

• Initial conditions are assumed for Cell temperature and heat transfer coefficients to run the simulation.

• Wind speed is considered in the calculation. Wind direction is postponed for future research.
Chapter 5

Results and Discussion
5 Results and Discussion
In order to validate and check the simulation model outputs, the model results are compared and investigated with the real measurements in the Kassel site, polycrystalline Silicon and micromorphous silicon μ-Si technologies are simulated with respect to the presence and absence of isolation material at the back cover of the PV module. Irradiation measurements, module temperature, real time output power and energy yield in relation to the module and system level are evaluated by calculating the relative RMSE, MBE and the correlation coefficient (r).

Also, the model is applied on three PV modules and systems in the Ma’an site in order to predict the output power and energy yield, two polycrystalline and Cadmium Telluride (CdTe) technologies are simulated. The results will be explained.

5.1 Simulation results and evaluation in Kassel
In order to validate and check the simulation results MBE, relative RMSE and the correlation coefficient are calculated. Irradiation measurements through two different sensors are evaluated. Also, module temperature, real time output power and hourly, daily and monthly energy yield based on the module and system levels are evaluated with the real measured data.

5.1.1 Solar Irradiation evaluation
Solar irradiation is measured by different technologies. In the PV test field in IWES, it is measured by pyranometer at 0° (horizontal) and at 30° south orientation. Also, it is measured by ISET sensor at 30° south orientation. The starting point is to compare the pyranometer measurement with ISET sensor measurement at 30° south orientation, and by taking into consideration that the Pyranometer measurement does not include the optical losses which occur from the front cover of the PV module, while ISET sensor considers the optical losses. In this section two points are discussed; the effect of the optical losses on the pyranometer measurement, and the resultant irradiation measurement of the pyranometer for the different mentioned orientation.

• Optical loss effect
  Figure 5.1 shows the global tilted irradiation at 30° south orientations in Kassel in 2009, the measurement performed by ISET sensor and pyranometer by considering the effect of the optical losses; pyranometer measurement is converted from horizontal plane to 30° south (G0° → G30°).
The incident irradiation in winter season is very low when compared with summer season. In summer, the measurement recorded an instantaneous irradiation around 1.4 kWh/m². The period (4-15, Jan) is ignored because of the snow effect. The pyranometer measurement shows lower values of irradiation than ISET sensor measurement.

Figure 5.2 compares the monthly solar irradiation measurement at 30° south orientation. The measurements are determined through ISET sensor and pyranometer at IWES PV test field-Kassel. Pyranometer measurement is converted from horizontal plane to 30° south orientation as discussed in section (4.1.1.2). Furthermore, the figure shows the results of pyranometer measurement in the presence and absence of the optical loss (effective irradiation).
The maximum value for ISET sensor measurement is equal to 158.41 kWh/m$^2$ which is recorded in August, while the daily extreme value is equal to 8.07 kWh/m$^2$ which is obtained in 13$^{th}$, July. The maximum value obtained by Pyranometer is equal to 159.13 kWh/m$^2$ which is recorded in August, and the daily extreme value is equal to 8.63 kWh/m$^2$ which is obtained in 13$^{th}$, July. By considering the optical loss for the pyranometer, the maximum value is equal to 148.54 kWh/m$^2$ which is recorded in July, and the daily extreme value is equal to 7.6 kWh/m$^2$ which is obtained in 13$^{th}$, July.

As a result the optical loss decreases the effective incident irradiation which is measured by pyranometer as well as the predicted output power of the simulation. Thus, it is recommended to use a PV cell sensor such as ISET sensor for irradiation measurement; because it considers the optical loss. Moreover, it compensates the spectrum response of the PV technologies; this approach decreases the uncertainty of the predicted outputs.

**Orientation effect**

As explained in the previous figure, pyranometer is based on horizontal mounting structure and converted to 30$^\circ$ south orientation. Also, it can be mounted directly to a certain tilt angle. Because of the most of pyranometer measurements in the world depend on the horizontal base more than inclination base. The pyranometer irradiation measurement in this thesis is based on a horizontal structure. Figure 5.3 shows the comparison between the effective monthly irradiation which is measured in IWES facility by using ISET sensor at 30$^\circ$ south orientation, pyranometer measurement at 30$^\circ$ south orientations (G Pyranometer 30$^\circ$ south), and pyranometer measurement by converting the measured data from horizontal orientation to 30$^\circ$ south orientation (G Pyranometer “G 0$\rightarrow$30$^\circ$ south”). Pyranometer data appears with the consideration of optical loss which.

![Figure 5.3: Monthly solar irradiation measurement in Kassel by silicon sensor and Pyranometer sensor at 30$^\circ$ south orientation (pyranometer converted from 0$^\circ$ to 30$^\circ$, and at 30$^\circ$ orientation)]
It is seen that the incident irradiation in June is the lowest in the summer season. Also, it is noticed that, ISET sensor measurement is higher than Pyranometer measurement for both cases. (G Pyranometer 30° south) gives higher energy than (G Pyranometer “G 0\rightarrow 30 ^\circ south”) among the year. In order to check the deviation between the mentioned values of pyranometer measurements, RMSE, MBE and the correlation coefficient (r) of the pyranometer measurements in relation to ISET sensor measurement are determined. Table 5.1 summarizes the results.

<table>
<thead>
<tr>
<th></th>
<th>RMSE [%]</th>
<th>MBE [%]</th>
<th>Cor. Factor (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G\textsubscript{Pyr} 30° &amp; G\textsubscript{ISET}</td>
<td>22.6%</td>
<td>-4.51%</td>
<td>0.995</td>
</tr>
<tr>
<td>G\textsubscript{Pyr} 0\rightarrow 30° &amp; G\textsubscript{ISET}</td>
<td>23.78%</td>
<td>-8.04%</td>
<td>0.997</td>
</tr>
</tbody>
</table>

Table 5.1: Solar irradiation Deviation

It is concluded that the measurement of 30° inclined orientation gives better deviation than converting the incident irradiation from horizontal to inclined plane. RMSE and MBE show better results for inclination measurement. However, the two pyranometer cases show underestimated measurement compared to ISET measurement.

ISET sensor measurement and Pyranometer at horizontal mounted structure are accounted in the simulation. Although pyranometer at horizontal mounting structure shows more deviation, it is accounted in the simulation instead of the inclined one; this is because most of pyranometer measurements in the world depend on the horizontal case rather than inclined case.

As a result; For Photovoltaic modeling, ISET sensor gives more accurate measurement rather than pyranometer. It is preferable to use the same material of PV cell sensor for the PV module under test to be compatible with the PV material under test, to obtain more accurate results and to minimize the uncertainty which is occurred by the mismatching of spectrum response and optical loss of the PV materials\textsuperscript{[54]}.

5.1.2 Module temperature

Module temperature is determined under the assumption that the electrical power is constant during simulation time steps. This leads to deviate the predicted module temperature from the measured values. Figure 5.4 shows the predicted and measured curves for the first two days of July for the polycrystalline module without isolation material at the back cover.
It is seen that the module temperature curves are closer to each other at the day time compared to the night time. It can be seen the fluctuation during the day in the predicted curve; this is because the effect of the thermal model loop function in the simulation. The deviation at the night does not affect the calculation, because there is no generated power from the PV module and system.

Table 5.2 shows the MBE, RMSE and the correlation coefficient for the predicted and measured module temperature during the year and based on each 15 seconds resolution, and by considering ISET sensor and pyranometer irradiation measurement.

<table>
<thead>
<tr>
<th></th>
<th>Poly cr.-162Wp (not isolated)</th>
<th>Poly cr.-162Wp (isolated )</th>
<th>μ-Si-85Wp ( not isolated )</th>
<th>μ-Si-85Wp (isolated )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE[%]</td>
<td>G_{ISET}</td>
<td>G_{Pyr}</td>
<td>G_{ISET}</td>
<td>G_{Pyr}</td>
</tr>
<tr>
<td></td>
<td>10.48%</td>
<td>8.15%</td>
<td>21.49%</td>
<td>17.77%</td>
</tr>
<tr>
<td></td>
<td>14.10%</td>
<td>11.62%</td>
<td>26.52%</td>
<td>22.58%</td>
</tr>
<tr>
<td>RMSE[%]</td>
<td>G_{ISET}</td>
<td>G_{Pyr}</td>
<td>G_{ISET}</td>
<td>G_{Pyr}</td>
</tr>
<tr>
<td></td>
<td>18.22%</td>
<td>17.25%</td>
<td>29.05%</td>
<td>25.67%</td>
</tr>
<tr>
<td></td>
<td>23.18%</td>
<td>20.97%</td>
<td>37.82%</td>
<td>32.11%</td>
</tr>
<tr>
<td>r</td>
<td>0.9881</td>
<td>0.9875</td>
<td>0.9882</td>
<td>0.9869</td>
</tr>
<tr>
<td></td>
<td>0.9837</td>
<td>0.9837</td>
<td>0.9838</td>
<td>0.9839</td>
</tr>
</tbody>
</table>

Table 5.2: Modules temperature deviation by using ISET sensor and pyranometer as a solar irradiation measurements

It is noticed that MBE and RMSE results are deviated; the main reason is the fluctuation predicted results during the day. It can be seen from the figure 5.4 the night time is also deviated. The other reasons are the assumption of the thermal model (the constant generated output power assumption during the simulation time steps), and the assumed initial conditions for the convection and radiation heat transfer coefficients and PV module temperature. These initial conditions will not affect the electrical power prediction, because the simulation starts at the midnight for each month, and at this time the output is zero.
μ-Si module with back isolation material shows higher deviation results. MBE and RMSE are considered high values compared to the other structures. This is the same for polycrystalline module with isolation material, but with significantly lower deviation. The reason for these high values is the assumption of the physical characteristics of the isolation material. However it can be improved by changing the assumed physical characteristics of this material.

It is noticed that the deviations which are based on pyranometer measurement, are lower than ISET sensor bases measurement. This is because the effective irradiation is lower in the pyranometer case, and so the input thermal power is lower. The output power results which will be discussed in following sections proves that, by using pyranometer as a base of irradiation measurement the output power is underestimation compared to ISET sensor based measurement.

In relation to the correlation coefficient, the predicted and measured curves show very good results. Correlation coefficient concerns about the shape of the curves rather than the magnitude.

### 5.1.3 Output power

#### 5.1.3.1 Module level (DC power)

The modules under test are simulated by using the irradiation data from ISET sensor and pyranometer. DC electrical power output is obtained and evaluated under different technologies (Micromorphous and polycrystalline) and with different module structures (isolation and without isolation at the back cover). Table 5.3 shows the maximum predicted and measured instantaneous DC output power and the MBE deviation.

<table>
<thead>
<tr>
<th>Type</th>
<th>Module structure</th>
<th>Measured max. DC power [W]</th>
<th>Predicted max. DC power [W]</th>
<th>MBE [%]</th>
<th>Irradiation measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polycrystalline</td>
<td>Not isolated</td>
<td>208.9</td>
<td>205.6</td>
<td>-1.58%</td>
<td>ISET sensor</td>
</tr>
<tr>
<td>162 Wp</td>
<td>Isolated</td>
<td>205.1</td>
<td>198.3</td>
<td>-5.07%</td>
<td>Pyranometer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>197.9</td>
<td>-3.50%</td>
<td>ISET sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>192.1</td>
<td>-6.34%</td>
<td>Pyranometer</td>
</tr>
<tr>
<td>Micromorphous silicon</td>
<td>Not isolated</td>
<td>118.2</td>
<td>112.3</td>
<td>-4.99%</td>
<td>ISET sensor</td>
</tr>
<tr>
<td>85 Wp</td>
<td>Isolated</td>
<td></td>
<td>107.7</td>
<td>-8.88%</td>
<td>Pyranometer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>108.8</td>
<td>-4.48%</td>
<td>ISET sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>104.9</td>
<td>-7.90%</td>
<td>Pyranometer</td>
</tr>
</tbody>
</table>

**Table 5.3: maximum instantaneous output DC power of the module level**

It can be seen that the modules with isolation cover generate less power than the modules without isolation, and this is because they have higher operating module temperature than the modules without isolation at the back cover. Looking to the predicted values, based on ISET sensor irradiation measurement for the four module structures, the absolute MBE is less than 5%, it is less than 3.5% for polycrystalline modules. The best deviation occurs for polycrystalline
without isolation cover module. The deviation is not more than 3.3Wp. Predicted values based on pyranometer measurement shows more deviation, it reaches to 8.9% for μ-Si without isolation cover. The reason of this high deviation is the optical loss which affects the pyranometer measurement.

The following two figures show the relation between the irradiation measured by ISET sensor and Pyranometer for the modules under test with the related output power. Four different days from different seasons are selected. The effective irradiation which is measured by ISET sensor is higher than pyranometer measurement; this leads to a higher power output and energy yield gained from PV modules when used ISET sensor measurement.
Figure 5.5: ISET irradiation measurement and DC output power for four different days
Figure 5.6: Pyranometer irradiation measurement and DC output power for four different days
In Figure 5.5 the measured and predicted values are close to each other, regarding the simulation model output, it gives slightly lower prediction values in summer time, while it gives slightly higher prediction in winter time, this relies on the technology. Also, It is seen that the measured and predicted power can be more than the module rated power in summer and this is because the irradiation exceeded the STC irradiation (1000W/m²).

In Figure 5.6 the measured values are always higher than the predicted values among the year. It has slightly higher values in winter time, however, it is obvious in summer season that the measured values are much higher than the predicted values when compared with winter season.

Significantly, by depending on ISET sensor as the base of irradiation measurement, the simulation model gives closer predicted results to the measured data. However, by using the pyranometer as a base of irradiation measurement, the predicted output power is underestimated with a higher deviation than using ISET measurement.

Regarding module structure, the modules with isolation cover generate less energy than modules without isolation cover, because the operating module temperature is higher than the modules without isolation material.

In 15th January the technologies under test give the minimum output power. However, in summer time and mainly in July the maximum output power and energy yield is achieved. Although Kassel is blessed with a good irradiation in summer, there are fluctuations in the measurement because of the location climatic conditions. This is a very important factor to be considered; because it has an important effect on the PV module/system performance as well as the real time output power, which is the key factor for controlling the grid performance.

In order to evaluate the predicted DC output power with the measured data of the modules under test. MBE, RMSE and the correlation coefficient are calculated. Table 5.4 shows the yearly deviations based on 15 seconds time resolution simulation for polycrystalline and μ-Si modules.

<table>
<thead>
<tr>
<th></th>
<th>Poly cr.-162Wp (not isolated)</th>
<th>Poly cr.-162Wp (isolated)</th>
<th>μ-Si-85Wp (not isolated)</th>
<th>μ-Si-85Wp (isolated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G_{iset}</td>
<td>G_{pyr}</td>
<td>G_{iset}</td>
<td>G_{pyr}</td>
</tr>
<tr>
<td>MBE(%)</td>
<td>1.39%</td>
<td>-6.00%</td>
<td>-0.87%</td>
<td>-7.40%</td>
</tr>
<tr>
<td>RMSE(%)</td>
<td>15.74%</td>
<td>27.68%</td>
<td>18.10%</td>
<td>30.49%</td>
</tr>
<tr>
<td>r</td>
<td>0.9967</td>
<td>0.9945</td>
<td>0.9950</td>
<td>0.9954</td>
</tr>
</tbody>
</table>

Table 5.4: DC output power deviation based on 15 seconds time resolution

As can be seen, by using ISET sensor irradiation measurement G_{iset} a higher accuracy is achieved than using pyranometer measurement G_{pyr}. By using G_{iset} MBE is not exceeded 1.39%. Micromorphous without isolation back cover gives the minimum MBE (0.11%). On the
other hand by using G\textsubscript{Pyr}, the MBE is more than 6%, polycrystalline without isolation back cover gives the minimum MBE. However, based on G\textsubscript{ISET} measurement polycrystalline without isolation cover shows the best RMSE value (15.74%). Nevertheless, based on G\textsubscript{Pyr} measurement, Polycrystalline with isolation cover shows the largest RMSE value (30.49%).

In relation to the linearity between the measured and predicted curves, the correlation coefficient is determined and in all the measurement the correlation coefficient is more than 99%, which means that the measured and predicted curves are matched with each other.

### 5.1.3.2 System level (AC power)

Two PV modules are designed in relation to 1200W inverter, the first system is based on micromorphous silicon technology, and the peak power is 1020Wp peak. The second system is based on polycrystalline silicon technology, the peak power is 1134Wp.

There is no such a real PV system with the previous criteria in IWES PV test field. Therefore, the measured DC peak power from the module level is converted to a system level with the same criteria of the simulated system in order to comply them with the same inverter. Then the evaluation of the two systems can be obtained. The system level is based on ISET sensor irradiation measurement because it gives a higher accuracy than pyranometer measurement.

Table 5.5 shows the maximum instantaneous AC output power for the four PV systems under test, a comparison is performed regarding the MBE deviation between the measured and predicted instantaneous values.

<table>
<thead>
<tr>
<th>Type</th>
<th>Module structure</th>
<th>Measured max. AC power [kW]</th>
<th>Predicted max. AC power [kW]</th>
<th>MBE [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polycrystalline 162 Wp</td>
<td>Not isolated</td>
<td>1.293</td>
<td>1.272</td>
<td>1.65%</td>
</tr>
<tr>
<td></td>
<td>Isolated</td>
<td>1.270</td>
<td>1.227</td>
<td>3.50%</td>
</tr>
<tr>
<td>Micromorphous silicon 85 Wp</td>
<td>Not isolated</td>
<td>1.257</td>
<td>1.198</td>
<td>4.92%</td>
</tr>
<tr>
<td></td>
<td>Isolated</td>
<td>1.214</td>
<td>1.162</td>
<td>4.48%</td>
</tr>
</tbody>
</table>

**Table 5.5: maximum instantaneous output AC power of the system level**

The PV systems with isolation at the back cover generate less power than systems without isolation cover. Polycrystalline systems show better MBE than μ-Si system. The minimum MBE is recorded by polycrystalline without isolation cover (1.65%). it is concluded that the deviation results are quite similar to the module level (Table 5.3). Because the inverter is quite direct proportional to the output power of the module level,

Figure 5.7 shows the relation between the irradiation measured by ISET sensor for the systems under test with the same criteria which is used in the module level part.
Figure 5.7: ISET irradiation measurement and AC output power for four different days
The effect of fluctuations should be highly considered for the system level, since the output power of the PV system increases, and so the fluctuations in the generated output power proportionally increase. This affects the grid performance and mainly it affects the nearest substation to the PV system.

Table 5.6 shows the yearly deviations which are based on 15 seconds time resolution simulation, between the predicted and measured values of polycrystalline and μ-Si modules, and by considering ISET sensor as a base of irradiation measurement.

<table>
<thead>
<tr>
<th></th>
<th>Poly cr.-1134Wp (not isolated)</th>
<th>Poly cr.-1134Wp (isolated )</th>
<th>μ-Si-1020Wp (not isolated )</th>
<th>μ-Si-1020Wp (isolated )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE[%,]</td>
<td>1.31%</td>
<td>-1.05%</td>
<td>0.07%</td>
<td>-1.09%</td>
</tr>
<tr>
<td>RMSE[%,]</td>
<td>15.82%</td>
<td>18.21%</td>
<td>19.24%</td>
<td>21.98%</td>
</tr>
<tr>
<td>( r )</td>
<td>0.9968</td>
<td>0.9970</td>
<td>0.9950</td>
<td>0.9945</td>
</tr>
</tbody>
</table>

Table 5.6: AC output power deviation for 15 seconds time resolution

As it is seen, MBE is not exceeded 1.31%, the minimum value is achieved by μ-Si without isolation material (0.07%), while polycrystalline without isolation back cover gives the largest MBE value (1.31%). On the other hand polycrystalline without isolation back cover shows the best RMSE value (15.82%) while μ-Si with isolation back cover shows a largest RMSE value (21.98%). Its conclude that RMSE slightly increases when converting from the module level to the system level, while that is not a condition in relation to the MBE, because RMSE refers to the scattering of the predicted results when compared with the measured results, and since the output power is increased the scattering is also increased linearly.

The correlation coefficient of all measurements are more than 99% which means the measured and predicted curves are highly compatible to each other, and no differences appears between the module and systems level.

### 5.1.4 Energy yield

In this section, the generated energy yields for the module and system level are evaluated. This evaluation gives a deep view for how the predicted energy is compatible with the measured data.

#### 5.1.4.1 Module level (DC Energy yield)

Generated DC energy yield from the four PV modules under test are predicted and evaluated as it is seen in table 5.7.
<table>
<thead>
<tr>
<th>Type</th>
<th>Module structure</th>
<th>Measured DC energy yield [kWh&lt;sub&gt;DC&lt;/sub&gt;]</th>
<th>Predicted DC energy yield [kWh&lt;sub&gt;DC&lt;/sub&gt;]</th>
<th>MBE [%]</th>
<th>Irradiation measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly crystalline 162 Wp</td>
<td>Not isolated</td>
<td>163.942</td>
<td>166.11</td>
<td>1.32%</td>
<td>ISET sensor</td>
</tr>
<tr>
<td></td>
<td>Isolated</td>
<td>155.77</td>
<td>154.00</td>
<td>-6.06%</td>
<td>Pyranometer</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>154.33</td>
<td>-0.92%</td>
<td>ISET sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>144.17</td>
<td>-7.45%</td>
<td>Pyranometer</td>
</tr>
<tr>
<td>Micromorphous silicon 85 Wp</td>
<td>Not isolated</td>
<td>89.438</td>
<td>89.434</td>
<td>0.00%</td>
<td>ISET sensor</td>
</tr>
<tr>
<td></td>
<td>Isolated</td>
<td>87.198</td>
<td>86.247</td>
<td>-1.09%</td>
<td>ISET sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>79.913</td>
<td>-8.35%</td>
<td>Pyranometer</td>
</tr>
</tbody>
</table>

Table 5.7: DC energy yield of the module level

The predicted DC energy yield which is based on G<sub>ISET</sub> measurement achieves better and closer results to the measured values compared to the G<sub>Pyr</sub> measurement based simulation. A compatible value and zero MBE is achieved by the μ-Si without isolation material, the measured and predicted DC energy yield are around 89kWh, the other values are close to the measured values and they are accepted, the best MBE which is based on G<sub>Pyr</sub> measurement is achieved by polycrystalline without isolation on material module, the MBE is 6% underestimation.

The specific energy (kWh/kWp) is an important factor to compare between different photovoltaic technologies. Specific energies for the modules under test are obtained and evaluated with the measured values. The values are obtained by referring the DC energy yield to the STC peak powers of each module. The results are shown in table 5.8.
<table>
<thead>
<tr>
<th>Irradiation measurement</th>
<th>Module Type</th>
<th>Specific DC energy [kWh$_{DC}$/Wp]</th>
<th>MBE [Wh$_{DC}$/Wp]</th>
<th>MBE [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISET sensor</td>
<td>Poly cr.-162Wp (not isolated)</td>
<td>1.011</td>
<td>1.025</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Poly cr.-162Wp (isolated)</td>
<td>0.961</td>
<td>0.952</td>
<td>-9</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>Poly cr.-162Wp (not isolated)</td>
<td>1.011</td>
<td>0.950</td>
<td>-61</td>
</tr>
<tr>
<td></td>
<td>Poly cr.-162Wp (isolated)</td>
<td>0.961</td>
<td>0.889</td>
<td>-72</td>
</tr>
<tr>
<td>ISET sensor</td>
<td>μ-Si-85Wp (not isolated)</td>
<td>1.052</td>
<td>1.052</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>μ-Si-85Wp (isolated)</td>
<td>1.025</td>
<td>1.014</td>
<td>-11</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>μ-Si-85Wp (not isolated)</td>
<td>1.052</td>
<td>0.971</td>
<td>-81</td>
</tr>
<tr>
<td></td>
<td>μ-Si-85Wp (isolated)</td>
<td>1.025</td>
<td>0.940</td>
<td>-85</td>
</tr>
</tbody>
</table>

Table 5.8: Specific DC energy yield

It is seen that the μ-Si module without isolation material has the maximum specific DC energy, and this is because thin film technologies response better to the high operating temperature than the silicon technologies, and practically it has a good response to the long wavelength irradiation\cite{8}. Also, the predicted specific energy which is based on $G_{\text{ISET}}$ measurement records good matched values with the measured values. The maximum absolute MBE is not more than 14Wh/Wp which is around 1.32%. The minimum MBE is recorded in the μ-Si without isolation material, it is seen that the predicted and measured value are similar which gives zero deviation.

By using pyranometer irradiation measurement, the deviation is higher compared to ISET sensor measurement, the maximum deviation is occurred in μ-Si with isolation back cover module, whereas the predicted specific energy is less than the measured value by 85Wh/Wp.

In order to validate the predicted results during the whole year, accumulated DC power is evaluated, in this evaluation MBE, RMSE and the correlation coefficient are calculated. Table 5.9 shows the evaluation which is performed between the predicted and measured accumulated DC power among the year. The evaluation is based on each 15 second resolution; this means that for each step (iteration) the simulated energy (accumulated power) is evaluated regarding the each iteration with a real measured data. This clarifies the matching between the results during the year.
Table 5.9: Accumulated DC power evaluation among the year

<table>
<thead>
<tr>
<th></th>
<th>Poly cr.-162Wp (not isolated)</th>
<th>Poly cr.-162Wp (isolated )</th>
<th>μ-Si-85Wp (not isolated )</th>
<th>μ-Si-85Wp (isolated )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE[% ]</td>
<td>G_{iset} 1.35% G_{pyr} -5.76%</td>
<td>G_{iset} -0.98% G_{pyr} -7.21%</td>
<td>G_{iset} 0.52% G_{pyr} -6.91%</td>
<td>G_{iset} -0.60% G_{pyr} -7.62%</td>
</tr>
<tr>
<td>RMSE[% ]</td>
<td>1.47% 6.96%</td>
<td>1.76% 8.87%</td>
<td>1.68% 9.08%</td>
<td>2.37% 9.98%</td>
</tr>
<tr>
<td>( r )</td>
<td>1.0000 1.0000</td>
<td>1.0000 1.0000</td>
<td>0.9999 1.0000</td>
<td>0.9999 0.9999</td>
</tr>
</tbody>
</table>

The MBE for Predicted DC energy yield by considering \( G_{iset} \) for \( \mu\)-Si modules gives better matching than polycrystalline modules, but when considering \( G_{pyr} \) measurement, polycrystalline modules give better MBE values. For RMSE polycrystalline modules gives better values in both irradiation measurement cases. Correlation coefficient shows a well linear matching between the predicted and measured curves.

Figure 5.8 shows monthly DC energy yield of the polycrystalline module with and without back isolation, the prediction and measurement are based on ISET sensor and pyranometer irradiation measurements.
It’s clearly that the DC energy yield for the module structure without back isolation in both cases of irradiation measurement is achieved a higher monthly energy yield. The maximum predicting value of polycrystalline module is obtained by the structure without isolation at the back cover, and based on \( G_{\text{ISET}} \) measurement. It is equal to 22.8 kWh and occurred in May, and it is closed to the measured value at the same month which is equal to 22.5 kWh. However, the minimum values are recorded in December for the isolation module, and based on \( G_{\text{Pyr}} \) measurement; the predicted value is equal to 2.77 kWh, while it’s very close to measured value, which is equal to 2.78 kWh. The lowest monthly energy yield in summer season occurred in July, the reason is related to the incident irradiation. The prediction of the modules with isolation material at the
back cover is obviously deviated than the measurement; this is because of the assumption of the physical characteristic of the isolation material.

Figure 5.9 shows monthly DC energy yield of the micromorphous silicon module with and without back isolation, the prediction and measurement are based on ISET sensor and pyranometer irradiation measurement.

As it is illustrated, the approach in the micromorphous silicon modules are similar to polycrystalline modules, the maximum predicted value is obtained by the structure without back isolation and based on G_{ISET} measurement, it is equal to 12.37 kWh and occurred in August, while the maximum measured monthly DC energy yield is equal to 12.97 kWh and occurred in July, However, the minimum values are recorded in December for the isolated module and based
on $G_{Pyr}$ measurement, the predicted value is about 1.42 kWh, while it is closed to the measured value which is about 1.36 kWh. The measured values are obviously higher than the predicted value. The reason is the thermal annealing which affects thin film technologies, it means that the module electrical output power becomes higher at a higher operating temperature, and this phenomenon needs further investigation.

The following table shows the MBE, RMSE and the correlation coefficient of the DC energy yield deviations. This evaluation is based on an hourly, daily and monthly yield. Polycrystalline and $\mu$-Si modules with and without isolation material are evaluated, and by considering $G_{ISET}$ and $G_{Pyr}$ as the base of irradiation measurement.

<table>
<thead>
<tr>
<th>Interval</th>
<th>MBE</th>
<th>RMSE</th>
<th>( $r$ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hourly</td>
<td>1.39%</td>
<td>10.72%</td>
<td>0.9983</td>
</tr>
<tr>
<td></td>
<td>-6.00%</td>
<td>24.06%</td>
<td>0.9962</td>
</tr>
<tr>
<td></td>
<td>-0.87%</td>
<td>13.91%</td>
<td>0.9983</td>
</tr>
<tr>
<td></td>
<td>-7.40%</td>
<td>26.97%</td>
<td>0.9966</td>
</tr>
<tr>
<td></td>
<td>0.11%</td>
<td>14.01%</td>
<td>0.9970</td>
</tr>
<tr>
<td></td>
<td>-7.57%</td>
<td>23.50%</td>
<td>0.9977</td>
</tr>
<tr>
<td></td>
<td>-1.02%</td>
<td>17.21%</td>
<td>0.9966</td>
</tr>
<tr>
<td></td>
<td>-8.29%</td>
<td>29.00%</td>
<td>0.9964</td>
</tr>
<tr>
<td>Daily</td>
<td>1.39%</td>
<td>4.55%</td>
<td>0.9987</td>
</tr>
<tr>
<td></td>
<td>-6.00%</td>
<td>11.30%</td>
<td>0.9954</td>
</tr>
<tr>
<td></td>
<td>-0.87%</td>
<td>6.09%</td>
<td>0.9992</td>
</tr>
<tr>
<td></td>
<td>-7.40%</td>
<td>12.78%</td>
<td>0.9966</td>
</tr>
<tr>
<td></td>
<td>0.11%</td>
<td>7.06%</td>
<td>0.9982</td>
</tr>
<tr>
<td></td>
<td>-7.57%</td>
<td>12.01%</td>
<td>0.9970</td>
</tr>
<tr>
<td></td>
<td>-1.02%</td>
<td>8.16%</td>
<td>0.9974</td>
</tr>
<tr>
<td></td>
<td>-8.29%</td>
<td>14.09%</td>
<td></td>
</tr>
<tr>
<td>Monthly</td>
<td>1.39%</td>
<td>2.45%</td>
<td>0.9996</td>
</tr>
<tr>
<td></td>
<td>-6.00%</td>
<td>7.54%</td>
<td>0.9978</td>
</tr>
<tr>
<td></td>
<td>-0.87%</td>
<td>3.81%</td>
<td>0.9999</td>
</tr>
<tr>
<td></td>
<td>-7.40%</td>
<td>9.08%</td>
<td>0.9988</td>
</tr>
<tr>
<td></td>
<td>0.11%</td>
<td>5.43%</td>
<td>0.9989</td>
</tr>
<tr>
<td></td>
<td>-7.57%</td>
<td>10.27%</td>
<td>0.9991</td>
</tr>
<tr>
<td></td>
<td>-1.02%</td>
<td>6.34%</td>
<td>0.9990</td>
</tr>
<tr>
<td></td>
<td>-8.29%</td>
<td>11.35%</td>
<td>0.9988</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interval</th>
<th>Poly cr.-162Wp (not isolated)</th>
<th>Poly cr.-162Wp (isolated )</th>
<th>$\mu$-Si-85Wp (not isolated )</th>
<th>$\mu$-Si-85Wp (isolated )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hourly</td>
<td>MBE 1.39% -6.00% -0.87% -7.40% 0.11% -7.57% -1.02% -8.29%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMSE 10.72% 24.06% 13.91% 26.97% 14.01% 23.50% 17.21% 29.00%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( $r$ ) 0.9983 0.9962 0.9983 0.9966 0.9970 0.9977 0.9966 0.9964</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily</td>
<td>MBE 1.39% -6.00% -0.87% -7.40% 0.11% -7.57% -1.02% -8.29%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMSE 4.55% 11.30% 6.09% 12.78% 7.06% 12.01% 8.16% 14.09%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( $r$ ) 0.9987 0.9954 0.9992 0.9966 0.9982 0.9970 0.9974</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly</td>
<td>MBE 1.39% -6.00% -0.87% -7.40% 0.11% -7.57% -1.02% -8.29%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RMSE 2.45% 7.54% 3.81% 9.08% 5.43% 10.27% 6.34% 11.35%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( $r$ ) 0.9996 0.9978 0.9999 0.9988 0.9989 0.9991 0.9990 0.9988</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.10: MBE and RMSE for hourly, daily and monthly DC energy yield

It is seen that in all cases, the MBE which is based on $G_{ISET}$ measurement shows a very good results, it is not exceeded 1.5%, this value means, a high level of convergence between the measured and predicted values is achieved. The best MBE value is recorded by $\mu$-Si without isolation material at the back cover, while the best record for $G_{Pyr}$ measurement is for the polycrystalline without isolation material. However, this value (6%) is relatively high when compare it to the deviation which is achieved by considering $G_{ISET}$ measurement as the base of simulation.

Hourly, daily, monthly MBE values are similar; the reason of this convergence is the different values of the mean (average) of the measurement which are based on hourly, daily and monthly calculations. This leads to obtain very close results in each case, for example and in relation to MBE equation; for polycrystalline module based on $G_{ISET}$ measurement. The hourly, daily and monthly MBE are 0.26Wh, 6.25Wh and 190.2Wh respectively, while the mean values (denominator) are 18.7Wh, 448Wh and 13653Wh; and so the division of these values are nearly the same.
Based on $G_{\text{ISET}}$ measurement, polycrystalline modules give better RMSE values rather than micromorphous; this means that the scattering of the predicted values for polycrystalline modules are closer to the measured values when compared with $\mu$-Si modules. Also, the modules without isolation material give better RMSE than modules with isolation material. The hourly DC energy yield has the highest deviation in all cases. For ISET sensor measurement, the deviation is acceptable, while for pyranometer case it shows a high deviation especially for isolated module.

The correlation coefficient is more than 99%, this means that the measured and predicted curves are highly compatible although the predicted energy yields based on $G_{\text{Pyr}}$ measurement are deviated from the measured values; The correlation coefficient describes the linear matching between the shape of measured and predicted curves.

5.1.4.2 System level (AC Energy)

The PV systems are also evaluated regarding the AC energy yield. The first PV system is based on micromorphous silicon technology; the peak power is 1020Wp peak. The other system is based on polycrystalline silicon technology, the peak power is 1134Wp. The PV systems are integrated with the mathematical inverter model. The inverter model is designed with respect to the inverter loading and the effect of ambient temperature. The following table shows the predicted and measured generated AC energy yield. The measurements are based on ISET sensor irradiation measurement.

<table>
<thead>
<tr>
<th>Type</th>
<th>Module structure</th>
<th>Measured AC energy yield $[\text{kWh}_{\text{AC}}]$</th>
<th>Predicted AC energy yield $[\text{kWh}_{\text{AC}}]$</th>
<th>Difference $[\text{kWh}_{\text{AC}}]$</th>
<th>MBE [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly cr.</td>
<td>Not isolated</td>
<td>1025.1</td>
<td>1038.5</td>
<td>13.40</td>
<td>1.31%</td>
</tr>
<tr>
<td>162Wp</td>
<td>Isolated</td>
<td>973.49</td>
<td>963.27</td>
<td>-10.22</td>
<td>-1.05%</td>
</tr>
<tr>
<td>Micro.-silicon</td>
<td>Not isolated</td>
<td>958.67</td>
<td>959.29</td>
<td>0.62</td>
<td>0.06%</td>
</tr>
<tr>
<td>85Wp</td>
<td>Isolated</td>
<td>934.32</td>
<td>924.11</td>
<td>-10.21</td>
<td>-1.09%</td>
</tr>
</tbody>
</table>

| ![Table 5.11: AC energy yield of the system level](image) |

It is seen that the values are close to each other, and the calculated deviation is not more than 1.31% which is recorded for polycrystalline modules (PV array in BOS) without isolation material. The $\mu$-Si modules without isolation at the back cover gives the closest predicted to measured value. The predicted values for isolation systems are under estimation, while the systems without isolation material show over estimation values.

Specific AC energy yields of the systems under test are obtained; the values are calculated by referring the AC energy yield to the STC peak power of each system, the following table shows the results of the calculation.
The system which is based on the μ-Si without isolation material gives the maximum specific AC energy yield. This is because it responds better to the operating temperature than polycrystalline modules. Also, the predicted specific energy measurement records a good matching with the measured values. The maximum absolute deviation is equal to 12Wh/Wp which is around 1.31% over estimation. On the other hand, the minimum deviation is recorded to the μ-Si without isolation material, the difference between the predicted and measured values is just 1Wh/Wp.

AC specific energy values are lower than DC specific energy values (Table 5.8). This difference is caused mainly from the efficiency of the inverter and the effect of the inverter loading. By obtaining the AC specific energy, the exact inverter losses can be determined through subtracting the AC specific energy of the system level from the DC specific energy of the module level. The following table shows the results of the calculation,

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Specific AC energy yield Wh/ac/Wp (AC) System</th>
<th>Deviation Wh/Wp</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly cr.-162Wp not isolated</td>
<td>903</td>
<td>915</td>
<td>12</td>
</tr>
<tr>
<td>Poly cr.-162Wp isolated</td>
<td>858</td>
<td>849</td>
<td>-9</td>
</tr>
<tr>
<td>μ-Si-85Wp not isolated</td>
<td>928</td>
<td>929</td>
<td>1</td>
</tr>
<tr>
<td>μ-Si-85Wp isolated</td>
<td>905</td>
<td>895</td>
<td>-10</td>
</tr>
</tbody>
</table>

Table 5.12: Specific AC energy yield

It can be seen that the measured and predicted values are closed to each other. Polycrystalline technology shows a lower difference between AC and DC specific energy than micromorphous technology. The inverter loss which affects the polycrystalline systems ranges between
(10.68-10.82%), while it ranges between (11.69-11.79%) for micromorphous systems. The determined losses are highly accepted taking into account the maximum efficiency (92.1%).

Table 5.14 shows the evaluation for accumulated AC power among the year, MBE, RMSE and the correlation coefficient are considered, the calculation are based on the same criteria as the accumulated DC power.

<table>
<thead>
<tr>
<th>Time interval</th>
<th>Poly cr.-1134Wp (not isolated)</th>
<th>Poly cr.-1134Wp (isolated )</th>
<th>μ-Si-1020Wp (not isolated )</th>
<th>μ-Si-1020Wp (isolated )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBE[ % ]</td>
<td>1.27%</td>
<td>-1.15%</td>
<td>0.48%</td>
<td>-0.66%</td>
</tr>
<tr>
<td>RMSE[ % ]</td>
<td>1.39%</td>
<td>1.93%</td>
<td>1.70%</td>
<td>2.44%</td>
</tr>
<tr>
<td>r</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.9999</td>
<td>0.9999</td>
</tr>
</tbody>
</table>

Table 5.14: Accumulated AC power evaluation

The μ-Si system shows better MBE values than polycrystalline; the systems without isolation material show over estimation results, while the systems with isolation cover show under estimation results. In relation to the RMSE, the polycrystalline systems give better values than μ-Si systems. Also, the systems without isolation cover give better RMSE than the systems with isolated modules. Correlation coefficient shows a linear matching between the predicted and measured curves.

The following two figures show the monthly AC energy yield of the four PV systems under test, the predictions and measurements are based on ISET sensor irradiation measurement, it’s clearly shown that the energy yield of the modules (PV array in BOS) structure without isolation material gives a higher energy yield. Figure 5.10 shows monthly energy yield for polycrystalline PV system (1134Wp) with and without isolation material.

![Monthly AC Energy yield- poly crystalline system](image)

Figure 5.10: Monthly AC energy yield of poly-cr system, 1134Wp with and without back isolation cover
The maximum predicted value of polycrystalline system is equal to 141.5 kWh and it is obtained by the structure without isolation material, and it is close to the measured value which is equal to 143.3 kWh. These results are recorded in May. However, the minimum predicting value of the same structure is equal to 20.4 kWh and it is close to the measured value which is equal to 18.4 kWh. These values are recorded in December. On the other hand, the systems with isolation material, the maximum predicted and measured values are equal to 130.7 kWh and 135.6 kWh respectively, and are occurred in May. The minimum values are equal to 19.6 kWh and 16.9 kWh, and they are occurred in December.

Figure 5.11 shows the monthly energy yield for micromorphous PV system (1020 Wp) with and without isolation material.

![Figure 5.11: Monthly AC energy yield of μ-Si system, 1020Wp with and without back cover isolation](image)

The maximum predicted value is obtained by the structure without isolation back cover, it is equal to 133.5 kWh and it is occurred in August, while the maximum measured monthly energy yield is 139.7 kWh and it is occurred also in August. However, the minimum values are recorded in December; the predicted and measured values are equal to 17.8 kWh and 14.1 kWh respectively. In relation to the systems with isolation material the maximum predicted and measured values are equal to 127.9 kWh and 136.8 kWh respectively, and they are occurred in August. The minimum predicted and measured values are 17.4 kWh and 14.0 kWh. They are occurred in December.

In order to check how the model is properly giving results, an Hourly, daily and monthly energy yields are evaluated.

The following table shows the AC energy yield deviations based on an hourly, daily and monthly yield calculation. Polycrystalline and μ-Si systems with and without isolation material at the back of the modules are evaluated, with the consideration of ISET sensor as the base of irradiation.
measurement. MBE and RMSE and the correlation coefficient are determined. Table 5.15 shows the evaluation results.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Error</th>
<th>Poly cr.-1134Wp (not isolated)</th>
<th>Poly cr.-1134Wp (isolated)</th>
<th>μ-Si-1020Wp (not isolated)</th>
<th>μ-Si-1020Wp (isolated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBE</td>
<td>1.31%</td>
<td>-1.05%</td>
<td>0.07%</td>
<td>-1.09%</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>10.77%</td>
<td>13.96%</td>
<td>14.26%</td>
<td>17.38%</td>
</tr>
<tr>
<td></td>
<td>(r)</td>
<td>0.9984</td>
<td>0.9984</td>
<td>0.9970</td>
<td>0.9966</td>
</tr>
<tr>
<td>Hourly</td>
<td>MBE</td>
<td>1.31%</td>
<td>-1.05%</td>
<td>0.07%</td>
<td>-1.09%</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>4.55%</td>
<td>6.16%</td>
<td>7.17%</td>
<td>8.25%</td>
</tr>
<tr>
<td></td>
<td>(r)</td>
<td>0.9987</td>
<td>0.9992</td>
<td>0.9965</td>
<td>0.9970</td>
</tr>
<tr>
<td>Daily</td>
<td>MBE</td>
<td>1.31%</td>
<td>-1.05%</td>
<td>0.07%</td>
<td>-1.09%</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>2.42%</td>
<td>3.89%</td>
<td>5.50%</td>
<td>6.42%</td>
</tr>
<tr>
<td></td>
<td>(r)</td>
<td>0.9996</td>
<td>0.9999</td>
<td>0.9989</td>
<td>0.9990</td>
</tr>
<tr>
<td>Monthly</td>
<td>MBE</td>
<td>1.31%</td>
<td>-1.05%</td>
<td>0.07%</td>
<td>-1.09%</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>2.42%</td>
<td>3.89%</td>
<td>5.50%</td>
<td>6.42%</td>
</tr>
<tr>
<td></td>
<td>(r)</td>
<td>0.9996</td>
<td>0.9999</td>
<td>0.9989</td>
<td>0.9990</td>
</tr>
</tbody>
</table>

Table 5.15: MBE for hourly, daily and monthly AC energy yield

It is seen that the absolute MBE deviation lies between 0.07% and 1.31%, this values mean a high level of convergence between measured and predicted values are achieved; the best MBE value is recorded by μ-Si system without isolation material module. Hourly, daily and monthly MBE are almost the same values; the reason is explained in DC energy yield evaluation part.

Polycrystalline systems show better RMSE values rather than micromorphous systems. The systems without isolation material show better RMSE than the systems with isolation material. Correlation coefficients are more than 99%, and this can be expected clearly from the module level part,

Generally, In relation to PV modeling, using a PV cell sensor such as ISET sensor is better than using the pyranometer. Also, It is recommended to use a PV cell sensor of different technologies in order to compensate the spectrum response for each technology.

Polycrystalline module/system show better RMSE results than micromorphous silicon module/system. This means, the predicted values are less scattered for the polycrystalline case. On the other hand micromorphous silicon shows better MBE, which means that it shows better offset than polycrystalline module/system.

The simulation model does not match exactly with the PV behavior; because of the different environment and conditions between the simulation and the outdoor PV module/system measurements. In addition, the simulation doesn’t consider the effect of the short and long wavelengths of the irradiation spectrum, which affects the output power of the different technologies.
5.2 Simulation results in Ma’an

Three modules of different technologies are simulated in relation to the module and system levels. The two polycrystalline modules with the same peak power (230Wp) are considered. Also, Cadmium telluride CdTe module with (70Wp) is considered to represent thin film technology. The PV systems are considered to be 1150Wp for polycrystalline technology, and 1050Wp for CdTe technology.

The PV module and system are simulated for different tilt angles at south orientation. However, the module level is simulated to determine the module DC output power and DC energy yield. On the other hand, the system level is simulated to determine the AC output power and AC energy yield; this is performed by using SMA inverter with a rated power of 1200W.

The incident irradiation in Ma’an is measured by Rotating Shadowband Radiometer instrument (RSR), and as discussed before; the irradiation measurement of this instrument is converted to the format of pyranometer measurement. So it is expected that, the actual results of the PV systems in the field give a higher output power than the simulation results.

Figure 5.12 illustrate the global horizontal irradiation for Ma’an site, it is shown that the site is blessed with a good incident irradiation even in winter season. Generally, the irradiation reaches to more than 1000 [W/m²] in summer. Ma’an is considered as a very good site for the solar energy projects when compared with many sites around the world.
The following table shows the DC and AC energy yield for the PV module and system under test, the specifications of these modules are shown in table 3.1. The table shows the DC energy yield for the module level, and also the AC energy yield for the system level. The simulation is performed at different tilt angles in order to determine the optimum tilt angle, at which the PV system provides the highest energy yield.

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>Module level</th>
<th>System level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DC energy yield [kWh\textsubscript{DC}]</td>
<td>AC output energy [kWh\textsubscript{AC}]</td>
</tr>
<tr>
<td>20°</td>
<td>459.670</td>
<td>463.836</td>
</tr>
<tr>
<td>25°</td>
<td>463.768</td>
<td>467.963</td>
</tr>
<tr>
<td>30°</td>
<td>465.639</td>
<td>469.836</td>
</tr>
<tr>
<td>32°</td>
<td>465.755</td>
<td>469.945</td>
</tr>
<tr>
<td>35°</td>
<td>465.244</td>
<td>469.413</td>
</tr>
<tr>
<td>40°</td>
<td>462.582</td>
<td>466.696</td>
</tr>
<tr>
<td>45°</td>
<td>457.516</td>
<td>461.545</td>
</tr>
</tbody>
</table>

Table 5.16: DC and AC energy yield for the module and system level

Regarding the values in the table, two main results are introduced; the optimum tilt angle is about 32° south orientation. At the optimum tilt angle the maximum energy yield is generated. The tilt angle plays an important role in determining the expected energy yield and real time output power. The optimum tilt angle is close to the latitude angle of the site.

On the other hand, it is noticed that there is a deviation in the results of the polycrystalline modules even they have the same rated power. At the optimum tilt angle, polycrystalline ‘A’ achieved a DC energy yield of about 465.7 kWh in relation to the module level, and 2101kWh for the system level. While polycrystalline ‘B’ is recorded a DC energy yield of about 467kWh in relation to the module level and 2119kWh for the system level, this difference will be higher for a larger PV systems capacity. For this reason, different PV modules with the same peak power are tested before any large scale projects. The reasons of this difference are the electrical and thermal characteristics of the PV module such as electrical efficiency, material heat capacity, thermal behavior and spectrum response.

Figures 5.13, 5.14 shows the monthly DC and AC energy yield at different tilt angles for 230 Wp polycrystalline type ‘A’.
It is seen that the output energy depends on the tilt angle together with the incident angle. When the tilt angle is small such as 20°, PV produces more energy in summer than in winter, and this is because the PV module and system are lied almost in horizontal shape then the incident irradiation is more perpendicular in summer season, while it is more steeper in winter season, this tilt angle is preferable to use when the required energy in summer is more than in winter season. On the other hand, when the tilt angle is large such as 40° or more, PV produces more energy in winter than in summer. This tilt angle is preferable to use when the output energy from PV system is required in winter more than in summer season.

For tilt angle 32° degree, it is seen that there is no a big difference in the monthly energy yield between summer and winter even it is a bit lower in January and February. At the optimum tilt
angle the monthly energy yield can be an advantage for a stable load among the year. Also, it achieves the higher yearly energy yield. The rest of the graphics are attached in the [appendix E].

The two following tables show the exact monthly energy yield at different tilt angle of the polycrystalline module ‘A’.

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>20°</th>
<th>25°</th>
<th>30°</th>
<th>32°</th>
<th>35°</th>
<th>40°</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>10.2</td>
<td>10.0</td>
<td>11.3</td>
<td>11.5</td>
<td>11.8</td>
<td>12.2</td>
</tr>
<tr>
<td>February</td>
<td>9.6</td>
<td>10.0</td>
<td>10.3</td>
<td>10.4</td>
<td>10.5</td>
<td>10.7</td>
</tr>
<tr>
<td>March</td>
<td>13.1</td>
<td>13.2</td>
<td>13.3</td>
<td>13.4</td>
<td>13.4</td>
<td>13.3</td>
</tr>
<tr>
<td>April</td>
<td>13.1</td>
<td>13.0</td>
<td>12.8</td>
<td>12.7</td>
<td>12.5</td>
<td>12.2</td>
</tr>
<tr>
<td>May</td>
<td>13.5</td>
<td>13.1</td>
<td>12.7</td>
<td>12.5</td>
<td>12.2</td>
<td>11.7</td>
</tr>
<tr>
<td>June</td>
<td>13.5</td>
<td>12.9</td>
<td>12.4</td>
<td>12.2</td>
<td>11.8</td>
<td>11.2</td>
</tr>
<tr>
<td>July</td>
<td>13.7</td>
<td>13.3</td>
<td>12.8</td>
<td>12.6</td>
<td>12.2</td>
<td>11.7</td>
</tr>
<tr>
<td>August</td>
<td>13.6</td>
<td>13.4</td>
<td>13.1</td>
<td>13.0</td>
<td>12.</td>
<td>12.3</td>
</tr>
<tr>
<td>September</td>
<td>12.2</td>
<td>12.2</td>
<td>12.2</td>
<td>12.2</td>
<td>12.1</td>
<td>12.0</td>
</tr>
<tr>
<td>October</td>
<td>11.6</td>
<td>12.1</td>
<td>12.4</td>
<td>12.4</td>
<td>12.6</td>
<td>12.8</td>
</tr>
<tr>
<td>November</td>
<td>10.6</td>
<td>11.3</td>
<td>11.8</td>
<td>12.1</td>
<td>12.4</td>
<td>12.8</td>
</tr>
<tr>
<td>December</td>
<td>9.9</td>
<td>10.7</td>
<td>11.3</td>
<td>11.5</td>
<td>11.9</td>
<td>12.4</td>
</tr>
</tbody>
</table>

Table 5.17: Monthly DC energy yield at different tilt angles for 230Wp polycrystalline ‘A’

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>20°</th>
<th>25°</th>
<th>30°</th>
<th>32°</th>
<th>35°</th>
<th>40°</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>136.6</td>
<td>144.7</td>
<td>151.9</td>
<td>154.6</td>
<td>158.4</td>
<td>163.9</td>
</tr>
<tr>
<td>February</td>
<td>129.4</td>
<td>134.1</td>
<td>138.1</td>
<td>139.4</td>
<td>141.3</td>
<td>143.8</td>
</tr>
<tr>
<td>March</td>
<td>175.5</td>
<td>177.9</td>
<td>179.3</td>
<td>179.6</td>
<td>179.7</td>
<td>179.1</td>
</tr>
<tr>
<td>April</td>
<td>176.4</td>
<td>174.5</td>
<td>171.8</td>
<td>170.4</td>
<td>168.2</td>
<td>164.0</td>
</tr>
<tr>
<td>May</td>
<td>180.7</td>
<td>176.0</td>
<td>170.6</td>
<td>168.2</td>
<td>164.5</td>
<td>157.8</td>
</tr>
<tr>
<td>June</td>
<td>180.5</td>
<td>173.9</td>
<td>166.6</td>
<td>163.5</td>
<td>158.7</td>
<td>150.1</td>
</tr>
<tr>
<td>July</td>
<td>183.7</td>
<td>177.8</td>
<td>171.3</td>
<td>168.5</td>
<td>164.0</td>
<td>156.1</td>
</tr>
<tr>
<td>August</td>
<td>182.9</td>
<td>179.8</td>
<td>175.8</td>
<td>174.0</td>
<td>171.0</td>
<td>165.3</td>
</tr>
<tr>
<td>September</td>
<td>163.3</td>
<td>164.1</td>
<td>163.9</td>
<td>163.6</td>
<td>162.8</td>
<td>160.9</td>
</tr>
<tr>
<td>October</td>
<td>156.5</td>
<td>161.7</td>
<td>165.9</td>
<td>167.3</td>
<td>169.2</td>
<td>171.5</td>
</tr>
<tr>
<td>November</td>
<td>142.7</td>
<td>151.3</td>
<td>159.1</td>
<td>161.9</td>
<td>165.9</td>
<td>171.9</td>
</tr>
<tr>
<td>December</td>
<td>133.9</td>
<td>143.1</td>
<td>151.6</td>
<td>154.8</td>
<td>159.3</td>
<td>165.8</td>
</tr>
</tbody>
</table>

Table 5.18: Monthly AC energy yield at different tilt angles for 230Wp polycrystalline ‘A’
From the two tables it is seen that, for the tilt angles 30°, 32°, 35° and 40°, the maximum DC and AC monthly energy yields are recorded in March, while it is recorded in July for the tilt angle 20° and in August for the angle 25°. On the other hand, the minimum monthly energy yield for all orientation is occurred in February.

The highest monthly energy yield is recorded in July at 20° south orientation; it is 13.74 kWh\textsubscript{DC} for the module level and 183.7 kWh\textsubscript{AC} for the system level. On the other hand, the lowest monthly energy yield is recorded in February for 20° south orientation; it is 9.65 kWh\textsubscript{DC} for module level and 129.4 kWh\textsubscript{AC} for system level.

Regarding August, September, October and November the predicted energy yields are lower than what should they be; this is because there is a loss in the wind speed data between the period (11/8/2011-9/11/2011), which affects the module temperature since the forced convection does not occur for the module(s) in this period, so the module temperature becomes higher while the output power becomes lower as well as the energy yield.

In order to compare the different technologies behavior, a specific energy [kWh/Wp] is determined for all the orientation. Table 5.19 shows the calculation results.

<table>
<thead>
<tr>
<th>Tilt angle</th>
<th>Module level Specific energy [kWh\textsubscript{DC}/Wp]</th>
<th>System level Specific energy [kWh\textsubscript{AC}/Wp]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
<td>1.998</td>
<td>2.016</td>
</tr>
<tr>
<td>25°</td>
<td>2.016</td>
<td>2.034</td>
</tr>
<tr>
<td>30°</td>
<td>2.024</td>
<td>2.042</td>
</tr>
<tr>
<td>32°</td>
<td>2.025</td>
<td>2.043</td>
</tr>
<tr>
<td>35°</td>
<td>2.022</td>
<td>2.040</td>
</tr>
<tr>
<td>40°</td>
<td>2.011</td>
<td>2.029</td>
</tr>
<tr>
<td>45°</td>
<td>1.989</td>
<td>2.006</td>
</tr>
</tbody>
</table>

Table 5.19: DC and AC specific energy yield for the module and system level

In relation to the module level, it is seen from the results that CdTe technology has the highest specific energy among the three modules under test, and for all the simulated orientation. At the optimum angle, the highest specific energy is determined. It is 2.025 kWh\textsubscript{DC}/Wp for polycrystalline module ‘A’, 2.043 kWh\textsubscript{DC}/Wp for polycrystalline module ‘B’ and 2.098 kWh\textsubscript{DC}/Wp for CdTe module. The specific energy of the system level is lower than the specific energy of the module level; it is 1.827 kWh\textsubscript{AC}/Wp for polycrystalline system ‘A’, 1.842 kWh\textsubscript{AC}/Wp for polycrystalline system ‘B’ and 1.872 kWh\textsubscript{AC}/Wp for CdTe system. The result of this drop is related to the inverter losses. Figure 5.15 illustrates the module and system level specific energy yield at the optimum tilt angle.
From these results two conclusions can be observed, thin film module generates a higher energy yield than crystalline technologies, because it has a better response to the operating temperature. In relation to the crystalline modules, the module ‘B’ achieves a higher specific energy than module ‘A’, this is related to the electrical and thermal characteristics differences.
Chapter 6

Conclusion and recommendation
6 Conclusion and recommendation

Photovoltaic is considered as one of the most promising renewable energy technologies. Applying PV simulation models will enhance the prediction of the PV system performance. The uncertainty of the available performance model is still too high. Hence, real-time power-balance model with the influences of PV electrical and thermal characteristics, together with the degradation and dynamic operating temperature have been developed in the simulation model.

Kassel and Ma’an are selected to be inspected in this thesis. By using different irradiation sensors and different PV technologies, the model was compared and evaluated with real data measured at the PV test field in IWES- Kassel. The evaluation was based on irradiation measurement, module temperature, output power and energy yield of the module and system levels. On the other hand, the model is applied to predict the electrical behavior of two different PV technologies in Ma’an by considering different tilt angles.

The model output provides appropriate and acceptable results by using the ISET sensor as the base of the irradiation measurement. However, the results were underestimated by using the Pyranometer. The pyranometer irradiation measurement does not consider the optical loss and the spectrum response compensation of the PV module material. Therefore, the measured effective irradiation by the pyranometer is lower than ISET sensor measurement, because of adding the optical loss effect to the pyranometer measurement.

The operating module temperature evaluation shows an obvious deviation from the measured values, the reasons are the following: the assumption of the constant electrical output power during the simulation time steps, the assumed initial conditions and the fluctuation of the predicted module temperature values.

By using the ISET sensor as the base irradiation measurement, the predicted outputs of the module and system levels were almost matching with the measured data. The deviation of the real-time output power of the module and system levels were highly accepted; MBE was in the range of (0.07-1.39%), and RMSE was within a range (15.74-21.98%).

Also, the deviation of the energy yield between the predicted and measured values was within a range of (0 -1.32%). On the other hand, hourly, daily and monthly energy yield were evaluated for the four system structures of the module and system levels. Concerning the hourly energy yield, the relative RMSE was in the range of (2.24-6.42%) which was the highest when compared with the other values. However, it is between (4.55-8.25%) for daily energy yield, while it is within a range (10.72-17.38%) for the monthly energy yield. it can be seen that, by increasing the time interval, the RMSE decreases.
Correlation coefficients \( (r) \) of all the evaluations show a good matching between the predicted and measured curves, since the correlation coefficient concerns about the mismatching between the shapes of the curves.

All in all, the module temperature deviation results were accepted, because the evaluation of the output power and energy yield provided very good results.

Specific energy for the module level is higher than the system level; because of the inverter losses which depends on the inverter loading and derating. The calculated inverter loss based on the difference between the module and system specific energies was in the range (10.68-11.79%), this range is compatible with the maximum efficiency of the inverter (92.1%).

For Ma’an site, the optimum tilt angle is 32° south orientation; at this angle the highest energy yield for the photovoltaic was generated. Also, the two polycrystalline technology with the same peak power shows different energy yields and specific energy. On the other hand, CdTe technology achieves higher specific energy yield than crystalline technology. The specific energy for poly-cr ‘A’ is 1.827 kWh/Wp, for poly-cr ‘B’ is 1.842 kWh/Wp, while CdTe is 1.872 kWh/Wp.

In relation to the orientation, the output power is more in summer at the lower tilt angles, while the PV system can gain more energy in winter at the higher tilt angle such as the tilt angle (40°), this case is linked with the characteristics of the location irradiation.

The PV system orientation plays an important role in order to adjust the output power with the load profile consumption during the different seasons.

Utilizing thin film technology is more reasonable than crystalline technology under certain conditions regardless the required area.

Fluctuation of the irradiation should be considered; because it affects the real time output power as well as the grid performance, this has been noticed in the Kassel site during the summer season.

In order to simulate an efficient PV performance model with low uncertainty, all influences which affect the prediction should be considered such as optical losses, spectrum compensation, dynamic thermal model, real time power balance together with the exact electrical and thermal characteristic of the PV technology. This is an important point for short term prediction.
Outlook
To improve the short term prediction and to decrease the uncertainty of the prediction, which is very important especially for grid connected systems; further improvement for the thermal model is needed in order to decrease the module operating temperature deviation. Also, further study in the photovoltaic spectrum response is required in order to achieve more accurate results with a high compensation of optical losses and spectrum response. These factors could improve the performance of the simulation model.
References


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[52] I. 62548, Design requirements for photovoltaic (PV) arrays.


Appendices
Appendix A: Photovoltaic Environmental Impact Assessment (EIA)
The key parameter of studying EIA for PV system is to take into consideration all aspects through the life-cycle of the PV system in order to clarify and evaluate how much the system is environmental friendly. In this section the Photovoltaic life cycle is introduced, because the main hazardous impacts are in the fabrication process. The following block diagram explains the life cycle for PV systems.

- **Fabrication impact**
The Fabrication process starts from mining the raw material till producing a complete PV module. The first step is the mining operation with associated hazards to the miners and inputs of diesel fuel and machinery. In relation to silicon purification and doping hazardous material can be produced and emit such as silane, diborane and phosphine. Monitoring and control is well established in the factories. The materials of the PV module structure other than the PV modules are steel, aluminum and concrete which are associated with the standard industrial hazards.\(^{(55)}\)

The main negative impact of manufacturing the PV modules is resulting from the conventional fuel used for production, which is associated with greenhouse gas emissions and acidic gases. “The energy content of PV modules using silicon wafers has been measured as 235 kWhel/m\(^2\) for 1990 technology at 1.5 MWp per annum production rate. The electrical production during the lifetime of the PV modules is around 1,500 kWhel/m\(^2\). In this case, the CO\(_2\) emission is around 400,000 Tonnes/GWyr of energy output. This compares with the CO\(_2\) output from the most modern and efficient coal-fired plant of 9 million tones/ GWyr”. The CO\(_2\) emission estimation for the various current PV cell technologies are shown in the following table.\(^{(55)}\)
<table>
<thead>
<tr>
<th>Cell material</th>
<th>Production scale</th>
<th>CO₂ output (kTonnes/GWyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline –Si</td>
<td>Small</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>150</td>
</tr>
<tr>
<td>Multicrystalline-Si</td>
<td>Small</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>100</td>
</tr>
<tr>
<td>Thin film- Si</td>
<td>Small</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Large</td>
<td>50</td>
</tr>
<tr>
<td>Thin film polycrystalline</td>
<td>Small</td>
<td>100</td>
</tr>
<tr>
<td>materials</td>
<td>Large</td>
<td>40</td>
</tr>
</tbody>
</table>

**CO₂ emissions of different photovoltaic technologies**[55]

It can be seen that thin film technology has lower CO₂ emission than crystalline technology. The mass production leads to a noticeable decrease of the emissions.

When considering the final Photovoltaic module energy, thermal pollution emissions is ignored since the fuel for the PV module is the sun irradiation. The other environmental impacts concern the PV system implementation.

- **Floura & Fauna**

  It is important to study the effects of any project on Floura and Fauna. PV ground mounted installation has some, but not a significant impact on the flora and fauna, and it is almost ignored in BIPV. Of course there will be some disturbance during construction. But a site survey before construction and at intervals during operation is always recommended[56].

  In relation to vegetation: the targeted lands for ground mounted PV system are flat and not cultivated, except some grassed land like the situation in Germany, in this situation the concrete casting can affect the grassed area. Vegetation can be planted under the PV modules benefiting from shading for a certain types for grasses or vegetation which will flourish better. The promising large scale projects in Jordan are in the desert landscape which doesn’t affect the vegetation rather than improving it[56].

  Photovoltaic systems do not affects birds taking into consideration birds are not harmed by collision with cables. Another benefit of the ground mounted PV project is creating shade under the PV array, this can be a suitable habitation for a certain kind of animals such as sheeps specially in the warm areas, the following figure shows how can sheeps benefiting from shade, also grazing is a good aspect with a lot of care[56].
• **Land use**

Occupation of lands should be considered to keep the ecosystem quality and stability, land use is a significant factor when installing a large scale PV system while it is not a significant factor for BIPV roof-top or façade mounting, also in remote area application. For large scale PV projects its recommended as mentioned above to use the unused land for implementing projects.

Large scale PV project is recommended to be implemented near landfill areas, because it’s a remote area and no inhabitants live there. Projects near landfill gas environment should be highly controlled or avoiding if there is any possibility; because it has a hazardous effects on the workers during installation, operation and maintenance, it risks there health through the toxic compounds in ambient air, explosion, fire, and asphyxiation and nuisance odors\(^{[56]}\).

• **Infrastructure**

PV Projects infrastructure consists of the following\(^{[57]}\):

- PV modules: Bounded by the technology used and design.
- Consumed area: Bounded by BIPV or large scale ground mounted project.
- Support structure: Primary aluminum or Galvanized steel.
- Foundation: Cast iron stakes or concrete.
- Cabling: Copper, aluminum and PVC.
- Transformers and inverters.
- Complementary infrastructures: steel reinforced concrete or steel wire fences.

Roof-top installation leads to less infrastructure impacts compare to ground mounted installation. To evaluate infrastructure impacts the mentioned components should be classified explicitly as part of the generated energy impact\(^{[58]}\).
• **Visual impacts**

Some people criticize PV projects concerning their visual impacts; Visual intrusion is highly dependent on the type of the scheme and the surroundings of the PV systems. It is obvious that, if PV system is near to a natural beauty area, the visual impact would be significantly considered

In relation to PV façade projects modules, architects should select the implementing criteria to minimize these impacts. For countries which have feed in law it is recommended to use BIPV façade instead of the mirrors façade which is an economical solution for saving energy. For ground mounted system the structure should be integrated and harmonized to minimize the visual impact

![Hybrid Solar Façade of Fiat Research Centre (CRF), Orbassano, Italy](image)

• **Socioeconomic effects**

Photovoltaic projects have many benefits and they are summarized as the following points.

- increase of the national energy independency
- diversification and security of energy supply
- Support of the deregulation of energy markets.
- Acceleration of the rural electrification in developing countries.
- Provision of significant work opportunities and that will sustain during the life time of the project as a result of operation and maintenance and guard duty.
- Awareness and encouraging people to invest in clean energies.
- **Noise and pollution**
  Photovoltaic system is absolutely silent; it represents a clear advantage as opposed to other renewable energy systems, also during the life time of the project no pollution is considered from the PV system.

- **Decommissioning**
  The decommissioning of silicon photovoltaic modules does not cause any environmental problem. It can be considered as construction waste. This is not the case when other types of materials are used to manufacture the photovoltaic cells, such as (CIS) and CdTe modules. The disposal of CdTe modules should be controlled more strictly than CIS modules and recycling the materials is more important both for environmental reasons and for the value of the Cd and Te$^{[55]}$. For aluminum structures or cables recycling is also the solution for protecting the nature.

According to the Environmental Impact analysis it is concluded that the main hazardous impacts from Photovoltaic are during fabrication process. Many advantages can be gained such as clean silent energy production, revival of lands, job creation and saving energy.
### Single Glazing

<table>
<thead>
<tr>
<th>Nominal thickness (mm)</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg/m²)</td>
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<td>10</td>
<td>12.5</td>
<td>15</td>
</tr>
<tr>
<td>Light factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LT %</td>
<td>91</td>
<td>91</td>
<td>91</td>
<td>91</td>
</tr>
<tr>
<td>LRE %</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>LRj %</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>UV %</td>
<td>87</td>
<td>86</td>
<td>84</td>
<td>83</td>
</tr>
<tr>
<td>Solar radiant heat factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T %</td>
<td>91</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Rê %</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Rj %</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>A %</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Solar factor</td>
<td>G EN 410</td>
<td>0.91</td>
<td>0.91</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>G ISO 9050 M1</td>
<td>0.91</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Shading coefficient</td>
<td>1.05</td>
<td>1.04</td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td>U-value (W/(m².K))</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.7</td>
</tr>
</tbody>
</table>
Appendix C: Sunny boy, SMA Solar Technology AG

3 Sunny Boy 1200

3.1 Efficiency

<table>
<thead>
<tr>
<th>Output power / Rated power</th>
<th>Efficiency [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>97.5%</td>
</tr>
<tr>
<td>0.2</td>
<td>99.2%</td>
</tr>
<tr>
<td>0.4</td>
<td>98.9%</td>
</tr>
<tr>
<td>0.6</td>
<td>98.6%</td>
</tr>
<tr>
<td>0.8</td>
<td>98.3%</td>
</tr>
<tr>
<td>1.0</td>
<td>98.0%</td>
</tr>
</tbody>
</table>

Maximum efficiency, $\eta_{\text{max}} = 92.1\%$
European weighted efficiency, $\eta_{\text{EU}} = 90.9\%$

### Efficiency profile

<table>
<thead>
<tr>
<th>Standardized output power</th>
<th>Minimum MPP voltage 100 V</th>
<th>Rated input voltage 120 V</th>
<th>Maximum MPP voltage 320 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>80.7%</td>
<td>79.7%</td>
<td>72.7%</td>
</tr>
<tr>
<td>10%</td>
<td>87.8%</td>
<td>87.1%</td>
<td>81.3%</td>
</tr>
<tr>
<td>20%</td>
<td>91.2%</td>
<td>90.8%</td>
<td>86.9%</td>
</tr>
<tr>
<td>25%</td>
<td>91.7%</td>
<td>91.5%</td>
<td>88.1%</td>
</tr>
<tr>
<td>30%</td>
<td>92.0%</td>
<td>91.8%</td>
<td>88.8%</td>
</tr>
<tr>
<td>50%</td>
<td>92.1%</td>
<td>92.0%</td>
<td>89.9%</td>
</tr>
<tr>
<td>75%</td>
<td>91.3%</td>
<td>91.2%</td>
<td>89.5%</td>
</tr>
<tr>
<td>100%</td>
<td>90.3%</td>
<td>90.2%</td>
<td>88.7%</td>
</tr>
</tbody>
</table>
3.2 Derating Behavior

![Graph showing derating behavior for different ambient temperatures and output power ratios.](image)
Appendix D: Simulation model
Appendix E: Ma’an module and system levels monthly energy yields at different tilt angle.
تطوير أدوات تحليل وتقييم الخلايا الشمسية وأداء أنظمتها تحت الظروف المناخية في الأردن وألمانيا

تعتبر الخلايا الشمسية من أهم أشكال الطاقة المتجددة الواعدة، وقد أخذت قدرا كبيرا من الاهتمام بالعقد الماضي، حيث حققت نموا سريعا في مجال استغلال الطاقة المتجددة.

تعتبر قوة أشعة الشمس الساقطة (Incident Solar Irradiation) في الجو المحيطية وعلى الخصائص الحرارية والكهربائية لتقنية الخلايا الشمسية المستخدمة.

هدف من إجراء هذه الدراسة هو تطوير أدوات للتحليل وتقييم أنواع مختلفة من تقنيات الخلايا الشمسية. تمكنت هذه الأداة الباحثين من إجراء الدراسات الكهربائية والتحليلية على لوح واحد من الخلايا الشمسية وعلى النظام بشكل كامل، وذلك من خلال استخدام برامج (Simulation Model) وبرنامج (Matlab Simulink).

تم بناء نموذج محاكاة الكتروني (Simulation Model) باستخدام تقنيتين مختلفتين من الخلايا الشمسية ومقارنة الأداء بينها.

تم بناء نموذج محاكاة الكتروني (Simulation Model) لدراسة تقنيتين مختلفتين من الخلايا الشمسية ومقارنة الأداء بينها.

يقوم نموذج المحاكاة بحساب الكهربائية (Electrical Power) المولدة من لوحة الخلايا الشمسية ودرجة حرارة لوحة الخلايا الشمسية في لحظة ما وتمثل من أجل حساب كمية الطاقة الكهربائية المولدة سنويا (Annual Energy Yield) من لوحة الواحد ومن النظام بشكل كامل (ألواح الخلايا الشمسية وقابل الطور والملحقات مجتمعة).

بالنسبة لمعمل كاسل، فقد تم استخدام مجسين مختلفين لقياس شدة الإشعاع الشمسي، الأول مجس يدعى البيرانوميتر (Pyranometer) والثاني محسس يعتمد تقنية الخلية الشمسية (ISET Silicon Sensor) وال треть تقنية الخلايا الشمسية (Polycrystalline Silicon). تم استخدام تقنيتين مختلفتين من (Micromorphous Silicon) والسيليكون الدقيق غير المتبلور في دراسة (Fraunhofer-IWES).

بالنسبة لمعمل معان، تم دراسة نوعين مختلفين من تقنيات الخلايا الشمسية، النوع الأول هو السيليكون متعدد البلاورات (Cadmium Telluride CdTe) والثاني هو الكادميوم تيلورايد (Silicon Polycrystalline Rotating) وتم الحصول على معلومات لشدة قياس الإشعاع الشمسية، وتم تقييم مقصد قياس الإشعاع الشمسية، و נובד وجواب قياسات قياسات ظروف Для (Shadowband Radiometer) وهذا حقق مقصد قياسات قياسات ظروف Для (Optimum)

المؤسسة للبحث الكهربائي والجهة الحكومية الأوروبية (NERC) و من خلال العلاقة التي تنتج على هذه المعلومات عن طريق المركز الوطني لبحث الطاقة للمؤسسة "مؤسسة منطقة الأردن والتعاون مع المالك الرسمي لمحطة قياس الإشعاع الشمسي" معان النموذجية."
رسالة ماجستير

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إعداد

ليث سعد باشا

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كلية الهندسة

كاسل، ألمانيا
جامعة كاسل

الجيزة، مصر
جامعة القاهرة

آذار، 2012
رسالة ماجستير

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تتح إشراف

جوزيف الأستاذ الدكتور. بورشوك

الأستاذ الدكتور. أحمد القوسي

أستاذ بقسم هندسة الكهرباء و علم الحاسوب أستاذ بقسم هندسة القوى الكهربائية والالات

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كجزء من متطلبات الحصول على رسالة الماجستير في الطاقة المتجددة و كفاءة الطاقة

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Declaration

I, Laith Sa’d Basha, declare that this master thesis is my own genuine work and has not been submitted in any form for another degree or diploma at any university or other institute of tertiary education. Information derived from the published and unpublished work of others has been acknowledged in the text and a list of references is given in the bibliography.

March 5, 2012
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