Development of a methodology to simulate simple mismatching in photovoltaic systems

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Abstract

The currently available tools to simulate solar photovoltaic (PV) systems do not offer a reliable solution to simulate string or module level inverter systems with partial shading and modules with mismatching electrical characteristics. The available methodologies to simulate this satisfying require computational power that is not commonly available. To make it possible to simulate these kinds of systems a methodology based around the software “System Advisory Model” (SAM) is proposed. The methodology assumes that shading is binary, meaning a module can either be fully shaded or not shaded at all. Two different global IV curve models are presented and evaluated in comparison with a more detailed Matlab global IV model based on the one diode equivalent circuit. All these methodologies disregards the impact of the bypass diodes in the PV module and this is considered a significant error, which has to be quantified. It is proposed that this should be done by using the two-diode equivalent circuit instead of the one diode model. Finally the methodology is not concluded to be reliable until verified in comparison with real world data.
Sammanfattning

De för närvarande tillgängliga simuleringsverktygen för solcellssystem erbjuder inte en tillförlitlig metod för simulering av delvis skuggade system eller system med moduler med olika elektriska egenskaper. De metoder som är tillgängliga för att simulera detta tillförlitligt kräver datorkraft som inte är allmäntillgänglig. För att göra det möjligt att simulera dessa typer av system föreslås en metod baserad kring programvaran "System Advisory Model" (SAM). Metoden utgår från antagandet att skuggning är binärt, vilket innebär att en modul kan antingen vara helt skuggad eller inte skuggad alls. Två olika globala IV-modeller presenteras och utvärderas i jämförelse med en detaljerad Matlab global IV-modell baserad på enkel-diods ekvivalenta kretsen. Denna metod bortser dock från effekterna av bypass-dioderna i PV-modulen och detta antas medföra betydande fel som måste kvantifieras, detta bör då göras med hjälp av två-diods ekvivalenta kretsen. Slutligen så kan metoden inte anses pålitlig förrän den har blivit verifierad med verkliga data.
Acknowledgement

First I want to thank my beloved partner who stood by me through all these years of seemingly never ending studies, for listening even though no one of us understood what I was talking about but still tried to encourage me to find my way. I want to thank my supervisor Nelson Sommerfeldt for his support throughout this project, his willingness to answer my questions and help me to sort my sometimes-confused ideas. I also want to thank my classmates for all the fun times and my family for all encouragement during my master studies.
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1 Introduction

The solar industry worldwide is growing fast since policy makers have realized the potential that this “free” energy has in the development of sustainable energy systems. In this area PV technology has seen a dramatic growth over the past decade with accumulated installed capacity increase of 100 GW (2002 – 2012) [1]. This growth was partially sparked by effective incentives from environmentally aware governments and has resulted in dramatic price drops over past decade (22% 2013 for mono-crystalline) [2]. PV has previously been used in niche markets such as off grid systems (space, telecom etc.) and large scale grid connected systems where the economy of scale brought down the investment. Since PV is becoming more affordable it is possible to justify installations in places where it previously could not compete with other more cost effective generation technologies. This lowered investment has enabled smaller distributed grid connected systems and systems built on different surfaces like rooftops and walls. However when smaller PV systems are constructed the modules are sometimes placed in such a way that all modules don’t get the same amount of solar irradiation. This can be due to shading obstacles or modules with different tilt and this introduces mismatch losses (MML). MML occurs when modules connected in a string have different electrical properties often due to shading and soiling but also due to manufacturing processes and different ageing of the modules. The shading and soiling is often more uniform on large PV plants, which reduces the MML. To increase the efficiency when panels mismatch and to allow modular design with possibility to increase system size by adding one module at a time, each module can be connected to its own inverter; a so called module level inverter (MLI). The MLI allows the module to operate at its maximum power regardless of the electrical properties of the other modules in the system. However by using MLI the investment cost is likely to increase since system cost for MLIs are currently more expensive than string inverters.

1.1 Problem description

To justify this higher cost of MLI this has to be simulated properly so the increased energy yield can be compared against the increased cost. In many modern simulation tools such as System Advisor Model (SAM) created by the National Renewable Energy Laboratory (NREL) in USA [3] or PV Sys [4] the ability to simulate MML are limited, particularly with regards to shading which is thought to be quite significant. In these tools shading is implemented as one shading factor for the whole array, which eliminates the possibilities to see the effects of partial shading. This makes it hard to see the benefits of MLI in cases with mismatching modules and complex shading.

1.2 Objective and research question

In this thesis the objective is to develop a simulation methodology that has the ability to capture the difference between a string inverter and MLI in a PV system under partial shading and to perform annual energy yield simulations while maintaining reasonable processing times.

1.3 Methodology

From existing PV models, two simple global IV curve models for a string inverter system are created with various levels of detail. Alongside this a detailed global IV curve model is created in Matlab based on the SAM PV performance model and the one diode equivalent circuit. This Matlab model is then validated in comparison with SAM simulations for a fully shaded and unshaded module. To evaluate the different models against SAM a simple shading scene is used to run full year simulations with the simple models, the detailed Matlab model and SAM model for a string and MLI system. The computer used to run the Matlab simulations is an Intel® Core™ i7-4770S at 3.10 GHz and 16 Gb working memory, the SAM simulations is carried out on a Macbook 5,1 with 2,4 GHz Intel Core 2 Duo processor and 8 Gb of 1067 MHz DDR3 memory.
1.4 Scope and limitations

The process of simulating a PV system can be carried out in different levels of detail and there are several programs that can handle this. All these programs have different approaches that suit different applications. This thesis is limited to the simulation software SAM and its abilities to simulate the performance of string inverter systems and MLI systems under mismatching conditions. The program SAM is chosen since it is easy to access and it is based on the accepted single diode equivalent circuit, which is a well-documented model of a PV cell. The PV module used in the simulations is a Sunon Solar 170W Module. This module is used since it is available in a string and MLI setup in the KTH renewable energy park so these systems can be used to verify the methodology. The weather data used in the simulations is from Stockholm Arlanda airport.
2 Background

The research area of PV array simulation with mismatching modules has been widely investigated. This research has been done with many different objectives, for example; to increase the efficiency of maximum power point tracking (MPPT) algorithms as described by G. Petrone et al. [5]. The possibility to arrange modules in the most efficient layout due to mismatching caused by ageing is discussed by N.D. Kaushika [6]. Most research in this field approaches the simulation of partial shading and mismatching in PV arrays by increasing the resolution of the simulation by breaking down the PV array in smaller elements. These elements can be the size of one module, one sub-string (in the module) or even a PV cell. This increased resolution, requires increased need for computational power since the similar calculations are done for more elements.

Incorporation of mismatch into the PV simulation model in this way is described in [5], but the simulations are not practical for energy yield simulations with large amount of modules. Research by G. Petronea et al. [7] try to reduce the required computational power to be able simulate energy yield over a whole year and still include important properties that affect the MML. The resulting simulation time is 10 minutes to simulate one day of the year, which would amount to approx. 60 hours of simulation time when simulating a whole year (on a 2.4 GHz PC notebook). They also describe a complex analytical methodology that decreases the simulation time of these simulations in programs like Matlab. However there is limited research regarding simple models that can run energy yield simulations for multiple time steps such as the hours of a year, without requiring a lot of computational power or simulation time.

This thesis is focusing on a methodology that enables energy yield simulations with mismatching modules for multiple time steps that requires limited computational resources. To investigate this, the behaviour of PV modules and PV strings has to be examined; this is described in section 2.1. Since the simulation tool SAM is used, the equations, algorithms and assumptions regarding this software are explained, this is done in section 2.2. In section 3 the proposed methodology is explained along with its benefits and drawbacks. In section 4 the methodology is evaluated and compared to pure SAM simulations and section 5 contains the discussion and conclusion.

2.1 Photovoltaics

To understand the behaviour of a PV system under mismatching conditions, the basic function of a PV module is described. The smallest building block of a PV module is the PV cell, which uses the photoelectric effect to convert light to direct current (DC). The cells electrical properties: current, voltage and resistance vary with the environmental conditions: radiation and temperature.

2.1.1 The IV-curve

The photoelectric effect means; that when a PV cell is exposed to a light source it generates a current and a voltage. The relationship between absorbed irradiance and generated current is considered linear; however the voltage is dependent on the type of material used in the cell and the operating temperature. When the cell is illuminated and not connected to a load, it operates at the open circuit voltage \( V_{oc} \). When the cell is connected to a load with an adjustable voltage, which is lowered in small steps from the \( V_{oc} \), the current from that cell will increase significantly (going “backwards” from \( V_{oc} \) along the IV curve in Figure 1). The increase in current will continue to a breaking point called the maximum power point (MPP), which is the optimal operation point for the cell (if maximum power is required). Further decrease of the voltage after this point will just slightly increase the current until the voltage is reduced to zero. This is called the short circuit state and this is where the maximum current occurs; called short circuit current \( I_{sc} \). This behavior is plotted in a current/voltage diagram called IV-curve seen in Figure 1. The PV cell can only be operated along the IV curve and this should be at MPP as mentioned to get the maximum power.
2.1.1.1 Temperature and irradiance dependence

The electrical properties of the PV cell will change due to the environmental conditions of solar radiation and the temperature at which the cell operates. A simplified explanation of this is that a reduced irradiance will reduce the current delivered by the cell at any given voltage and a reduction in cell temperature will increase the voltage produced by the cell. This is visualized with the IV-curves seen in Figure 2 and Figure 3 that shows how the PV cell IV characteristic depends on irradiance and temperature respectively.

Figure 1: IV and PV curve of a PV cell.

Figure 2: IV characteristics dependency on irradiance cell temp =25°C.

Figure 3: IV characteristics dependency on temperature irradiance = 1000W/m².
2.1.1.2 The global IV curve of a string of PV cells

The voltage of a typical silicon cell is relatively low for practical use (~0.6 V) so several cells are connected in series to create a module with higher voltage and power. When cells are connected in series their voltages are added and when connected in parallel their currents are added, as shown in Figure 4.

When the cells are connected in series, the operation of the cells is restricted to the same current running through all cells in that string. If one cell in the string is shaded this will lower the current generated in that cell and effectively force the unshaded cells in the string to operate at the lower $I_{sc}$ of the shaded cell. If the shaded cell does not generate any current at all the excess power generated by the unshaded cells will be dissipated in the shaded cell resulting in a “hotspot” and potential damage to that cell. To avoid this, a bypass diode can be introduced to allow the dissipated power to bypass the shaded cell resulting in that cell being “shut off”. This could be done to every cell but it is not cost effective so a module with 72 cells in series typically uses 3 bypass diodes resulting in a module with three “substrings” with each 24 cells. When 24 cells are connected to one bypass diode and just some of the cells in the string are shaded this can result in all of those 24 cells being bypassed (shut off) to limit the dissipated power in the shaded cells. This will drastically change the global IV curve of that module. In Figure 5 and Figure 6 the behavior of a 170 W solar module with 72 cells and 3 bypass diodes is seen with module IV curve for different cases of bypass diodes being activated and partial shading substring respectively.
2.1.2 **Global IV curve of a PV array**

When several modules are connected in series to form a string and these strings in parallel to form an array the global IV curve gets more complex. The shading (or partial shading) and soiling of one or more modules will create a similar effect as mentioned for the module with 3 bypass diodes above. The IV curve of an array under partial shading will be very complex. To illustrate this, a string inverter system consisting of 15 solar modules at 170 W is simulated. Each module has individual electrical properties to simulate different ageing and soiling. To show the impact of partial shading, three different shading states are simulated and the global IV and PV curve is seen in Figure 8. Five of the modules are not shaded at all, five are medium shaded and five are heavily shaded, these three shading states are illustrated in Figure 7 and represent the big steps on the global IV curve in Figure 8. The shading can be interpreted as the shadow of a structure casting a long shadow which is large in one end of the system and small in the other. The small variations in ageing and soiling are represented by the smaller variations on the global IV curve. Partial shading of the PV modules will result in parts of modules and most often entire modules being unused due to the fact that they are connected in series and cannot operate at the global $I_{MP}$P. In Figure 8 the unused modules are the part of the IV curve to the right of the global MPP. If each module were allowed to operate at its own MPP regardless of the other modules, the unused part of the IV curve would not be wasted; this would obviously result in higher system power output. The loss of power due to this difference is called mismatching losses.

![Figure 7: Shading scenario for Figure 8.](image)

![Figure 8: Global IV & PV curve of 15 modules with different electrical properties.](image)

2.1.3 **Maximum Power Point Tracking**

To be able to extract the maximum power from a PV module or a string of modules at any given time the load connected to the module has to be adjusted so the voltage is at MPP ($V_{MP}$) and the current at $I_{MP}$P. This is done by a Maximum Power Point Tracker (MPPT), which analyzes the power extracted from the module and the operational voltage. A DC/DC converter then adjusts the voltage at which the module is operated. The field of MPPT is very well developed and there exists several algorithms to do this as fast and efficient as possible but this is outside the scope of this thesis.
2.1.4 Distributed MPPT

It is only possible to use one global MPPT (GMPPT) for each string of modules; this is called a string inverter and this setup limits all modules in that string to operate a common $I_{MPP}$ (as seen in Figure 8). If some modules are shaded in such a way that their IV curve ($I_{sc}$) does not reach this current-level those modules will be unused. To avoid this problem with mismatching losses and to allow each module to operate at its maximum potential, each module needs to have its own MPPT this is called a distributed MPPT (DMPPT). A DMPPT system can be realized by either connecting each module to its own inverter, then called MLI or by connecting each module to a DC optimizer (a DC/DC converter). The DC optimizer is then connected to a string inverter that converts the power to AC. It could be argued that each cell should operate at its MPP since this is the smallest building block in a PV system however it would be too costly to include an inverter for every cell and could even result in lower system efficiency.

2.2 System Advisory Model

The simulation software SAM [9] is basically a user interface built on top of a simulation core with a set of functions specific for the different renewable energy systems it is capable of simulating. The simulation of a PV system in SAM can be divided in four parts: irradiation model, shading & soiling models, performance models and economic models. In this thesis the economic models is not regarded since the aim is only to simulate energy yield. From here on, the use of the name SAM will refer to the collection of models which work together to simulate PV system production. These models are described in the following sections.

2.2.1 Irradiation model

The irradiation models in SAM; isotropic, HDKR and Perez all utilize the irradiation data from the weather file, which is described as W/m² on a horizontal plane. This is used in combination with position (lat, long) to calculate the diffuse and beam irradiance that reaches the plane of the array (POA) for every hour of the day. In the calculation of diffuse irradiation the ground reflected and the sky diffuse irradiation is calculated with the Perez model for diffuse irradiance described in Perez et al. 1990 [10] and SAM technical reference [11].

2.2.2 Shading and soiling model

Near shading and soiling in SAM are applied as reductions of the POA irradiance; the soiling effects both the beam and diffuse irradiation but the near shading can be applied separately as diffuse and beam shading. The beam shading is applied as either 288 month-by-hour factors, 8760 hourly factors or by azimuth by altitude factors. These factors are applied as a direct reduction of the POA beam irradiance. The diffuse shading factor is applied as a constant reduction of the POA diffuse irradiance for the whole year. The shading factors are applied for the whole array as one derate factor so SAM does not have the capability to simulate partial array shading. This basically means that the whole array is considered to be one module or PV element and the shading factor represents the intensity of the reduction in POA irradiance reaching that element. Since the whole array is considered to be only one active surface, SAM assumes that all modules are operated at the same MPP for the given environmental factors which considerably reduces the simulation time. However this is a major simplification, which effectively means that only uniform shading is possible to simulate in SAM. There is a possibility to include partial shading by using four different sub-arrays where each sub-array can have its own shading factor and SAM can calculate mismatch between these sub-arrays, however this would only be practical for a system with four modules, which is a very rare situation. This type of partial shading still assumes uniform shading within each sub-array.
2.2.3 PV performance model

SAM can utilize three different performance models; a simple efficiency model, the CEC model and the Sandia PV array model. The simple efficiency model only requires module area, efficiency values and temperature correction coefficients and is only suited for fast preliminary predictions. The Sandia model [12] uses values measured from realistic situations for different module types. The CEC model [11] is based on the single diode equivalent circuit model of a PV cell and requires data provided by the manufacturer datasheet combined with weather data. In this thesis the CEC model will be used in the SAM simulations since this is considered very reliable and it requires fewest input data.

2.2.3.1 Single diode equivalent model

The CEC model in SAM is as mentioned based on the “single diode equivalent circuit” or as called hereafter “the 5-parameter model”, which is a simplification of a PV cell to a circuit with a light generated current, a diode, a parallel resistance called shunt resistance and a series resistance, see Figure 9. The 5-parameter model is described by De Soto [13] and [14].

![Figure 9: Single diode equivalent circuit.](image)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_L$</td>
<td>Light current</td>
<td>A</td>
</tr>
<tr>
<td>$I_D$</td>
<td>Diode current</td>
<td>A</td>
</tr>
<tr>
<td>$I_{sh}$</td>
<td>Shunt resistance current</td>
<td>A</td>
</tr>
<tr>
<td>$R_{sh}$</td>
<td>Shunt resistance</td>
<td>Ω</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Series resistance</td>
<td>Ω</td>
</tr>
<tr>
<td>$I_o$</td>
<td>Diode saturation current</td>
<td>A</td>
</tr>
<tr>
<td>$a$</td>
<td>Modified ideality factor</td>
<td>-</td>
</tr>
<tr>
<td>$N_s$</td>
<td>Number of cells</td>
<td>-</td>
</tr>
<tr>
<td>$n_1$</td>
<td>Usual ideality factor</td>
<td>-</td>
</tr>
<tr>
<td>$q$</td>
<td>Electron charge</td>
<td>eV</td>
</tr>
<tr>
<td>$T_c$</td>
<td>Cell temperature</td>
<td>K</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann’s constant</td>
<td>eV/K</td>
</tr>
<tr>
<td>$E_g$</td>
<td>Cell material band-gap</td>
<td>eV</td>
</tr>
<tr>
<td>$a$</td>
<td>Modified ideality factor</td>
<td>-</td>
</tr>
</tbody>
</table>
By using Kirchhoff’s current law Equation (2.2.1) and substituting Ohm’s law for the currents through the resistors and the Shockley diode Equation (2.2.2) for the current through the diode it is possible to describe the current to the load by the characteristic Equation (2.2.3).

\[ I = I_L - I_D - I_{sh} \]  

\[ I_D = I_o (e^{V_D/(nV_T)} - 1) \]  

\[ I = I_L - I_o \left( e^{V + IR_s \over a} - 1 \right) - {V + IR_s \over R_{sh}} \]  

In Equation (2.2.3) there are 5 parameters that have to be determined to calculate the current or voltage, hence the 5-parameter equation. These parameters are: \( I_L \), \( I_o \), \( R_s \), \( R_{sh} \) and \( a \). The modified ideality factor \( a \), is calculated by Equation (2.2.4) and represents the ideality factor for a series of cells, in this case a whole module.

\[ a = {N_s n_1 k T_c \over q} \]  

The five parameters can be calculated by using a reference state where some parameters are known; this is usually the standard test conditions (STC). From STC the following conditions are known: \( I_{sc}, V(I_{sc}) = 0, V_{oc}, I(V_{oc}) = 0, I_{MPP}, V_{MPP} \) and that the derivative of the power curve at MPP \( {dI \over dV} = 0 \) as seen in Figure 10. By substituting these into Equation (2.2.3) the five parameters can be evaluated for the reference state.

![Figure 10: Known points from the STC measurements.](image)

In SAM the five parameters for the reference state has already been evaluated for all modules in their database. So when a simulation is performed in SAM the five parameters are calculated for every time step by Equations (2.2.5)-(2.2.10):
Table 2: Nomenclature for SAM CEC module model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{\text{ref}}$</td>
<td>Reference irradiance</td>
<td>$\text{W/m}^2$</td>
</tr>
<tr>
<td>$E_g$</td>
<td>Cell material band gap energy</td>
<td>eV</td>
</tr>
<tr>
<td>$T_{\text{ref}}$</td>
<td>Reference cell temperature</td>
<td>K</td>
</tr>
<tr>
<td>$\mu_{l,sc}$</td>
<td>Temperature coefficient of short circuit current</td>
<td>A/K</td>
</tr>
</tbody>
</table>

\[
I_L = G \frac{G_{\text{ref}}}{G} \left[I_{L,\text{ref}} + \mu_{l,sc}(T_c - T_{c,\text{ref}})\right] \tag{2.2.5}
\]

\[
I_0 = I_{0,\text{ref}} \left(\frac{T_c}{T_{c,\text{ref}}}\right)^3 e^{\left[1\left(C_{\text{ref}} - E_{\text{ref}}\right)C_{\text{ref}}\right]}
\]

\[
E_g(T_c) = E_{\text{ref}}(T_{\text{ref}})\left[1 - 0.0002677(T_c - T_{\text{ref}})\right] \tag{2.2.7}
\]

\[
a = a_{\text{ref}} \frac{T_c}{T_{c,\text{ref}}} \tag{2.2.8}
\]

\[
R_{sh} = R_{sh,\text{ref}} \frac{G_{\text{ref}}}{G} \tag{2.2.9}
\]

\[
R_s = R_{s,\text{ref}} \text{ (assumed constant)} \tag{2.2.10}
\]

In Equation (2.2.6) and (2.2.7) the cell material band gap energy $E_g(T_{\text{ref}}) = 1.12 \text{ eV}$ for silicon and the Boltzmann constant $k = 8.618 \times 10^{-5} \text{ eV/K}$. The series resistance $R_s$ is assumed to be constant and equal to reference condition in SAM since it has been recognized to have little effect on the MPP [13] and SAM only calculates that point not the whole IV curve. Since no more information than what is available from the manufacturer of the PV module is necessary, this model makes it easy to simulate nearly any module. The 5-parameter model is applicable on cell, group of cells, module level or group of modules.

### 2.2.4 Inverter performance model

The inverter performance model used for the simulations conducted in this study is the CEC model. This handles the conversion of DC to AC and it is based on the Sandia inverter model by King [15] and an inverter efficiency curve. If the simulated system includes more than one inverter, SAM models this inverter as a single large inverter with the DC string voltage as input voltage [11]. This assumption limits the possibilities to simulate an MLI system with mismatch since the different modules are going to perform on different positions on the efficiency curve and thus have individual efficiencies.

### 2.2.5 PV simulation algorithm

The algorithm used in SAM starts with calculation of the sun position; this is then used in combination with the direction of the PV surface to calculate the POA- beam, diffuse sky and ground reflected irradiance. To include losses from shading, soiling and the module cover, the different POA irradiiances are first reduced by shading and soiling derate and then by the module cover losses. This reduced irradiance is used to calculate the gross DC output from the modules. The gross DC output is then reduced by a set of DC derate factors to include losses due to wiring, tracking error and simple mismatch. This net DC output is used by the inverter model, which calculates the gross AC output. The net AC output is obtained by applying the AC derate factor. The net AC output is used as input for the financial model, all these steps is shown in Figure 11 and described in SAM technical reference [11].
2.2.6 Limitation of SAM

Since SAM essentially considers the array as one “module” and applies one shading factor, this represents one case most accurate. This is the case when all modules in the array have the exact same electrical properties and thus identical IV-curves. In that situation there is only a minimal difference between a GMPPT and DMPPT system and these are the possible DC or AC losses. Simulating each module, substring or even cell with its own shading factors could simulate partial shading of a DMPPT system in SAM. This has been shown to be a very time consuming process and could potentially be streamlined by utilizing SAMS built in script generator. Still many tasks would have to be done manually. However there are limited possibilities to simulate a GMPPT system since the combination of IV curves have to be done to find the GMPP.

3 Development of simulation methodology

Since the main drawback of SAM is that it cannot distinguish between string and MLI system the starting point for a methodology would be to make this possible by including mismatch into the model. To do this, more details than just the MPP point and a better shading assumption is needed. As with many problems there is a trade-off between accuracy of the model and available computational power. The more detailed the model is, the more complicated it becomes and as a result more computational resources is required to run the model. As mentioned previously from a module point of view, mismatch occurs when one module has different electrical properties than another. In reality the shading often occurs in smaller parts of a module such as a couple of cells or a substring. If the resolution would be increased to include module substrings then the mismatch within the module is dependent on different electrical properties between the cells since these build the substring. This mismatch is also affected by the bypass diode, which can shut off one substring if that substring includes cells with sufficient shading and the other modules in the system produce sufficient power. So to be as detailed as possible the simulation model would have to include a cell-level model and a bypass diode model. These kinds of simulations have been researched and described by G. Petronea et al. [5], [7] and requires a lot of computational resources when a system consists of a couple of modules with 72 cells each and 3 bypass diodes per module.
3.1 Simple mismatch derate model

To limit the needed computational resources and allow a fast simulation, this model incorporates MML as a simple derate into SAM. This is possible by using the excel-exchange feature in SAM, which can export and import data to and from an excel sheet. Since the resolution in SAM is on module-level, there is no possibility to see how partial shading of a module will affect a system therefore a module is considered the smallest element.

3.1.1 Shading assumptions

To maintain simplicity in the model, shading is considered binary which means a module can have full near field beam shading or no shading at all. This changes the interpretation of the shading factors from shading intensity to “part of system” that is fully shaded. SAM includes a near field-shading calculator that calculates the shading factors from a 3D shading scene where obstacles can be placed around the PV surface. This shading tool calculates the shading for each time step based on the part of the active area that is fully shaded, however SAM interprets these values as shading intensity, as mentioned previous. So this binary interpretation can be considered closer to what the shading factors actually represents. If the smallest element instead were a PV cell it would be correct to interpret the shading as intensity since the output from a cell is directionally proportional to the irradiance it receives so it does not matter if it receives 1000 W/m² on half of the cell or 500 W/m² on the whole cell. However this simple model only considers full beam shading or no shading at all on module-level. A drawback from this assumption is that in cases when the actual shaded area, similar size of a module, are overlapping multiple modules this will only be interpreted as shading of one module in the system instead of partial shading of several modules.

3.2 Global IV curve model

To be able to build a string inverter system the global IV curve has to be generated as mentioned in Section 2.1.2. Since the shading is considered binary two cases are simulated, each with only one module. The different cases are one with full shading (only diffuse irradiance) and one with no shading at all (beam and diffuse irradiance) as mentioned in section 3.1.1. The actual shading factors are then used to combine these two simulations to one system with preferred amount of modules. Meaning that if the shading factor is 50 % and the system consists of 10 modules, 5 are considered fully shaded and 5 unshaded. Since the shading is only considered on module level the shading factors are rounded to the nearest full module.

3.2.1 Square global IV model

The available simulation data from SAM is only the MPP values for each time step; the complete IV curve is not available but it is needed to build the complete global IV curve as explained in section 2.1.1. Since $I_{MPP}$ and $V_{MPP}$ are known, a crude way to do this is to assume that $I_{SC} = I_{MPP}$ and $V_{OC} = V_{MPP}$, which means that the IV curve is a simple “square” as seen in Figure 12. With this assumption the simulation data in SAM is sufficient to generate the global IV curve for a string inverter system as well as an MLI system. In Figure 13 this is done for a string system with 10 modules at 170W each and a shading factor of 20 % for a sunny hour (hour 3660). To calculate the yearly yield this procedure is carried out for every time step in the simulation, in this case 8760 hours. The Matlab code for this simulation is described in Appendix B – Matlab code.
3.2.1.1 **Benefits and disadvantages with Square IV model**

The benefits with this approach is that it is simple to implement since SAM delivers $V_{MPP}$ and $P_{MPP}$, which is the only required input for this model. These parameters are also available as exportable variables the SAM excel-export tool so the simulations can be carried out within the same software. Due to the simplicity of the calculations the simulation time is only increased slightly. However the assumption that the IV curve is square introduces an error. Since the IV curve has a “knee” at MPP, which means that the IV curve has a slope from $I_{SC}$ to $I_{MPP}$ and $V_{MPP}$ to $V_{OC}$. This will have an impact on the shape of the global IV curve when this is generated. In Figure 14 the full IV curve at STC and the square IV curve of the 170W module are shown along with a 2-module combination of the same, to show the impact of the bend shape of the real IV curve on the global IV curve. The $V_{OC}$ of the STC curve is seen to be much higher than the same of the square IV “curve”.

![Figure 14: Real IV curve (at STC) vs Square IV.](image)
3.2.2 **Generic global IV model**

To neglect the bend of the IV curve is no problem when the assumption is that all modules have the exact same IV curve, the global IV curve as well as the MPP is then simply just scaled version of one IV curve (this is what SAM does). However when combining modules with two different IV curves (shaded and unshaded), neglecting this “knee” introduces an error. To limit this error a generic IV curve can be used instead of the square interpretation, this generic IV curve is positioned so the MPP matches the given MPP from SAM. For simplicity this generic IV curve is assumed to be the IV curve at STC. To illustrate this difference the STC IV curve of the 170W module in Figure 14 is combined with a copy of itself but with lowered $I_{sc}$ to represent global IV curve of a string system of two modules with different IV characteristics this is seen in Figure 15 and Figure 16 below. The square interpretation of these IV curves is also combined and plotted. The PV curve for each global IV curve is plotted and global MPPs are marked red. From Figure 15 it is clearly seen that the error, between the square and the “generic” MPP is significant. In Figure 16 it is seen that the error is smaller when the MPP moves from the second peak to the first peak on the PV curve and through simulations it is also seen that the error is small when the combined curves has a more similar $I_{sc}$. However this only illustrates the difference between using a square IV curve interpretation and a generic IV.

![Figure 15: Real vs square IV curve model, different MPPs (error).](image1)

![Figure 16: Real vs square IV curve model, same MPPs (no error).](image2)

### 3.2.2.1 Benefits and disadvantages with Generic IV model

The benefit with this generic global IV model is that this reduces the error caused by neglecting the bent shape of the curve when two IV curves are combined. However, to assume that a generic IV curve will be perfect for all different operation conditions still includes an error since the IV curve does not maintain its shape regardless of environmental conditions as mentioned in section 2.1.1. To reduce the error caused by using a square or a generic IV curve, the complete IV curve has to be evaluated for each time step. Since the model is assumed to be binary with two cases, the IV curves for the unshaded or fully shaded modules has to be evaluated for each time step. The complete IV curve can be evaluated by incorporating the 5-parameter model; this is done by solving the Equation (2.2.3) for each time step and voltage or current value. This will greatly increase the simulation time and most of the calculation has to be done outside of SAM. This is a good approach to make it possible to compare the faster square IV model and the generic IV model against a more detailed model.
3.2.3 Matlab global IV model

The 5-parameter equation is already included in the simulations since SAM is based on this. However as SAM only evaluates the MPP and not the whole IV curve, these equations are implemented in a Matlab code. Since SAM uses the 5-parameter equations this will make it possible to use SAM as a benchmark for the detailed model created in Matlab. As a base for this model the technical reference to the PV performance model (pvsam1) in SAM [11] is used in combination with the 5-parameter model described by De Soto [14] and [13]. The fact that SAM has a comprehensive user interface and allows export of the most important data, this Matlab model is basically dependent on SAM for most input data. SAM is used to calculate the solar angles, the solar incidence angle on the array, the cell temperature and all reference parameters stated in Equations (2.2.5) - (2.2.10). SAM is also used as a source for all other data that is needed. The Matlab model consists of three parts: first a variation of the Perez 1990 model [10] that calculates the POA-sky diffuse and ground reflected diffuse irradiance, secondly the irradiance losses caused by the glass cover on top of the module are included, thirdly the 5-parameter equations are solved for every time step, and lastly the global IV curve is generated based on the system shading factor from the shading scene. In Figure 17 a schematic diagram of the Matlab model is shown.

3.2.3.1 Perez model

SAM only delivers the total diffuse irradiance as an output but to calculate the module cover losses the ground reflected and the sky reflected diffuse irradiance are needed separately. So the Perez model is used to calculate these and this is done by calculating the sky clearness $\epsilon$ (eps) and $\Delta$ (DELTA) and using empirical functions to calculate the isotropic $D_i$, circumsolar $D_c$ and horizon $D_h$ brightening components of the diffuse irradiance. The Perez incident diffuse irradiance is then $I_d = D_i + D_c + D_h$. This is described in section 7.2.3 in SAM technical reference draft [11]. The ground reflected diffuse irradiance $I_r$ is calculated according to Equation (3.2.1). Since SAM gives the combined value of $I_d + I_r = I_{dot}$ as an output, these calculations are compared to the output from SAM in Figure 18 and the corresponding RMS error is calculated to 0.808 W/m² per year by Equation (3.2.2). From Figure 18 it is seen that the calculations corresponds well except for lower values where Matlab under predicts $I_{dot}$.
Table 3: Nomenclature for Perez diffuse irradiance model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>Sky clearness factor</td>
<td>eV</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Sky clearness factor</td>
<td>eV</td>
</tr>
<tr>
<td>$D_i$</td>
<td>Isotropic brightening</td>
<td>W/m²</td>
</tr>
<tr>
<td>$D_c$</td>
<td>Circumsolar brightening</td>
<td>W/m²</td>
</tr>
<tr>
<td>$D_h$</td>
<td>Horizon brightening</td>
<td>W/m²</td>
</tr>
<tr>
<td>$I_d$</td>
<td>Incident diffuse irradiance</td>
<td>W/m²</td>
</tr>
<tr>
<td>$I_r$</td>
<td>Ground reflected diffuse irradiance</td>
<td>W/m²</td>
</tr>
<tr>
<td>$I_b$</td>
<td>Beam irradiance on a tilted surface</td>
<td>W/m²</td>
</tr>
<tr>
<td>$E_b$</td>
<td>Beam irradiance on a horizontal surface</td>
<td>W/m²</td>
</tr>
<tr>
<td>$Z$</td>
<td>Solar zenith angle</td>
<td>○</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Module surface tilt</td>
<td>○</td>
</tr>
</tbody>
</table>

\[
I_r = \text{albedo}(E_b \cos Z + I_d)(1 - \cos \beta) \quad (3.2.1)
\]

\[
RMS_{E,I,d,tot} = \sqrt{\frac{\sum_{i=1}^{N}(I_{d,tot,SAM} - I_{d,tot,model})^2}{N}} \quad (3.2.2)
\]

Figure 18: Comparison of calculated $I_{d,tot}$ Matlab vs SAM.

3.2.3.2 Module cover losses

The module cover losses caused by the refraction of light are included in the effective irradiance that reaches the solar cell $G_0$, Equation (3.2.3) by calculating the incidence angle modifier Equation (3.2.4) for the different components of irradiance that reaches the cover; beam, sky diffuse and ground reflected diffuse. The incidence angle modifier is calculated based on the transmittance through the cover, Equation (3.2.6) with proportionality constant $K = 4 \text{ m}^{-1}$ and the cover thickness $L = 0.002 \text{ m}$. The angle of refraction is calculated with Equation (3.2.5) assuming that the refractive index of air $n_i = 1$ and the refractive index of the glass $n_r = 1.526$. 

-16-
Table 4: Nomenclature for module cover losses.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_0$</td>
<td>Effective irradiance reaching solar cell</td>
<td>W/m²</td>
</tr>
<tr>
<td>$G_b$</td>
<td>Effective beam irradiance after soiling</td>
<td>W/m²</td>
</tr>
<tr>
<td>$G_d$</td>
<td>Effective diffuse irradiance after soiling</td>
<td>W/m²</td>
</tr>
<tr>
<td>$G_g$</td>
<td>Effective ground reflected diffuse irradiance after soiling</td>
<td>W/m²</td>
</tr>
<tr>
<td>$K_{ta,i}$</td>
<td>Incidence angle modifier for each component</td>
<td></td>
</tr>
<tr>
<td>$n_i$</td>
<td>Refractive index of incidence medium (air)</td>
<td></td>
</tr>
<tr>
<td>$n_r$</td>
<td>Refractive index of refraction medium (air)</td>
<td></td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>Incidence angle</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>Angle of refraction</td>
<td>°</td>
</tr>
<tr>
<td>$\tau a$</td>
<td>Transmittance through module cover</td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td>Proportionality constant</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>$L$</td>
<td>Module cover thickness</td>
<td>m</td>
</tr>
<tr>
<td>$\theta_n$</td>
<td>Incidence angle normal to the surface</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_b$</td>
<td>Incidence angle normal for beam irradiance</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_d$</td>
<td>Incidence angle normal to sky diffuse irradiance</td>
<td>°</td>
</tr>
<tr>
<td>$\theta_g$</td>
<td>Incidence angle normal to ground reflected diffuse irradiance</td>
<td>°</td>
</tr>
<tr>
<td>$M$</td>
<td>Air mass modifier</td>
<td></td>
</tr>
<tr>
<td>$am$</td>
<td>Air mass</td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>Elevation relative to sea-level</td>
<td>m</td>
</tr>
<tr>
<td>$G$</td>
<td>Irradiance absorbed by PV cell</td>
<td>W/m²</td>
</tr>
</tbody>
</table>

$G_0 = G_bK_{ta,b} + G_dK_{ta,d} + G_gK_{ta,g}$  \hspace{1cm} (3.2.3)

$K_{ta,i} = \frac{(\tau a)_i}{(\tau a)_n}$  \hspace{1cm} (3.2.4)

$\theta_r = \sin^{-1}\left(\frac{n_i}{n_r}\sin\theta_i\right)$  \hspace{1cm} (3.2.5)

$\tau a(\theta_i) = e^{-KL/\cos\theta_r}\left(1 - \frac{1}{2}\left(\frac{\sin(\theta_r - \theta_i)^2}{\sin(\theta_r + \theta_i)^2 + \tan(\theta_r - \theta_i)^2}\right)\right)$  \hspace{1cm} (3.2.6)

Equation (3.2.5) - (3.2.6) is calculated for incidence angle; $\theta_n$, $\theta_b$, $\theta_d$ and $\theta_g$. The sky diffuse and ground diffuse incidence angles are described by Equation (3.2.7) and (3.2.8). When calculating Equation (3.2.6) for the incidence angle normal to the surface the angle is 1 degree, this should be zero degrees but since numerical calculations cannot handle division by zero, 1 degree is used.

$\theta_d = 59.7 - 0.1388\beta + 0.001497\beta^2$  \hspace{1cm} (3.2.7)

$\theta_g = 90 - 0.5788\beta + 0.002693\beta^2$  \hspace{1cm} (3.2.8)
When the irradiance losses due to the module cover have been calculated the air mass modifier is calculated \cite{11} to take into account the effect of air mass on spectral distribution, Equation (3.2.9). The coefficients $a_0 - a_4$ are dependent on the technology of the cell if it is mono crystalline, poly crystalline, thin film or amorphous these are found in Appendix C – Relevant input data.

$$M = a_0 + a_1 am + a_2 am^2 + a_3 am^3 + a_4 am^4$$  \tag{3.2.9}$$

$$am = \left[ \cos \left( \frac{\pi}{180} Z \right) + 0.5057(96.08 - Z)^{-1.634} \right]^{-1} e^{-0.0001184 h} \tag{3.2.10}$$

$$G = MG_0$$  \tag{3.2.11}

### 3.2.3.3 5-parameter module model

To calculate the IV curve for each time step, Equation (2.2.3) is solved with Equations (2.2.5) - (2.2.10). Since the aim is to build a string inverter system, where the current through the string is constant and the voltages for each current operating point are added. The Equation (2.2.3) is evaluated for pre-determined steps of the current to make it easy to combine the IV curves of different operating conditions see Equation (3.2.12). The IV curve is then calculated by iterating the Matlab function "fzero" with start guess of $V = V_{oc}$ at $I = 0$ and then continuing with $V_{j+1} = V_j$ as start guess for next step in the iteration.

$$I = I_L - I_o \left( e^{V(L) + IR_s \over a} - 1 \right) - {V(I) + IR_s \over R_{sh}} \tag{3.2.12}$$

### 3.2.3.4 Matlab model comparison with SAM data

To investigate the correspondence of the Matlab model to the SAM model, the $P_{MPP}$ of every time step for each model are compared using the Arlanda weather file for a fully shaded and unshaded module. In Figure 19 and Figure 20 the Matlab and SAM simulations for $P_{MPP}$ is plotted against each other. From Figure 19 and Figure 20 it is seen that the difference for the unshaded module is contained within 10 % when power output is 30W and decreases to 1 % for 80 W whereas the fully shaded module has a difference of around 0 – 10 % for all power outputs. Under 10 W both modules shows greater differences than 10 %. Since the shaded module only is dependent on diffuse irradiance this could be caused by the error of the Matlab diffused irradiance model. The difference for both modules is however contained within 2W and -8W.

![Figure 19: $P_{MPP}$ comparison Matlab vs SAM, unshaded.](image1)

![Figure 20: $P_{MPP}$ comparison Matlab vs SAM, shaded](image2)
To investigate how the error occurs in detail, the $P_{MPP}$ of the Matlab and SAM simulations are compared for a 6-day period (27/5 – 1/6). The results are shown in Figure 21 looks quite similar. The difference of the Matlab and SAM predictions for the same period is shown in Figure 22 and it is clear that the relative error is periodic, either 100 % or -60 % to -75 % differences. The periodic error is assumed to be related to the diffuse irradiance (see Figure 18) and the module cover losses; if the effective irradiance is under 1W this causes the model not to run. To investigate this periodic error further, the $I_{MPP}$ and $V_{MPP}$ is plotted for the same period, shown in Figure 23 and Figure 25 respectively. The difference between the Matlab and SAM predictions of $I_{MPP}$ and $V_{MPP}$ is also shown in Figure 24 and Figure 26 respectively.

From Figure 23 - Figure 26 it is seen that the $I_{MPP}$ predictions of the shaded module is around 10 % overestimated (if the periodic error is neglected) and the $V_{MPP}$ predictions for the same is around 20 % underestimated. These two errors can equalize each other in $P_{MPP}$ since $P_{MPP} = V_{MPP} \times I_{MPP}$, however this might have a negative impact when generating the global MPP since errors on voltage predictions are scaled in the global IV models.

To investigate the impact of this on a yearly energy yield calculation, the production over the year was calculated for the unshaded and shaded module and the difference was calculated to 0.91 kWh (0.5 %) for the unshaded module and 7.06 kWh (8 %) for the shaded module as seen in Table 5. The difference is considered acceptable for the unshaded module. The shaded module difference is more significant, and the impact of these differences on the IV curve model must be investigated in greater detail. Therefore so the same is done for $V_{MPP}$ and $I_{MPP}$, this is seen in Table 6 and Table 7.

<table>
<thead>
<tr>
<th>Module</th>
<th>SAM [kWh/yr]</th>
<th>Matlab [kWh/yr]</th>
<th>Diff. [kWh/yr]</th>
<th>Rel. diff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshaded</td>
<td>169,01</td>
<td>169,92</td>
<td>0,91</td>
<td>0,5%</td>
</tr>
<tr>
<td>Shaded</td>
<td>88,01</td>
<td>95,07</td>
<td>7,06</td>
<td>8,0%</td>
</tr>
</tbody>
</table>

Table 5: Yearly yield comparison of one module (shaded and unshaded) SAM vs Matlab model.
Figure 21: Matlab module $P_{\text{MPP}}$ comparison with SAM, for one module, unshaded and shaded.

Figure 22: Absolute and relative $P_{\text{MPP}}$ difference SAM vs Matlab, unshaded and shaded.
Figure 23: IMPP SAM and Matlab, unshaded and shaded.

Figure 24: Relative IMPP difference Matlab vs SAM, unshaded and shaded.

Figure 25: VMPP SAM and Matlab, unshaded and shaded.

Figure 26: Relative VMPP difference Matlab vs SAM, unshaded and shaded.
Since the 6-day plots above only give insight in the error behavior for a part of the year the differences in $I_{\text{MPP}}$ and $V_{\text{MPP}}$ between the SAM and the Matlab simulations are investigated by calculating the RMS error (RMS$_E$). This is done according to Equation (3.2.13) where the data from the SAM simulations is $X_{\text{SAM}}$ and $X_{\text{Mat}}$ is the data from the Matlab simulations. The relative RMS$_E$ (RMS$_{E,\text{rel}}$) is calculated according to Equation (3.2.14). To limit the impact of the periodic error seen in Figure 22 - Figure 26 all the time steps with 100 % and -60 % differences are removed. The RMS$_E$ and RMS$_{E,\text{rel}}$ is calculated for $I_{\text{MPP}}, V_{\text{MPP}}$ and $P_{\text{MPP}}$ and is seen in Table 6 and Table 7 respectively. Since the IV model constructed to build a string system the $V_{\text{MPP}}$ model error might have a greater impact since this is scaled during global IV generation, however the error is only significant for the shaded module. Further verification of the accuracy of the Matlab model should be done in comparison with real world IV data.

$$RMS_E = \sqrt{\frac{\sum_{i=1}^{N} (X_{\text{SAM}} - X_{\text{Mat}})^2}{N}}$$

(3.2.13)

$$RMS_{E,\text{rel}} = \sqrt{\frac{\sum_{i=1}^{N} \left(100 \cdot \frac{X_{\text{SAM}} - X_{\text{Mat}}}{X_{\text{SAM}}}\right)^2}{N}} / 100$$

(3.2.14)

<table>
<thead>
<tr>
<th>RMS$_E$</th>
<th>$I_{\text{MPP}}$ [A]</th>
<th>$V_{\text{MPP}}$ [V]</th>
<th>$P_{\text{MPP}}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshaded</td>
<td>0,016</td>
<td>0,250</td>
<td>0,703</td>
</tr>
<tr>
<td>Shaded</td>
<td>0,080</td>
<td>7,290</td>
<td>2,193</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RMS$_{E,\text{rel}}$</th>
<th>$I_{\text{MPP}}$ [%]</th>
<th>$V_{\text{MPP}}$ [%]</th>
<th>$P_{\text{MPP}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshaded</td>
<td>7%</td>
<td>1%</td>
<td>18%</td>
</tr>
<tr>
<td>Shaded</td>
<td>10%</td>
<td>21%</td>
<td>24%</td>
</tr>
</tbody>
</table>

### 3.2.4 Revised shading assumptions

The shading assumptions are very simple in all of the above models since the impact of the bypass diodes is neglected. The behavior of the bypass diodes can be included by adding a bypass diode to the single diode equivalent model as seen in Figure 27. This is described by G. Petrone et al. [5] and will allow a more accurate simulation of the behavior when a string is partly shaded.

![Figure 27: Circuit model of a PV string including bypass diode [5].](image-url)
To implement this in the Matlab model increases the complexity and requires more computational resources or longer simulation time compared to the Matlab model developed which requires approx. 70 minutes for a full simulation on an Intel® Core™ i7-4770S at 3.10 GHz and 16 Gb working memory. All the other methodologies are finished within 2 minutes if manual export times are included. To avoid this greatly increased model complexity while still including the function of a bypass diode a greatly simplified bypass diode model can be adopted. This model could assume that every substring is treated the same way as a module is treated in the simple shading assumptions. This means that the modules in the string are divided into substrings by dividing the module voltage by the number of bypass diodes in that module. The full string is then built up by substrings instead of modules. This model does not capture the on and off behavior that is essential for a bypass diode in a PV string and should merely be seen as an increased resolution of the simple shading assumptions mentioned in section 3.1.1.

4 Simulation and comparison

To evaluate the global IV curve models, square and generic, a shading scene is constructed in the 3D shading tool provided by SAM; this shading scene is shown in Figure 28. The shading scene represents a tall structure, similar to a chimney or a ventilation duct placed in front of the PV array the size of 10 Sunon 170W modules in portrait orientation (8.08*1.58 m). The corresponding month by hour shading factors can be seen in Table 12 in Appendix C – Relevant input data.

4.1 String system simulation comparison

This shading configuration is used to run the square, generic and Matlab global IV model as well as the SAM simulations of the full string and MLI system. The DC power output (P_MPP,DC,gross) before inverter and DC losses for the string systems is compared in Figure 29. From this it is seen that the SAM simulation presents the highest predictions of the power output, while the Matlab and the generic model is slightly lower. The square IV model reaches approx. half or less during time steps with high irradiance but it is seen that for time steps with low irradiance and no shading all models predict approx. the same value as seen in Figure 30. The maximum shading factor in the simulations is 20% and for time steps with this shading factor the output looks very similar to what is seen in Figure 29 so no figure is needed to display this.
4.2 MLI simulation comparison

To represent the output from an MLI system, where each module has its own MPP tracking, the power output from each module is simply summed together. In Figure 31 and Figure 32 the MLI predictions of Matlab and SAM are compared for the same time steps used for the string systems. This shows that the Matlab and SAM simulations of a MLI system are very close even though some difference is observed for high irradiance and shading. There is no notable difference when the shading is less than one module (<10%). The MLI simulations for the Square and Generic model are identical to Matlab model energy output this is also seen in Table 8 and Figure 33 in Section 4.3.
Figure 31: $P_{APP, DC, \text{gross}}$ comparison SAM vs Matlab, high irradiance.

Figure 32: $P_{APP, DC, \text{gross}}$ comparison SAM vs Matlab, low irradiance.
4.3 Yearly yield comparison

To see the effect of the proposed models on annual energy yield, a comparison is done for both a string system and a MLI system simulation. The energy output, the absolute, percentage and RMS differences between the square, generic, and Matlab models to the SAM model as well as the respective computation time can be seen in Table 8, the power output is also seen in Figure 33. The SAM MLI simulation where build from recommendations in SAM to set the mismatch to zero but with otherwise similar setup. The results show that the relatively simplistic and fast square and generic models give significantly lower outputs, producing 46.4% and 15.6% less energy annually relative to SAM. The more descriptive Matlab model shows a 1.2% reduction in annual output when considered as an MLI, and a 1.5% reduction in output when considered as a string. These differences are relatively small when considering the differences identified in the model in section 3.2.3.4. The difference between the SAM string and MLI simulations is only represented by a static DC mismatch loss, in this case 2%. The difference between the Matlab string and MLI is 2.3%, the Square and Generic has 46.4% and 15.6% difference between the string and MLI simulations. Since the methodology is semi-automatic, including both SAM and Matlab calculations the computation time stated for each model is a sum of the calculation time for all procedures.

### Table 8: Yearly yield comparison of Square, Generic and Matlab IV models.

<table>
<thead>
<tr>
<th></th>
<th>Square String</th>
<th>Generic String</th>
<th>Matlab String</th>
<th>SAM String</th>
<th>Sq./Gen. MLI</th>
<th>Matlab MLI</th>
<th>SAM MLI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield [kWh/yr]</td>
<td>881</td>
<td>1388</td>
<td>1619</td>
<td>1645</td>
<td>1657</td>
<td>1657</td>
<td>1677</td>
</tr>
<tr>
<td>RMSe vs SAM [W]</td>
<td>395</td>
<td>75</td>
<td>22</td>
<td>15</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMSe vs Matl. [W]</td>
<td>316</td>
<td>64</td>
<td>22</td>
<td></td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>String-MLI diff [%]</td>
<td>46,8%</td>
<td>16,2%</td>
<td>2,3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>String-MLI diff [kWh]</td>
<td>776</td>
<td>269</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diff vs SAM [%]</td>
<td>46,4%</td>
<td>15,6%</td>
<td>1,5%</td>
<td>1,2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diff vs SAM [kWh]</td>
<td>764</td>
<td>257</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Computation time [s]</td>
<td>45</td>
<td>45</td>
<td>4200</td>
<td>40</td>
<td>70</td>
<td>45</td>
<td>40</td>
</tr>
</tbody>
</table>

**Figure 33: Full year energy output, string and MLI for all simulation models**
5 Discussion and Conclusion

In the simulations of a partially shaded string inverter and MLI system with the standard methodology in SAM, there is no reliable solution to see a difference of the energy output. In this methodology mismatching needs to be specified in the simulations as a percentage DC loss. To be able to quantify this difference with a simple methodology and maintain a reasonable simulation time is the aim for this thesis.

The reinterpretation of the shading factor from SAM and the assumption that shading is binary with module level resolution mentioned in section 3.1.1 makes it possible to simulate partial shading. However, shading is often more complex, so different assumptions for shading could be investigated to allow partial shading of several modules simultaneously which is a more realistic scenario.

The detailed Matlab model that is presented is based on the same models as SAM and it extends this to allow more detailed global IV curve generation. This is thought to give a more detailed representation of the possible mismatching losses that occur in a string inverter system when it is subject to partial shading. Manufacturers of MLI suggest that the increased yield for MLI systems should be in the range of 5-25% but this strongly depends on the shading pattern for each system. In section 4.3 the annual energy yield is compared and it is seen that the Matlab representation of a string system has a slightly lower yearly energy production than SAM. The difference between the Matlab string and MLI is seen to be 2.3%. It should be noted that this difference is dependent on the shading pattern instead of the derate factor that determines the string-MLI difference for the standard SAM methodology. This indicates that this model can differentiate between string and MLI. This model does however require a very long simulation time for yearly yield simulations and is therefore not considered to be useful for full year simulations.

The simplistic Square and Generic IV models require less simulation time, however in section 4.3 it is seen that the Square model presents a 46.5% difference compared to the SAM simulations and same for the Square representation of string-MLI difference. This lack of detail provided by the Square model makes it undesirable to use for comparing string and MLI system output. The Generic model does present a more realistic output since it has a difference of 15.6% compared to SAM and the Generic string-MLI difference is the same. However this difference might still be too high considering that the Matlab model provides a more detailed representation of the global IV curve and that model has much higher production and smaller string-MLI difference.

As a final conclusion, both the Generic and Matlab models propose desirable traits but none of them can be used for simulation of a string and MLI system before they have been compared to real world data. However the long simulation time of the Matlab model makes it unpractical to use in full year energy simulations, therefore focus should be on the Generic model and the development of this.

5.1 Future work

All comparisons in this study are done using computer simulation tools. To validate the methods described, the accuracy of the global IV models has to be verified in comparison with real world IV data. This could be done by using the co-located string and MLI systems on the roof of the KTH energy lab. The string system consists of 11 Sunon 170W solar modules connected to a Sunnyboy string inverter and the MLI system consists of 11 similar modules connected to an Optistring™ MLI inverter system. This makes it possible to simulate real shading scenarios and compare to the developed models. Further improvement of the Matlab model would be to include the bypass diode, which could be done using the two diode equivalent circuit as mentioned by G. Petronea [7]. Finally the Matlab code of the 5-parameter model contains some inefficient loops that could be revised to increase computation speed.
Bibliography


## Appendix A – Module datasheet

Table 9: Module datasheet.

<table>
<thead>
<tr>
<th>Module</th>
<th>SETA 170W</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>SETA-125-170W-72M</td>
<td></td>
</tr>
<tr>
<td>Maximum power at STC</td>
<td>$P_{\text{MPP}}$</td>
<td>170  W</td>
</tr>
<tr>
<td>Voltage at MPP, STC</td>
<td>$V_{\text{MPP}}$</td>
<td>35.4 V</td>
</tr>
<tr>
<td>Current at MPP, STC</td>
<td>$I_{\text{MPP}}$</td>
<td>4.8  A</td>
</tr>
<tr>
<td>Open-circuit voltage</td>
<td>$V_{\text{OC}}$</td>
<td>44.3 V</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>$I_{\text{SC}}$</td>
<td>5.15 A</td>
</tr>
<tr>
<td>Nominal operation temperature</td>
<td></td>
<td>45.8 °C</td>
</tr>
<tr>
<td>Open circuit temp. coefficient</td>
<td></td>
<td>-0.444 %/°C</td>
</tr>
<tr>
<td>Short circuit temp. coefficient</td>
<td></td>
<td>0.072 %/°C</td>
</tr>
<tr>
<td>Solar module efficiency</td>
<td></td>
<td>13.3 %</td>
</tr>
<tr>
<td>Cell type</td>
<td>Mono Si</td>
<td></td>
</tr>
<tr>
<td>No. of cells</td>
<td></td>
<td>72</td>
</tr>
<tr>
<td>Length</td>
<td>1580</td>
<td>mm</td>
</tr>
<tr>
<td>Width</td>
<td>808</td>
<td>mm</td>
</tr>
<tr>
<td>Area</td>
<td>1.28</td>
<td>m²</td>
</tr>
</tbody>
</table>
Appendix B – Matlab code

clear all
% loading input data
load pvdata_sonun.mat % SAM data
load airmod.mat % air mass modifier
load perezcoeff.mat % Perez sky clearness coefficients
% "_ref" means at STC conditions | ----for each time step------
% G_ref   irradiance at STC (W/m2) | AM     air mass
% T_cref  cell temp at STC (C)     | albedo albedo
% I_mpref current at mpp           | alfa   solar altitude angle (degr)
% V_mpref voltage at mpp           | TETA   solar azimuth angle (degr)
% I_scref short circuit current    | Z      solar zenith angle (degr)
% V_ocpref open circuit voltage     | teta_i array angle of incidence (degr)
% a_scref Isc temp. coeff. (A/C)   | teta  surface azimuth (deg)
% Adj    adjust for temp coeff.     |
% I_Lref  light current            |
% I_oref  diode saturation current  |
% R_sref  series resistance        |
% R_shref shunt resistance         |
% a_ref   ref ideality factor      |
%------- following has subscript: 1=unshaded, 2=shaded --------
% T_c     cell temperature (C)
% V_mppSAM SAM calc Vmpp
% P_mppSAM SAM calc Pmpp
% POA_b   beam POA after shading+soiling (W/m2)
% POA_d   diffuse POA(ground+sky) after shading+soiling (W/m2)
% POA_tot total POA after shad+soil (W/m2)

O = 0.95; % soiling derrate
h = 61; % elevation above sea level from weather file
hh = (1:8760)'; % hours of the year
alfa(alfa==-999)=0;
Z(Z==-999)=90;
% calculating Id and Ir diffuse irradiance %
%---- Perez model for diffuse irradiance: sky and ground
a = max(horzcat(zeros(size(teta_i)),cosd(teta_i)),[],2);
b = max(horzcat(repmat(cosd(85),size(teta_i)),cosd(Z)),[],2);
k = 5.534*10^-6;
eps = ((Ed+Eb)./Ed+k*Z.^3)./(1+k*Z.^3); % sky clearness
AM_o = (b+0.15*((93.9-Z).^-1.253)).^-1; % absolute optical air mass
DELTA = Ed.*AM./1367; % sky clearness, use AM instead of AM_o
% assumed extraterrestrial irradiance 1367 W/m2
% calculating f11 - f23
eps(isnan(eps))=0;
p_c = zeros(length(eps),6); % pre-allocation
f1(eps>6.2) = 8; % building row sub-index for f11-f23
f1(eps<6.2) = 7;
f1(eps<4.5) = 6;
f1(eps<2.8) = 5;
f1(eps<1.95) = 4;
f1(eps<1.5) = 3;
f1(eps<1.23) = 2;
f1(eps<1.065) = 1;
f1 = repmat(f1,1,6);
f2 = repmat((1:6),length(eps),1); % column sub-index for f11-f23
for i=1:length(eps)*6
    p_c(i) = p_co(f1(i),f2(i)); % creating f11-f23 mat
end
def(f1 = zeros(length(eps),1); f1(eps==0)=1;
p_c = p_c.*repmat(f1,1,6);
% calculating F1 and F2
z_ = degtorad(2); % Solar zenith angle in radians
F1 = max(horzcat((zeros(length(eps),1)),
p_c(:,1)+p_c(:,2).*DELTA+p_c(:,3).*Z_),[],2); %
F2 = p_c(:,4)+p_c(:,5).*DELTA+p_c(:,6).*Z_; %
Dl1 = Ed.*((1-F1).*1/(1+cosd(tilt)))/2; %
Dl2 = (1+cosd(tilt))/2; %
Dc = Ed.*F1.*(a./b); %
Dh = Ed.*F2.*sind(tilt); %
Id_1 = zeros(size(a)); Id_2 = zeros(size(a)); Id_3 = zeros(size(a)); %
Id_1(Z<=87.5)=1; % should be <=87.5 (89 is better)
Id_2(Z>87.5)=1; % should be >87.5 (89)
Id_3(Z<90)=1; % should be <90 (89.2)
Id = Id_1.*(Dl1+Dc+Dh)+Id_2.*Id_3.*Dl2; %
Ir = Albedo.*(Eb.*cosd(Z)+Id).*(1-cosd(tilt))/2; %
I = horzcat(POA_b./0,Id,Ir); %

%----- soiling losses ------
G = I.*0; %
POA_dtot = G(:,:,2)+G(:,:,3); % POA diffuse after shading and soiling

%----- irradiation losses due to module cover
n_r = 1.526; % refractive index of glass SAM suggest 1.526, desoto 1.1
n_i = 1; % refractive index of air
L = 0.002; % (thickness of glass cover in meters)
K = 4; % (proportionality constant in meters^-1)
teta_d = 59.7-0.1388*tilt+0.001497*tilt.^2; % (sky diffuse angle)
teta_g = 90-0.5788*tilt+0.002693*tilt.^2; % (ground-reflected diffuse)
tet = horzcat(ones(length(teta_i),1),teta_i,teta_d,teta_g);
tet_i = degtorad(tet);
tet_r = asin((n_i/n_r)*sin(tet_i));
K_t = exp(-K*L./cos(tet_r)).*(1-0.5*((sin(tet_r-tet_i).^2)./...+sin(tet_r+tet_i).^2)+(tan(tet_r-tet_i).^2)./...+(tan(tet_r+tet_i).^2));
K_t(isnan(K_t)) = 0; % K_t(:,1)=[];

x = 2; % type of technology is determined by x
1 = Si thin, 2 = mono-c Si, 3 = poly-c Si, 4 = 3-junc amorph
M = mod(1,x)+mod(2,x).*AM+mod(3,x).*AM.*2+mod(4,x).*AM.*3+mod(5,x).*AM.*4;
GO = G.*K_t; %
G12 = GO.*repmat(M(1:2,1),3);
G1 = sum(G12(:,1)); G1(G1<1)=0; % only run model when G>1
G2 = sum(G12(:,2:3),2); G2(G2<1)=0; %

Gtot = [G1 G2];
T_c = T_c(:,2); %
I_1 = (); % pre-allocation
V_1 = (); %

%------ 5-parameter for loop ------
for l = 1:2
G = Gtot(:,l);
T_c = T_c(:,l);
G(l) = G_ref; % setting the first time step as STC
T_c(l) = T_cref; %
AM(l) = 1.5; %
T_cref = T_cref+273.15; % reference cell temp
T_c = T_cref.*T_c/T_cref+273.15; % change T_c from C to Kelvin
% (T_c/T_c to get NaN for zero values)
T_c(isnan(T_c)) = 0; % removes NaN from T_c
mu ISC = a_scref.*(1-Adj/100); %
mu VOC = b_ocref.*(1-Adj/100); %
I_L = ((G/G_ref).*((I_Lref+mu ISC*(T_c-T_cref)))); % The light current
% The diode reverse saturation current I0,
% assuming reference band-gap energy of silicon of 1.12 eV
% k = 8.618*10^-5; % Boltzmann constant in [eV/K]
E_bg = 1.12.*((1-0.0002677*(T_c-T_cref)); % cell material band-gap [eV]
I_o = Ioref.*((T_c/T cref).^3).*exp((1/k).*((1.121/T cref-E bg)/T_c));
as = a_ref.*T_c/T cref;
$$R_{sh} = R_{shref} \cdot G_{ref} / G;$$
$$I_{sc} = I_L / (1 + R_{sref} / R_{sh});$$  % short circuit current  
$$R_s = R_{sref};$$  % this is used since R_s effect on mpp is considered  
% small I think this must be changed since I want whole  
% IVcurve not just mpp  

%--- Find Voc for every time step  
$$V_{oc} = \text{zeros(length}(I_L),1);$$  % pre-allocation vector  
$$u_ = \text{find}(T_c);$$  % index vector for "active" time steps  
$$u = u_;$$  % u decides how many time steps that is simulated  
$$ux = \text{zeros(size}(V_{oc}));$$  % logical vector for active time steps  
for j = u'  % solve Voc for each time step  
ux(j) = 1;  % logical vector for active time steps  
$$f = @(Voc) I_L(j)-I_o(j) * \left(\exp(Voc/a1(j))-1\right) - Voc/R_{sh}(j);$$  
$$V_{oc}(j) = \text{fzero}(f,V_{ocref});$$ 
end  

%--- solves 5-parameter eq for V with known I-values  
$$\text{step} = 0.001;$$  % steps on current axis (I)  
$$I2 = \text{(max}(I_{sc}):-\text{step}:0);$$  
$$I1 = \text{zeros(length}(I_L),\text{length}(I2));$$  % pre-allocation  
$$V1 = \text{zeros(length}(I_L),\text{length}(I2));$$  % pre-allocation  
$$ii = \text{zeros(length}(I_L),1);$$  % pre-allocation  
for k = u'  % run for every time step in u  
$$I = (0:\text{step}:I_{sc}(k));$$  
$$V = V_{oc}(k);$$  % start guess for I=0 is Voc for that time step  
for i = 1:length(I)  % solving V for range of I values  
$$\text{V0} = V_;$$  
$$f = @(V) I_L(k)-I_o(k) * \left(\exp((V+I(i)*R_s)/a1(k))-1\right) - (V+I(i)*R_s)/R_{sh}(k) - I(i);$$  
$$V_ = \text{fzero}(f,V0);$$  
$$I1(k,i) = I(i);$$  % creating I vector with corresponding V vector  
$$V1(k,i) = V_;$$  % saving V for each I  
end  
$$ii(k) = \text{length}(I);$$  % saving "length" of each IV curve  
end  
$$I_L(:,:,l) = I1;$$  % saving each IV curve for every time step  
$$V_L(:,:,l) = V1;$$

end  

% sorting out un shaded and shaded module  
$$I_1(:,:,; ; ; ,l) = 0;$$  
$$V_1(:,:,; ; ; ,l) = 0;$$  
$$I_{11} = I_1(:,:,; ; ; ,l);$$  
$$V_{11} = V_1(:,:,; ; ; ,l);$$  % index _11 is for non-shaded  
if l==2  
$$I_{12} = I_1(:,:,; ; ; ,2);$$  
$$V_{12} = V_1(:,:,; ; ; ,2);$$  % index _12 is for fully shaded  
else  
$$I_{12} = 0;$$  
$$V_{12} = 0;$$
end  

% removing unnecessary data (time steps with no generation)  
$$\text{ux}(1) = 0;$$  
$$\text{ux hh inv} = hh;$$  
$$\text{ux hh inv}(\text{ux==1}) = [];$$  
$$\text{ux hh} = hh(\text{ux==0}) = [];$$  
$$\text{hh new} = (1:length(\text{ux hh}));$$  
$$I_{11}(\text{ux hh inv,;},:) = [];$$  
$$V_{11}(\text{ux hh inv,;},:) = [];$$  
$$I_{12}(\text{ux hh inv,;},:) = [];$$  
$$V_{12}(\text{ux hh inv,;},:) = [];$$  

% calculating module mpp unshaded shaded  
$$P_{11} = I_{11}.*V_{11};$$  
$$[P_{mpp1}, i_{mpp1}] = \text{max}(P_{11},[;],2);$$  
$$P_{12} = I_{12}.*V_{12};$$  
$$[P_{mpp12}, i_{mpp12}] = \text{max}(P_{12},[;],2);$$  
$$\text{i IV}_{11} = \text{sub2ind}(\text{size}(I_{11}), \text{hh new}, i_{mpp1});$$  
$$\text{i IV}_{12} = \text{sub2ind}(\text{size}(I_{12}), \text{hh new}, i_{mpp12});$$  
$$I_{mpp1} = I_{11}(\text{i IV}_{11});$$  
$$V_{mpp1} = V_{11}(\text{i IV}_{11});$$  
$$I_{mpp2} = I_{12}(\text{i IV}_{12});$$  
$$V_{mpp2} = V_{12}(\text{i IV}_{12});$$  

calculating stc mpp  
$$P_{stc} = I_{stc}.*V_{stc};$$  
$$[P_{mpp stc}, i_{mpp stc}] = \text{max}(P_{stc});$$  

calculating SAM data  
$$P_{mpp1} = P_{mppSAM1} * 1000;$$  
$$V_{mpp1} = V_{mppSAM1};$$  
$$P_{mpp2} = P_{mppSAM2} * 1000;$$  
$$V_{mpp2} = V_{mppSAM2};$$  
$$P_{mpp1}(\text{ux==1}) = [];$$  
$$V_{mpp1}(\text{ux==1}) = [];$$  
$$P_{mpp2}(\text{ux==1}) = [];$$  
$$V_{mpp2}(\text{ux==1}) = [];$$  
$$I_{mpp1} = P_{mpp1}./V_{mpp1};$$  

end

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\[ I_{\text{mpp}2} = P_{\text{mpp}2}/V_{\text{mpp}2}; \]

% Loading shading data
load shading.mat % vector: Sb = Sbns*Sss*O
B = csvread('shading_factors.csv'); % loading diurnal shading table
md = [31 28 31 30 31 30 31 31 30 31 30 31]; % days of month
Smh = []; % pre-allocation
% ---- converting diurnal 12x24 to 8760x1 array---
for m = 1:length(md)
    A_ = repmat(B(m,:),md(m),1);
    Smh = vertcat(Smh,A_);
end
Smh = Smh'; Smh = Smh(:);
Smh_control = (1-Sb/O)*100; % shading vector from SAM
Smh(ux==0)=[];
% --- Defining modules and module substrings
modules = 10; % number of modules in series
bp_diodes = 3; % number of by-pass diodes per module
sub_strings = modules*bp_diodes; % number of substrings in array
% --- String inverter system "string" ----
% global current is just based on step mentioned i 5-parameter loop
I_glob = (0:step:size(I_11,2)*step-step);
% only considering full module shading, if a module is partly shaded it is
% considered fully shaded if half and more is shaded and non-shaded if less
% than half
sh_full = repmat(round((Smh/100)*modules),1,size(V_11,2));
sh_no = modules-sh_full; % number of unshaded substrings
V_glob = V_11.*sh_no+V_12.*sh_full; % summing up global voltages
P_glob = repmat(I_glob,size(V_glob,1),1).*V_glob; % global power
[mpp_string, mpp_index] = max(P_glob,[],2); % global string MPP
% --- Module level inverter system "mli" ----
mli10 = round((Smh/100)*modules); % shaded modules
mli11 = modules-mli10; % non-shaded modules
mpp_mli = P_mpp11.*mli11+P_mpp12.*mli10; % MPP for mli system
% ---- SAM square system global mpp
mpp_SAM1 = P_mpp1.*sh_full(:,1);
mpp_SAM2 = (V_mpp1.*sh_full(:,1)+V_mpp2.*sh_no(:,1)).*I_mpp2;
mpp_SAM = max([mpp_SAM1 mpp_SAM2],[],2); % MPP Square
% ---- Generic IV curve global mpp
V_generic1 = zeros(length(I_mpp1),length(I_stc)*4);
V_generic2 = zeros(length(I_mpp2),length(I_stc)*4);
I_generic = zeros(length(I_mpp1),length(I_stc));
b1 = round(I_stc*100)/100;
b2 = round(I_mpp1*100)/100;
b3 = round(I_mpp2*100)/100;
for j=hh_new'
b4 = find(b1==b2(j));
V_generic1(j,b4+1:length(I_stc)+b4-1) = V_stc;
b5 = find(b1==b3(j));
V_generic2(j,b5+1:length(I_stc)+b5-1) = V_stc;
I_generic(j,:) = I_stc;
end
V_generic1 = V_generic1(:,1:length(V_stc));
V_generic2 = V_generic2(:,1:length(V_stc));
P_generic = (V_generic1.*sh_no(:,1:length(V_stc))+... 
            V_generic2.*sh_full(:,1:length(V_stc))).*I_generic;
mpp_gen = max(P_generic,[],2); % MPP generic
gmpp_sam_string(ux==0)=[];
gmpp_sam_mli(ux==0)=[];
gmpp_sam_string = gmpp_sam_string*1000;
gmpp_sam_mli = gmpp_sam_mli*1000;
Appendix C – Relevant input data

Table 10: Perez sky-clearness coefficients.

<table>
<thead>
<tr>
<th>$\varepsilon$</th>
<th>f11</th>
<th>f12</th>
<th>f13</th>
<th>f21</th>
<th>f22</th>
<th>f23</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 1.065$</td>
<td>-0.0083117</td>
<td>0.5877285</td>
<td>-0.0620636</td>
<td>-0.0596012</td>
<td>0.0721249</td>
<td>-0.0220216</td>
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<tr>
<td>$\leq 1.23$</td>
<td>0.1299457</td>
<td>0.6825954</td>
<td>-0.1513752</td>
<td>-0.0189325</td>
<td>0.065965</td>
<td>-0.0288748</td>
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<tr>
<td>$\leq 1.5$</td>
<td>0.3296958</td>
<td>0.4868735</td>
<td>-0.2210958</td>
<td>0.055414</td>
<td>-0.0639588</td>
<td>-0.0260542</td>
</tr>
<tr>
<td>$\leq 1.95$</td>
<td>0.5682053</td>
<td>0.1874525</td>
<td>-0.295129</td>
<td>0.1088631</td>
<td>-0.1519229</td>
<td>-0.0139754</td>
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<tr>
<td>$\leq 2.8$</td>
<td>0.873028</td>
<td>-0.3920403</td>
<td>-0.3616149</td>
<td>0.2255647</td>
<td>-0.4620442</td>
<td>0.0012448</td>
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<tr>
<td>$\leq 4.5$</td>
<td>1.1326077</td>
<td>-1.2367284</td>
<td>-0.4118494</td>
<td>0.2877813</td>
<td>-0.8230357</td>
<td>0.0558651</td>
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<tr>
<td>$\leq 6.2$</td>
<td>1.0601591</td>
<td>-1.5999137</td>
<td>-0.3589221</td>
<td>0.2642124</td>
<td>-1.127234</td>
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<tr>
<td>$&gt; 6.2$</td>
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<td>-0.2504286</td>
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<td>-1.3765031</td>
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Table 11: Air mass coefficients

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<tr>
<th>Si thin</th>
<th>Mono Si</th>
<th>Poly Si</th>
<th>3-junc Am</th>
</tr>
</thead>
<tbody>
<tr>
<td>a0</td>
<td>0.93811</td>
<td>0.935823</td>
<td>0.918093</td>
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<td>a1</td>
<td>0.062191</td>
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<td>a2</td>
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<td>a3</td>
<td>0.001217</td>
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<td>a4</td>
<td>-0.000034</td>
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Table 12: Diurnal shading factors.

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<th>07</th>
<th>08</th>
<th>09</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
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<th>17</th>
<th>18</th>
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<td>10.99</td>
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