TREND TRACKING OF EFFICIENCY AND CTM RATIO OF PV MODULES

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ABSTRACT: In this study, historical and present PV module concepts are analyzed concerning efficiency, output power and cell-to-module (CTM) ratio by simulating PV modules with different components over the period between 2009 and 2019. Furthermore, the changes occurring in important gain and loss channels within PV modules are illustrated as they are affected by the changes in module design and solar cell performance. Results show that in the last decade, the PV module output power and efficiency exhibit an absolute increase of about +85 Wp and +5.3% corresponding to a yearly rate of about +7.7 Wp and +0.48% respectively. Moreover, gain and loss factors show their impact on the CTM-ratio for both PV module power and efficiency, which also exhibits an absolute increase of about +3.2% and 3.4% respectively. Loss factors in the module such as power loss in cell interconnections show high sensitivity regarding the solar cell output current and the metallization pattern. On the other hand, optical loss and gain factors show a strong dependency on the use of the anti-reflective-coating and the encapsulation and backsheet materials used.

Keywords: Photovoltaic, Solar Cell, PV Module, Efficiency, Power, Cell-To-Module

1 INTRODUCTION

The demand for energy has been increasing for several decades due to the improvement in living standards of the continuously growing population [1]. Parallel to that, the potential of renewable energy technologies in general and specifically photovoltaic technology has evolved considerably fast in the past period of time [2]. The world record of efficiency for a single-junction crystalline silicon solar cell under laboratory conditions has increased from 24.7% to 26.7% during the period between 2000 and 2018 [3, 4], which corresponds to just 0.11% absolute yearly increment over a period of 18 years. This indicates that other means than the solar cell performance, such as PV module design and materials, are useful for improving the performance of commercial PV modules.

Next to module design changes, i.e. the use of half cut cell [5], the improvement of module components to enhance the PV module output is required. An important component of the PV module is the backsheet, which has an important role influencing the module temperature and the internal light management beside protecting the inner components of the module and electrically insulating it. The important role of the backsheet in the light management within the PV module was shown in several previous studies [6, 7]. Ota et al. improved the output of an existing PV system by 3.2% using an anti-reflective coat on the front glass which enhanced the light transmittance by 3.6% [8]. The development of photovoltaics in terms of efficiency and output power at solar cell and module level could be tracked easily using product datasheets, but it is technically and economically worthwhile to gain a fundamental understanding of the development of PV module performance concerning its materials and design technology by detailed loss channel analysis. This information is not accessible in datasheets because PV module manufacturers usually do not reveal the bill of materials or mention the specific solar cell characteristics in the PV module data sheet [9]. Therefore, we analyze historical and present module concepts by creating digital twins of PV modules with different components considering the changes from 2009 until 2019. We study the development of cell-to-module (CTM) ratio, output power and efficiency. Furthermore, we track the change of electrical and optical loss mechanisms and their dependence on module development over the same period of time.

2 CELL-TO-MODULE (CTM) ANALYSIS

In order to gain understanding of the PV module development over the last decade, the influence of components and design on power, efficiency and the different losses mechanisms, be it geometrical, optical or electrical, need to be analyzed. This can be realized by applying CTM analysis on various PV modules, components and designs available on the market for the period between 2009 and 2019. The analysis in this work is selective and not exhaustive for all changes regarding PV module materials and solar cell e.g. the number of fingers and surface texturing.

The CTM value describes the ratio between the performance of non-integrated solar cells to its performance after assembling them into a PV module, taking into account the different gains and losses resulted through that integration. Models to categorize the different gain and loss mechanisms regarding different module components have been presented in previous works [10, 11]. Using these models, the CTM ratio of a module in terms of output power as example can be calculated through Eq. (1), where k represents the optical and electrical gain and loss factors after integrating the cells into the module. These factors change for different cells, module designs and materials [12].

$$CTM_{power} = \frac{P_{module}}{\sum P_{cell}} = \prod_{i=3}^{m} k_i \tag{1}$$

3 DATA COLLECTION

Typical PV module data such as its geometrical dimensions and design is collected from datasheets of PV modules available on the market and produced during the mentioned period of time. Relevant geometrical, optical and electrical information of different PV module components such as glass, encapsulation layer, backsheet and interconnectors is collected from product datasheets as well as from performed lab measurements at Fraunhofer ISE on commercially available module materials produced within the same period of time. Due to lack of information in the PV module datasheets regarding the electrical parameters of the solar cells integrated in PV module, solar cells datasheets are separately collected and classified according to technology and design. After collecting all required data for PV module simulation, a typical year-specific dataset for each module component is created. Afterwards, a typical year-specific PV module is defined using the corresponding datasets of PV module components. Because PV module materials and solar cells information is collected from different sources, PV module components are assigned to the simulated PV modules during building the year-specific datasets depending on the manufacturing year. The year-specific PV module datasets are used as inputs to perform CTM analyses using *SmartCalc.CTM* [13], a software tool developed at Fraunhofer ISE that calculates the gain and loss factors of the solar cell integration in terms of output power and efficiency. The data collecting process is described in Fig. 1.

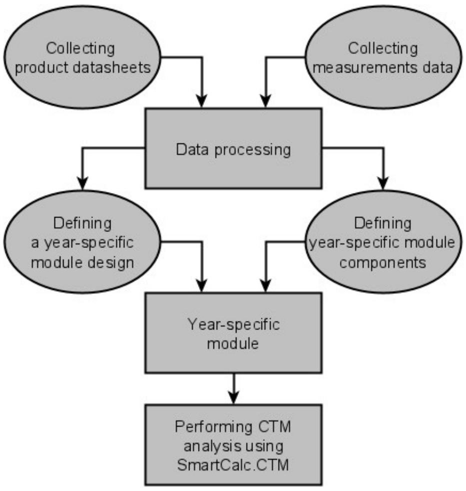

Figure 1: Flow chart of the used procedure by collecting the data.

4 SIMULATION

As explained in the previous section, the defined year-specific data sets of the PV module components are determined from product datasheets available on the market and lab measurements. The CTM analysis using *SmartCalc.CTM* requires geometrical, optical and electrical information of all PV module components. For the geometrical information, the PV module margins and external dimensions are calculated from module and corresponding cell information given in datasheets. The solar cell format and dimensions, number of busbars and metallization layout are defined specifically for each PV module. For lack of information, the cell and string distances are set to a conventional value of 2 mm for all simulated modules. Concerning the optical side, spectra of the encapsulation and cover materials (glass and backsheet) are used as inputs for the optical side of the simulation. Regarding the glass, the year 2012 is chosen as a starting point to simulate PV modules with an anti-reflective-coating (ARC) in reference to the available PV module datasheets. As to the electrical side, the cross section area of the used cell interconnectors and string connectors are considered to match the cell metallization of the cell for each module. Losses due to power dissipation in the junction box of the PV module are not considered in the simulation as they are typically negligible [14]. Exemplary PV module information of selected years used in the simulation is listed in table I, where T_{eff} and R_{eff} correspond to the effective transmission and reflection coefficients of the encapsulation material and the backsheet respectively. It is to be mentioned that for some years the same material is used since no significant developments on the material side could be identified based on the available data. This is the case for example for the encapsulation and backsheet material for the years 2018 and 2019. All simulated PV modules in this work are 60-cell monofacial modules arranged in a 6×10 cell layout where all cells are connected in series, corresponding to one of the most common PV module configurations. All PV modules use a front glass and a white backsheet and are simulated under standard test conditions (STC), which are 25 °C cell temperature, 1000 W/m^2 direct normal irradiance at the standard spectrum AM 1.5g.

5 RESULTS

In this section, the trend of the PV module performance in terms of output power and efficiency, as well as the trend of the calculated CTM-ratios and the impact of different gain and loss factors resulting from the simulation are shown and discussed.

5.1 Power, efficiency and CTM-ratio

The heretofore performed analyses regarding the output power and efficiency of PV modules show a rising trend as expected. Fig. 2 shows that PV module power and efficiency exhibit an absolute increase of about +85 Wp and +5.3% between the years 2009 and 2019 corresponding to a yearly rate of about +7.7 Wp and +0.48% respectively. The positive trend refers to the continuously increasing solar cell performance as well as the development of the module design regarding the used components in the simulation.

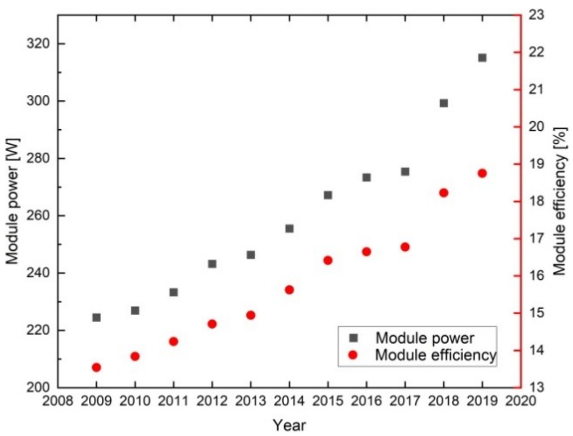

Figure 2: Temporal development of simulated 60 cells modules in terms of output power (black, left axis) and efficiency (red, right axis).

Table I: Exemplary information used in simulation of 60-cells PV modules for selected years.

Year	Cell area [mm^2]	Cell efficiency [%]	Cell short circuit current [A]	Number and type of busbars		Glass thickness and coating	T_{eff} [%]	R_{eff} [%]
2009	156×156	15.99	8.23	2	cont. cont.	3.2 mm (w/o ARC)	91.60	70.90
2011	156×156	16.87	8.58	2	cont. cont.	3.2 mm (w/o ARC)	91.60	70.90
2014	156×156	18.08	8.71	3	cont. non cont.	3.2 mm (w/ ARC)	91.32	70.24
2015	156×156	18.75	8.96	4	cont. non cont.	3.2 mm (w/ ARC)	91.32	71.68
2016	156.75×156.75	19.02	9.08	4	cont. non cont.	3.2 mm (w/ ARC)	91.38	72.19
2018	156.75×156.75	20.84	9.62	5	cont. non cont.	3.2 mm (w/ ARC)	91.53	76.92
2019	156.75×156.75	21.53	9.95	5	cont. non cont.	3.2 mm (w/ ARC)	91.53	76.92

In order to create a solid understanding of the development of PV modules performance, CTM-ratio of PV module output power and efficiency are analysed for the same period of time. The results in Fig. 3 show an overall increasing tendency for the CTM ratio, which is in good agreement with the predictions of CTM trend in [15]. The increase in CTM indicates that - beside cell improvement - module and component design play a vital role in the increasing competitiveness of solar power.

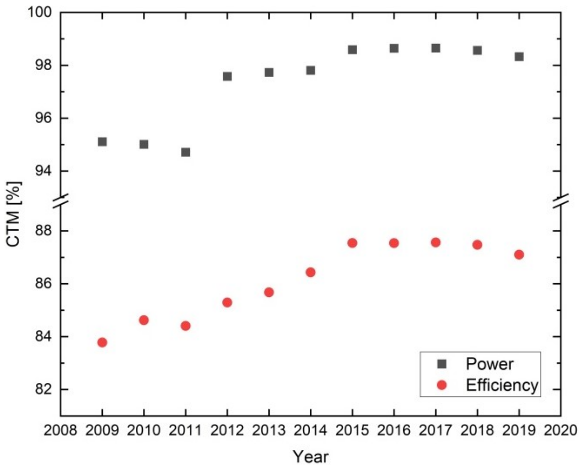

Figure 3: Trend of calculated CTM-ratio in terms of output power (black) and efficiency (red) of simulated 60 cells PV modules.

The CTM ratios feature an absolute increase of +3.2% and +3.4% in terms of output power and efficiency respectively. This increment is mainly due to the development of the PV module components and its optimized design. The big jump in the CTM ratio in terms of PV module output power in 2012 is due to the introduction of ARC-glass in the simulation, which optimizes the module optical performance by reducing light reflection at the front cover by approximately 50% compared to the years before. Beside the mentioned reasons for increasing the CTM ratio due to output power, the effective use of the module area and maximizing its active part by minimizing its margins is an additional factor for the increment of CTM ratio in terms of efficiency. It is also recognizable, that the CTM ratio of both output power and efficiency reaches a saturation state for the last couple of years. This indicates that improvements on the standard module configuration studied here have ceased to bring about large improvements. Furthermore, the increment of the solar cell performance, mainly its output current, has a slight negative impact on the CTM ratio due to the resulting electrical losses related to higher currents.

5.2 Loss and gain factors

In order to make the understanding of the development of PV module performance more comprehensive, the role of specific gain and loss factors in defining the CTM ratio is studied during the analysis.

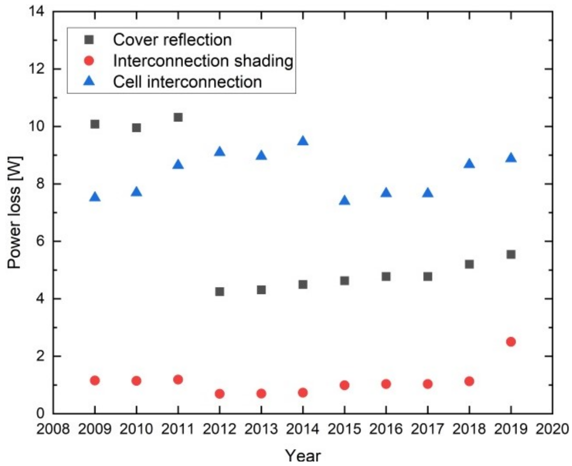

Figure 4: Temporal development of CTM-loss factors due to cover reflection (black), interconnection shading (red) and electrical losses in cell interconnection (blue) in simulated 60 cells modules.

Fig. 4 shows the change in three selected loss factors of the simulated PV modules over the same period of time. It is recognizable, that the drop of the cover reflection power loss between the years 2011 and 2012 in Fig. 4 refers to the use of ARC-glass in the simulation starting from that year. This corresponds to the big increase of the output power CTM ratio for the same period of time in Fig. 3. The increment in the absolute losses due to cover reflection after 2012 and in the loss due to interconnection shading can be explained by the increase in solar cell performance and therefore an overall increase in PV module output power. Electrical losses due to cell interconnections depend mainly on the solar cell output current, solar cell metallization pattern and the electrical resistance of the cell interconnector. These factors affect the electrical losses mutually. For example, the increase of losses between 2009 and 2014 is connected to the increase in the solar cell output current. The change from 2 continuous busbars to 3 non-continuous busbars within this period does not compensate the effect of increasing solar cell output current and the resulting losses. This does not apply for 2015, where the impact of increasing the number of busbars to 4 overcomes the negative effect of the ascending solar cell output current. Aside from that, it is to be mentioned, that the distribution of the busbars and the number of pads in case of non-continues busbars affect the current collection, the length of the used cell interconnectors and therefore the electrical resistance. All these factors are considered in our analysis of the electrical losses.

Fig. 5 shows different gain factors of the simulated modules over the same period of time. It is obvious that all gain factors have a positive trend, which is mainly associated with the continuous improvement of the solar cell performance. On the other hand, the increment of the gain factors is correlated with the optically enhanced encapsulation and cover materials of the PV module used in the simulation. This can be seen for example in the effective reflection coefficient values of the backsheet in table 1.

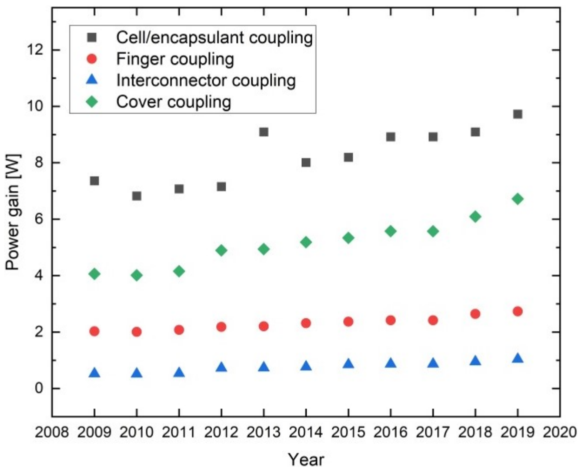

Figure 5: Temporal development of CTM-gain factors due to cell/encapsulant coupling (black), finger coupling (red), interconnector coupling (blue) and cover coupling (green) in 60 cells modules.

6 SUMMARY AND CONCLUSION

We study available solar cells and PV modules in the market from 2009 until 2019 and extract relevant data from available datasheets and measurements. We build year-specific data sets of all PV module components and use them to simulate PV modules regarding their efficiency, power and CTM ratio.

Results show a rising tendency of efficiency and power of PV modules over the last ten years. Results also show that the use of anti-reflective coating on the solar glass has a significant positive impact on the CTM_{power} ratio due to decreasing the cover reflection power losses by about 6 W. Moreover, results show that the optical gain factors exhibit a positive trend and are directly proportional to the cell performance. The solar cell performance, mainly the maximum power point current, and its metallization pattern exhibit a high impact on the electrical losses in the cell interconnections. Generally, the higher the solar cell current, the higher the electrical losses in the cell interconnections, but the results also show the important role of the current distribution within the solar cell due to different number of busbars. For the modules of years 2014 and 2015, increasing the number of busbars from 3 to 4 compensates the increment of the solar cell current and reduces the electrical losses by 2 W.

The CTM analyses enable a comprehensive understanding of the development of the PV modules considering the resulting loss and gain factors, which clarify the mutual impact of the solar cell performance and the PV module design leading to the overall output of the PV module.

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