Systematic PV module optimization with the cell-to-module (CTM) analysis software

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ABSTRACT

The key to efficient and powerful modules is an optimal cell-to-module (CTM) ratio. Interconnecting solar cells and integrating them into a solar module comes along with different optical and electrical effects. A profound understanding of all factors which influence the module efficiency is essential to derive methods to decrease the losses or to increase the gains caused by module integration. Several CTM calculation methods have been published in the past, mostly not available to a wide number of users in the form of a user-friendly tool. With SmartCal.CTM Fraunhofer ISE has released a software tool available for everybody, allowing to apply the previously published CTM analysis methodology. In this work we present the methodology and the tool, and demonstrate with some case studies how the software can be used to support the module development process.

Introduction

Understanding power losses in technical systems is vital to improve products in every industry and photovoltaic modules present no exception. Losses in solar modules are caused by optical and electrical effects or are determined by simple module geometry through inactive areas [1].

The majority of solar modules contain crystalline silicon solar cells, which can be described by their respective power and efficiency. Usually power and efficiency of the assembled photovoltaic modules do not match those of the initial cells. The ratio of the final module efficiency (or power) and the initial cell efficiency (or power) is called cell-to-module (CTM) ratio and represents an indicator for the performance-tuning of the photovoltaic device.

The importance of the CTM ratio results from the costs linked to the module integration power loss. The ITRPV Roadmap 2017 [2] states a CTM power ratio for modules using alkaline textured mono-si of 98.5%, which means that for every 275Wp-module a CTM loss of more than 4Wp occurs. Using a price of US$0.25/Wp (spot price mono crystalline cells [3]) and therefore loosing US$1 per module, the losses add up to a significant amount of money – for small national module manufacturers as well as for global players. Understanding the CTM losses and reducing them or even turning them into CTM gains therefore is not an academic dalliance but a necessary task to further improve photovoltaic modules.

Gain and loss mechanisms are well known and most of them have been described in detail for common photovoltaic cell and module concepts in several publications [1, 4, 5, 6, 7, 8]. The number of software tools, scripts, methods and algorithms to describe single gain and loss factors is high [9, 10, 11, 12] and every major research institute, university or company has its own set of tools to estimate the cell-to-module-losses. Unfortunately these tools are not accessible for everyone due to their nature as internally used development resources. Scripts without user interfaces, complex Excel-files or software for experts and insiders provide instruments for CTM analysis only to a very limited group of people. It is obvious that the internal nature of these tools leads to a disadvantage for the whole solar community; a transparent comparison of results, concepts and technologies is impossible.

Hädrich et al summarized the work on cell-to-module-analysis and published a comprehensive methodology to analyze contributing gain and loss factors in 2014 [1]. In 2016, Fraunhofer presented the software "SmartCalc.CTM" (www.cell-to-module.com) based on that methodology to allow a precise, convenient and comparable CTM analysis for the entire PV community.

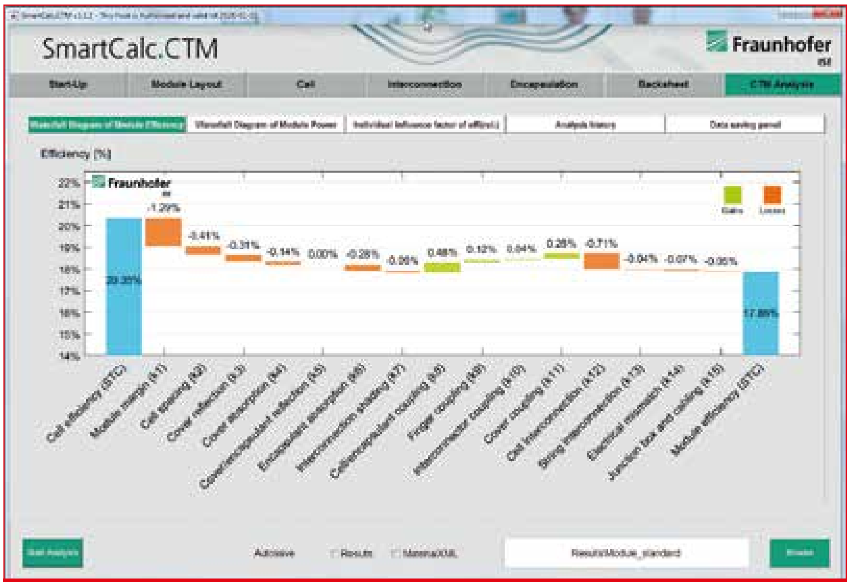

Figure 1. Screenshot of SmartCalc.CTM showing the result of a CTM analysis

The software features a user-friendly graphical user interface (GUI) with several material data input possibilities to allow a detailed CTM analysis of common and novel module and cell concepts. The GUI and the open data import both create the possibility for everyone aside from scientists or experts to perform precise analyses, to accelerate module development and to decrease costs at the same time.

The improvement of existing or the development of new module concepts or materials is an expensive task. Several materials or parameters have to be evaluated, test matrixes grow quickly and single isolated effects are rare. Thus lots of effort and prototyping is necessary to analyze the benefits and impacts of new materials, to find the important factors to focus on and to choose the right development path. SmartCalc.CTM supports the development with virtual prototyping, parameter sweeps and 'what-if' analysis. Simple changes of materials, parameters or components are possible and results only take some minutes: without the need to build a single prototype.

In an iterative development process Smartcalc.CTM saves costs by saving iterations and supporting the selection of promising development paths.

To demonstrate the possibilities of SmartCalc.CTM we improve a module by 21Wp in five simple steps from 287 to 308Wp by using SmartCalc.CTM. An analysis of the initial module is shown in Figure 1.

Software Implementation

Overview

SmartCalc.CTM is a software tool developed by Fraunhofer ISE to calculate and analyze the CTM of photovoltaic modules with crystalline solar cells. Single contributing gain and loss factors relate to physical effects (i.e. electrical resistance) and module components (i.e. interconnector ribbons). Currently 15 different factors are included in the calculation which considers geometrical, optical and electrical gains and losses as well as important module layers and components (Table 1).

Virtual prototyping and module optimization

Prototyping in R&D is expensive. Manufacturing novel modules requires planning, manual labour, complex and new processes, extensive testing, detailed result analyses, qualified personnel and – based on own practical experience – some iterations. Thus R&D prototyping is a costly endeavour and costs are likely to significantly exceed the US$0.40/Wp at which modules are being sold on the market today [2].

Car manufacturing, circuit layout design of computer chips or even architecture have profited from the possibilities of computer aided design or simulation tools (crash tests, thermal dissipation etc.). Prototypes are being virtually constructed, simulations are performed, unfeasible design options are discarded and the focus is put on the best and most promising solutions. With SmartCalc.CTM this product development approach is being enabled for photovoltaic modules.

Why build several modules to find the optimal cell spacing when you can precisely calculate it? Why stop the production and reprogram machinery just to test the potentials of 72 cells per module or 156.75mm solar cells? Simulation software and advanced scientific models allow us to answer questions before the expensive module testing begins. The possibility to change module materials, layers, properties and components with SmartCalc.CTM enables us to virtually build a module and to analyze the module power. By performing parameter sweeps focused optimization is possible.

Figure 2 includes the results of such a parameter sweep for the cell and string spacing (iterations 7 – 10). The cell distance is varied from 2 to 5mm and efficiency and power change accordingly. Variation 5 is the result of a what-if analysis. We asked what would happen if we changed the module layout from 60 to 72 cells. Variation 6 includes a new solar cell, 22% instead of 19% efficiency. In the last iteration we changed the cell design to half-cells.

If a module with more power output is desired the choice is now between three options: 72 cells, higher cell efficiency or half-cells. Simulation

k-factor	Description
Module margin k1	Inactive area at the module margin
Cell spacing k2	Inactive area between cells and strings
Cover reflection k3	Reflection of light at the front interface of the module
Cover absorption k4	Absorption of light in the front cover
Cover/encapsulant reflection k5	Reflection of light at the interface between front cover and encapsulation material
Encapsulant absorption k6	Absorption of light in the encapsulation material
Interconnection shading k7	Shading of the cell by interconnector ribbons
Cell/encapsulant coupling k8	Reduced reflection of the cell due to encapsulation (refractive index matching)
Finger coupling k9	Reflection of light from the cell metallization on the active cell area
Interconnector coupling k10	Reflection of light from the interconnector ribbons on the active cell area
Cover coupling k11	Internal reflection of light at the (rear) cover of the module in the cell spacing area
Cell interconnection k12	Electrical loss in cell interconnector ribbons
String interconnection k13	Electrical loss in cell string interconnectors
Electrical mismatch k14	Deviations in electrical cell parameters and from cell binning
Junction box and cabling k15	Electrical losses in cables and diodes of the junction box

Table 1. Single gain and loss factors of SmartCalc.CTM, loss factors are highlighted black, gains are marked green.

Module concepts & designs	Interconnection technologies	Cell designs
Glass backsheet	Ribbon-based interconnection	Back-contact (IBC, MWT)
Double glass	Round-wire interconnection	Free cell formats (including 5”, 6”, 6”+ formats, half-cells)
TPedge, NICE	Electrical conductive adhesives (ECA)	Full-square, pseudo-square
Layer properties (thickness, reflection etc.)	Shingled solar cells	Flexible number and position of busbars and pads
Layout (margins, distances, string length etc.)	Serial or parallel string interconnection	Electrical information (eta, ISC, PMPP, etc.)

Table 2. SmartCalc.CTM module design options (excerpt).

with SmartCalc.CTM enabled this quick analysis: without a single module prototype and in only a few hours.

Module, solar cell and interconnector concepts

The variation of cell spacing, glass thickness or spectral information of module layers is a smaller but nonetheless valuable task. Well-equipped R&D departments are capable of evaluating these changes even without simulation-aided development. To evaluate different novel module, solar cell or interconnection concepts a much deeper understanding of CTM effects, advanced and flexible scientific models and sophisticated measurement equipment is necessary. Bypassing scientific models becomes increasingly difficult for advanced concepts.

Comparing module concepts with back-contact solar cells (IBC or MWT), round-wire interconnection (SmartWire or multi-busbar), shingled cells, half-cells or new module topologies (e.g. all strings connected in parallel) is complex and it would be safe to say that most manufacturers do not have the manufacturing equipment to compare all module concepts by prototyping and measurement. When comparing different concepts they are highly dependent on external information. With SmartCalc.CTM a comparison of new concepts is possible and not only module manufacturers but also equipment producers or material suppliers can evaluate new technologies or materials.

While conventional module concepts are well understood and contributing CTM factors are known, the photovoltaic industry has been introducing new concepts to the market recently. Bifacial cells and modules or shingle cell interconnection are only some examples that demonstrate progress. While some technologies like half-cells or electrical conductive adhesives (ECA) do not require new methods for the CTM analysis, other module concepts need new approaches and a detailed scientific understanding of the resulting CTM changes.

Fraunhofer ISE provides a continued development of loss factors [8] or enhanced algorithms for new concepts (i.e. shingled modules [7]) to guaranty maximum flexibility for SmartCalc.CTM users. New features, concepts

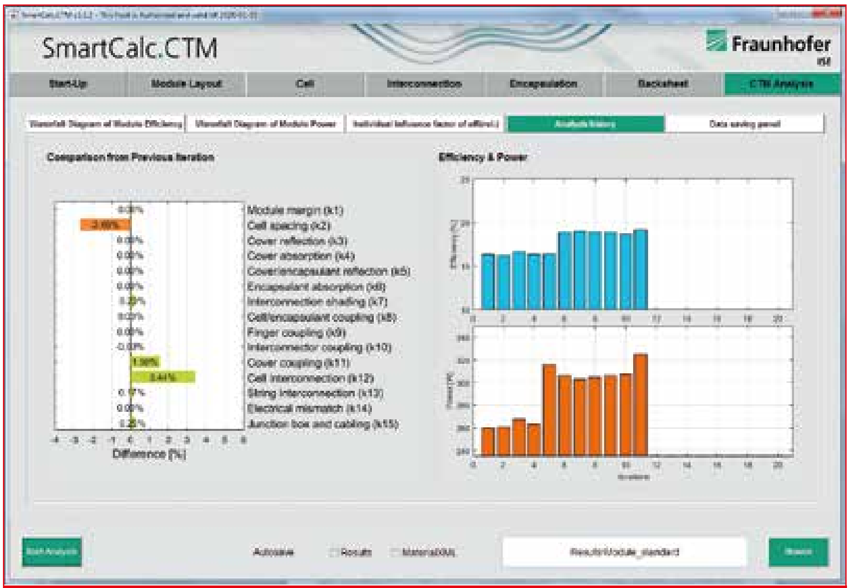

Figure 2. Screenshot of SmartCalc.CTM showing the progress during a module optimization session
Further information is provided at www.cell-to-module.com.

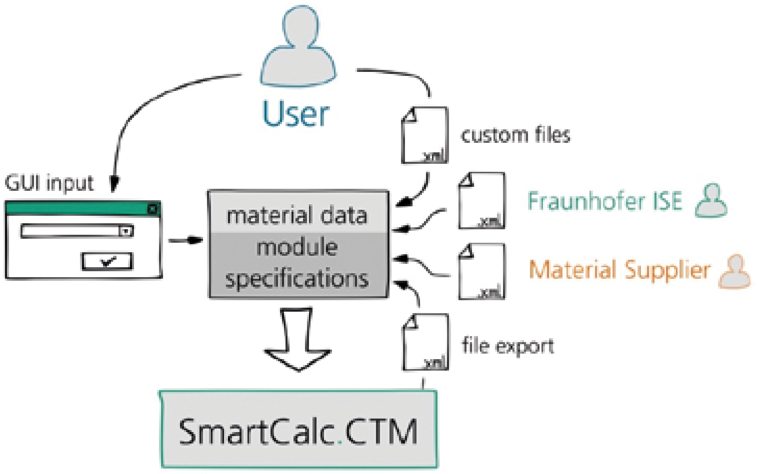

Figure 3. Data input into SmartCalc.CTM.

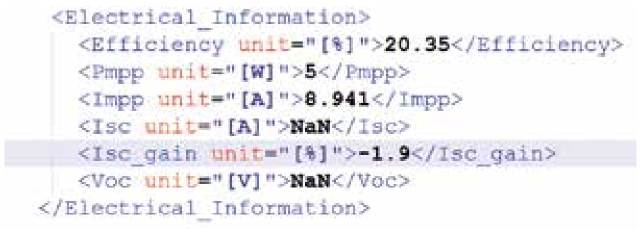

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Figure 4. Excerpt of a material data file containing electrical solar cell specifications.

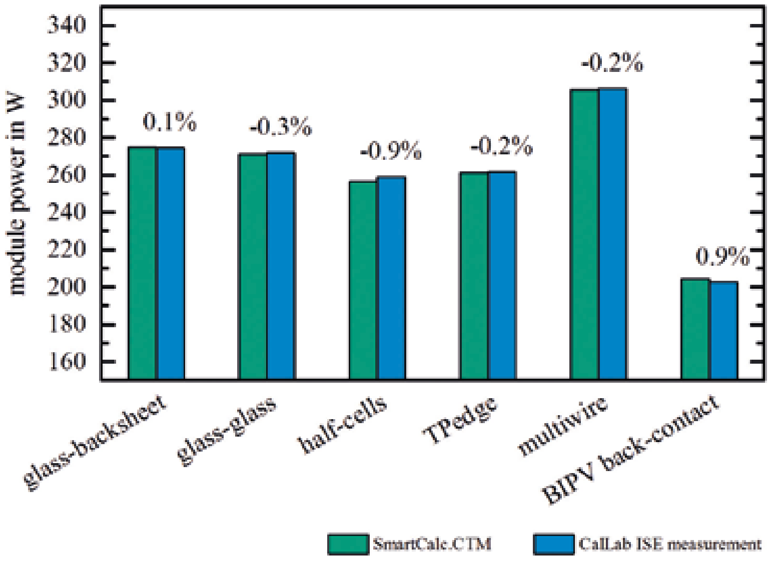

Figure 5. Results of SmartCalc.CTM simulation and measurement.

and calculation options are provided and continuous improvement by Fraunhofer ISE keeps SmartCalc.CTM up to date.

Data input

Key to every precise calculation is a good set of input parameters and material information. Geometrical information, spectral transmission and reflection data and electrical properties are the most important input parameters for solar modules. Data can be entered into SmartCalc.CTM in different ways (Figure 3).

The first and easiest way is to directly enter data into the user interface. Spectral information (reflectance etc.) can be loaded from text files and all inputs can be stored afterwards for later use.

The second possibility is to load previously created data files or to load files provided by external sources. Data is stored in a non-proprietary XML-based text file (Figure 4), which is an open format and can be edited without additional licences. Fraunhofer ISE provides precise measurements and data files, but also material suppliers or in-house R&D departments can create these files.

Fraunhofer ISE also provides assistance for material and component manufacturers to create data files to allow their customers a fast, reliable and easy CTM-analysis. To keep results confidential no web-based services or even an internet connection is required to run SmartCalc.CTM.

Validation

Fraunhofer ISE has been developing new concepts for photovoltaics for more than 35 years. Several innovative modules have been manufactured, evaluated and analyzed at the Fraunhofer ISE Module Technology Centre and of course results and experiences have been used for the development of SmartCalc.CTM. Together with Fraunhofer ISE CalLab PV Modules the development team of SmartCalc.CTM has performed validation measurements on several different photovoltaic modules. Results from selected modules are shown in Figure 5 and prove the flexibility and accuracy of SmartCalc.CTM.

Licensing

SmartCalc.CTM is licensed by Fraunhofer ISE and different packages all including material or component characterization are available. Three options ranging from an extended trial to a premium version can be selected. The premium version guarantees access to feature updates and consulting by Fraunhofer ISE. Upgrades from the extended trial to other versions are possible and the trial fee will be refunded. Fraunhofer ISE also offers the development of specialized or customized features and the accelerated implementation of customer-specific extensions to SmartCalc.CTM.

Module optimization: example

To demonstrate the possibilities of SmartCalc.CTM we perform the optimization of a conventional photovoltaic module and include some typical cases:

a) Switching from a three-busbar cell to a five-busbar cell
b) Evaluating an encapsulant from a different manufacturer
c) Increasing the cell interconnector cross-section
d) Using half-cells instead of full-format wafers
e) Change the cell and string spacing

The module we analyze contains 60 monocrystalline solar cells (full-square, H-pattern, 156.75mm, 20.35%, 5Wp), ribbon interconnection (1.2x0.2mm), commercial EVA foils (0.46mm), a commercial white backsheet and a glass with anti-reflective coating (3.2mm). A junction box with 1m cables (4mm^2) is used.

Results of the initial CTM-analysis are displayed in Figure 1. The module power is 287.3Wp, the efficiency 17.85% and the CTM power ratio is 95.8%.

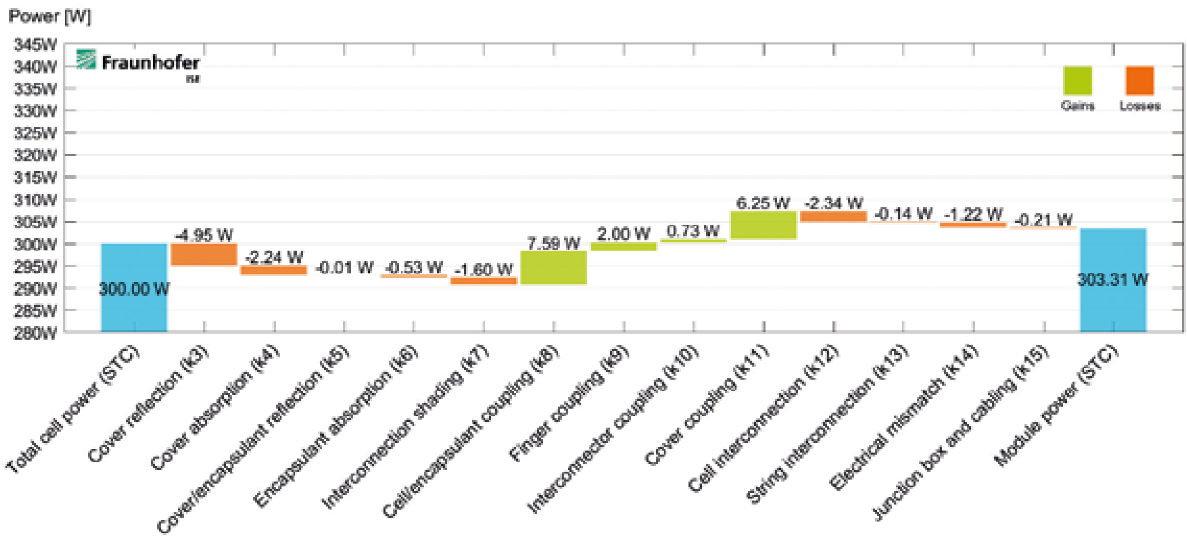

Figure 6. CTM-analysis of a half-cell module.

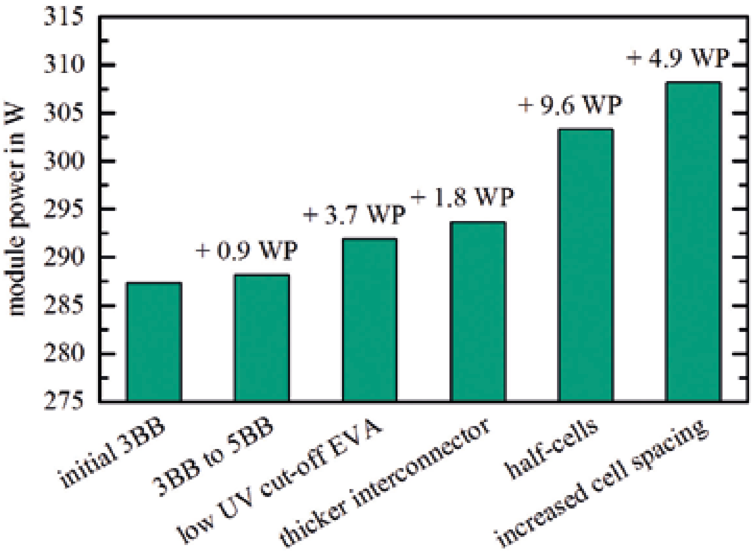

Figure 7. Module power and gain after several optimization steps.

Switching from a three-busbar cell to a five-busbar cell

To evaluate the effects of an increased number of busbars we replace the solar cell with a five-busbar version of the same manufacturer. We change the busbar width from 1.0 to 0.7mm and adapt the position of the busbars. The width of the interconnector ribbons is changed from 1.2 to 0.8mm. The cell performance and other parameters (e.g. cell metallization) remain unchanged.

Results of the analysis show an increase in module efficiency by $0.06\%_{\text{abs}}$ which equals a power gain of 0.9Wp (module 288.2Wp).

Evaluating a new encapsulation foil

We perform the comparative CTM analysis with a new encapsulation material offered by the same manufacturer. The new foil features a lower UV cut-off than the initial EVA and a slightly increased transmission. All parameters from the last case are taken and the five-busbar cells are used.

The module power increases by 3.7Wp (291.9Wp). The CTM power ratio is now 97.3% and the module efficiency increased to 18.14%.

Increasing the cell interconnector cross section

The next optimization changes the interconnector height from 0.2 to 0.25mm. As before, we perform this analysis using the same parameters as in the last optimization step. The module therefore includes five-busbar cells and a low UV cut-off EVA. The new interconnector is a copper-based ribbon with a cross-section of 0.8mm x 0.25mm with a coating thickness of 18µm.

The increase of the interconnector cross section increases the module power to 293.7Wp (+1.9 Wp).

Using half-cells instead of full-format wafers

Half-cells have been presented to increase the module power by reducing electrical losses and increasing gains from backsheet reflection. We therefore evaluate this possibility to further optimize our module.

Cell and string distance are kept set to 2mm. The cell parameters change to 2.5Wp and dimensions of 156.75 x 78.375mm. The rear side now only features three pads and the cell current is reduced to 4.48A. Cell strings now have a length of 20 cells each.

Using half-cells increases the module power to 303.3Wp and the efficiency reaches 18.6%, assuming equal cell efficiency. Because the sum of the initial cell power was 300Wp, we have now achieved the goal of having a CTM above 100%. A detailed CTM analysis is shown in Figure 6. The use of half-cells increased the module area due to a larger cell-spacing area.

Change the cell and string spacing

To further increase the gains from backsheet reflection (Figure 6, k11) we change the cell and string spacing from 2 to 4 mm. This increase will raise the gains of k11 but will also lead to higher electrical losses due to longer electrical paths. Also the efficiency will drop because of the larger module area.

Performing the analysis with SmartCalc.CTM we find the module power to be 308.2Wp and the efficiency to be 18.3%. As expected, the backsheet reflection gains increase (5Wp additional gain) as well the electrical losses in the cell interconnection (0.2Wp). The CTM power ratio is now 102.7%.

The initial module featured 287Wp and an efficiency of 17.85%. After performing five optimization steps we are able to achieve 308.2Wp and 18.30%. By using SmartCalc.CTM an increase of module power by 21.2Wp could be accomplished. No prototypes had to be built and therefore no equipment, material or additional process development was necessary. The simulations were performed on an office computer within minutes and could be easily continued for more advanced concepts (i.e. half-cells with round-wire interconnection). Figure 7 displays the progress of the module optimization.

While the introduction of new materials or processes (i.e. cell separation) requires further evaluation (i.e. reliability testing), SmartCalc.CTM supports the development by providing additional information. The gains from the introduction of a new encapsulation foil (+3.7Wp) can be weighted with module cost information (i.e. €0.4/Wp) to get the economic benefit of the new EVA (€1.48/Wp per module). We are now able to compare this to material prices of the new encapsulation foil.

SmartCalc.CTM can successfully participate in supporting decisions regarding the introduction of new materials, components or concepts.

Summary

The precise understanding and analysis of cell-to-module gains and losses are vital to improve photovoltaic modules, cells and materials. Many different approaches are known and several tools, algorithms and methods are used in industry and research to analyze CTM ratios. The access to these tools is limited to a very small group of researchers and experts and no common ground exists to compare results. This missing transparency is a lost opportunity for the photovoltaic community because no comparison of concepts and module components is possible.

Fraunhofer ISE presents SmartCalc.CTM, an accessible, precise and convenient software to perform CTM-analyses. The tool features a graphical user interface, open data interfaces and the possibilities to analyze several solar module concepts.

We use SmartCalc.CTM to optimize a solar module and increase the module power by 21 Wp. We demonstrate the possibilities of SmartCalc.CTM and perform five optimization steps including the change of materials, the change of material properties as well as a change in module design features.

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About the Authors

Max Mittag studied industrial engineering and management at the Freiberg University of Mining and Technology. In 2010 he completed his diploma thesis at Fraunhofer ISE and joined the department for photovoltaic modules. His current work includes the cell-to-module efficiency analysis and the development new photovoltaic module concepts.

Matthieu Ebert holds a master degree in renewable energy systems from the University of Applied Science, Berlin. Before joining Fraunhofer ISE in 2011 he completed research stays at the Fraunhofer CSE in Boston and at the Australian National University in Canberra. Since 2011 he has been undertaking research on PV module technology. Since 2015 he has led the module efficiency and new concepts team. His main areas of research are module efficiency and CTM analysis, building-integrated PV and PV for automotive applications.

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