Approach for a Holistic Optimization from Wafer to PV System

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***Abstract* — Models for the calculation of losses in PV systems are widely applied but typically focus on single components (i.e. the solar cell). We discuss relevant models and combinations thereof to analyze losses from wafer to system. We propose a holistic approach to analyze losses from laboratory to environmental conditions. The proposed approach focusses on practically relevant interfaces (i.e. STC module power) and is based on separated influence factors.**

***Index Terms* — loss analysis, modelling, CTM, energy rating**

I. Introduction

Losses are a fundamental property of energy systems and theoretical efficiencies are never achieved due to practical limits. Nonetheless the analysis of losses has always been an aim for the improvement of processes, facilities, components and products. Different loss analyses for solar cells, PV modules and systems have been presented [1–5] but each usually focusses on a selected component of the photovoltaic value chain, single influence factors or concepts [6–8] resulting in local optima. Opportunities to perform a global optimization are mainly unexploited. While photovoltaic products mature, a holistic approach covering all aspects becomes necessary to allow further optimization and the harvest of efficiency potentials. We discuss loss analysis models, combinations thereof and we present an approach for a loss analysis focusing on practical relevant interfaces (i.e. module STC power) and key figures (i.e. performance ratio).

II. Global Models

There are at least two major approaches to model gains and losses within photovoltaic systems. The first one takes the power of a solar cell at certain operating conditions and corrects the power output based on effects of module and system integration as well as changes based on shifts of environmental parameters compared to the initial operating conditions. The second approach analyzes the environmental conditions first and applies these conditions on the encapsulated cell. We call the first bottom-up approach "wafer-to-system" (WTS) modelling. It follows the chain wafer-cell-module-system. WTS is based on influence factors f_i as shown in Equation (1) which is similar to an approach we presented earlier [3] for modules only.

$$P_{system} = E_{STC} \cdot \Pi(f_i) \text{ with } f_i := 1 - P_{loss,i}/P_{loss,i-1} \qquad (1)$$

The WTS model focusses on relevant basic components of a photovoltaic system (i.e. the single solar cell). Important interfaces of the modelling chain are the Shockley-Queisser limit, the solar cell power at STC, the module power at STC, a site specific DC energy delivery, the system performance and finally the system yield.

Cell power is modelled using an arbitrary but commonly used irradiance of E_{STC} = 1000 W/m² as a starting point (Fig. 1). We allocate losses from this irradiance to the Shockley-

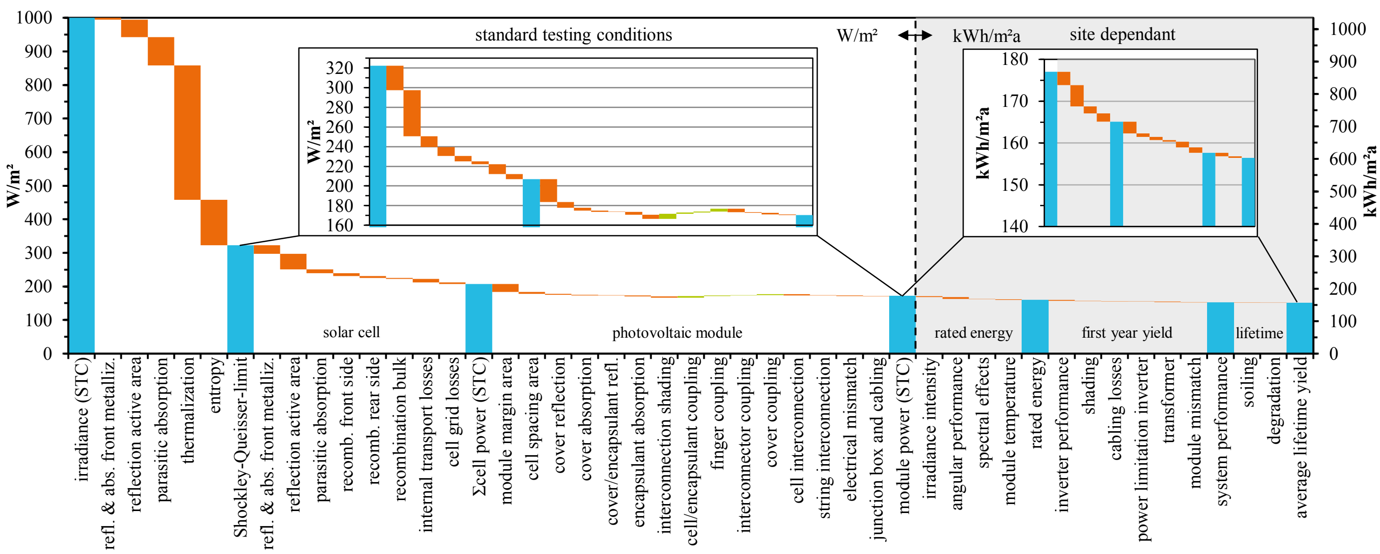

Fig. 1: Gains and losses from irradiance to system yield, Wafer-To-System (WTS) approach

Queisser limit (SQL) as an upper boundary for solar cells (in our example: single junction crystalline silicon, see section III). In case this methodology is applied to other concepts this intermediate result has to be adapted accordingly; i.e. for tandem solar cells losses in thermalization and entropy may be lower than in the example of Fig. 1.

Afterwards losses within solar cells are analyzed followed by module and system losses. One may notice that some losses occur twice within the waterfall chart in the first two sections. During the optimization of the solar cell some loss channels cannot be improved since constraints from the previous selection of the semi-conductor etc. occur (i.e. the power generation from light at wavelengths > 1200 nm for silicon solar cells). We therefore split some losses into a component that are technically accessible during solar cell production and some loss channels that are not.

System modelling may comprise three steps which include a rated module energy calculation, a "first-year-loss-analysis" of the system and an added degradation part for the lifetime. Power changes are displayed in a waterfall chart that illustrates the single influence factors (Fig. 1). The single modelling steps are discussed in the respective chapters below.

WTS uses carefully chosen interfaces to provide practically relevant information for manufacturers along the value chain. Therefore, cell to module loss calculation is using standard testing conditions (STC); however arbitrary conditions would also be possible. The physical effects from irradiance to lifetime yield are split into different influence factors (i.e. the optical effects) and a separation in power and energy is necessary to bridge the gap between single laboratory measurements and system yield.

The second approach follows the path from incident light over photovoltaic energy conversion to current transport within the practical application of photovoltaic devices. We call this top-down approach "operational performance analysis" (OPA) due to its focus on realistic operation of the solar cell which is influenced by module integration and environmental conditions.

In the first step environmental conditions are analyzed and the irradiance in module plane as well as other important environmental parameters are determined (Fig. 2). Afterwards these parameters are used to calculate the effects occurring within the PV module such as absorption in the encapsulant layers. In a third step the performance of the cell at the operation conditions as defined by environment and module are calculated.

Solar cell and module are usually not analyzed at standard-testing conditions in the OPA approach. It uses no arbitrary interfaces (such as cell at STC) between the different modelling stages. Therefore OPA falls short in provisioning some of the widespread reference values and intermediate results. Its interfaces between the modelling stages are not typically used in the PV industry which relies mostly on STC-datasheets. The integration of yield and annual performance as well as effects from the interconnection of different modules requires feedback loops between the different simulation stages (i.e. for heat exchange between cell, module and environment). Due to its focus on the actual operation of the solar cell within the environmental influenced photovoltaic system OPA is very reasonable and understandable approach. No arbitrary interfaces or operating conditions are necessary.

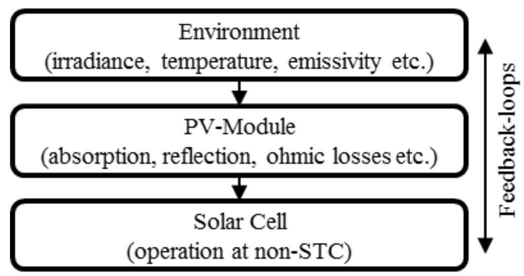

Fig. 2: Operational Performance Analysis (OPA) Approach

WTS uses such an arbitrary starting point (STC) and considers changes afterwards. OPA follows the path of energy conversion from incident light to cell power. Sub-models of WTS may also follow the idea of OPA and the path of occurring gains and losses.

Both approaches feature some disadvantages and each approach may be selected according to the suitability for a certain question. They both focus on the description of the current as-is status at given conditions contrary to other approaches which have been presented that aim at the potential efficiency gains of a photovoltaic device when suppressing loss mechanisms [9].

III. Solar Cell Modelling

Multiple approaches for evaluating the performance potential or loss channels within (crystalline) solar cells are available, each designed with a particular focus. The prospect on a cell analysis and thus its choice depends on the user's perspective.

A loss analysis based on any incoming power density P_{in}, be it 1000 W/m² for the WTS approach or a value obtained from environmental conditions for OPA, is the "Free-Energy-Loss Analysis" (FELA). In their initial publication Brendel et al.

[10] covered the electrical loss channels which are usually calculated in terms of volume recombination power loss P_r, surface recombination power loss P_s and transport power loss P_t, as given in [1], and can be regionally summed up in arbitrary collocation depending on the users preference. Depending on the focus of a loss study this can be diversified at will as the model has full insight into the local physics. This offers the possibility to directly compare the loss mechanisms

a) inside one cell configuration,
b) between two different parameter sets, and
c) in the context of a full system analysis also the impact of a loss reduction on cell level on the system yield.

Simply spoken, FELA multiplies local recombination losses with the local voltage and resistive losses with the squared local current density. Therefore it can be combined with any modeling tool that provides local fermi levels, currents and carrier densities. Deducing $P_r + P_s + P_t$ from the generated free energy P_g yields the solar cells output power density P_{out}.

Greulich et al. [1] close the gap from the cell's generated power density P_g to P_{in} with three additional components: The loss of reflected and non-silicon absorbed photons P_o in form of their equivalent in lost carriers, the entropy loss P_e and the loss P_{the} due to carrier thermalization to the band edges. As a result we have a complete loss catalog:

$$P_{in} = \overbrace{P_o + P_e + P_{the}}^{\substack{\text{Extended FELA} \\ \text{Greulich et al.}}} + \underbrace{\overbrace{P_r + P_s + P_t}^{\substack{\text{FELA} \\ \text{Brendel et al.}}} + P_{out}}_{P_g} \qquad (2)$$

Using eq. (1), we are able to compute change factors f_i for each of the losses shown in eq. (2). They can be used to create the "solar cell" region of the waterfall chart as displayed in of Fig. 1 which provides cell losses in context of the whole system.

The loss columns left of the SQL represent non-accessible losses for the solar cell due to physical limits (bandgap, absorption spectrum, thermalization, entropy). The solar cell loss columns on the right side of the SQL in Fig. 1 are technically accessible with improved material properties.

The shortcoming of this method is that the given power loss distribution describes just the actual state with limited predictability. A cutback in one loss channel leads to an increase of generated power potential (P_g) and shifts the remaining loss channels.

The "Modeling-Free Efficiency Gain Analysis" (MEGA) [9, 11] uses a similar physical approach (see [9], eq. 8-10) as the FELA, however with one big difference: It is designed to calculate accessible gains instead of free energy losses and thus can be directly related to measurable input parameters of the solar cell. This means the analytical calculations get along without numerical simulation. Like FELA it makes all loss channels within one analysis directly comparable in terms of efficiency, but a comparison of two different cell types is also not consistent. While FELA is more suited when a simulation study of a cell concept is performed, MEGA comes into play when characterizing a produced solar cell.

A "Synergistic Gain Analysis" (SEGA) [2] is another modelling based approach derived from FELA. It tries to overcome the above mentioned shortcoming of FELA by simulating the activated as well as the inactivated loss channel. Doing this for all loss channel combinations SEGA yields a detailed and accurate gain potential for every loss type. This, however, comes on the cost of greatly increased simulation effort. A comparison of SEGA and FELA can be found in Ref. [12].

FELA, MEGA and SEGA are usually associated with a calculation of a current-voltage curve and the cell's optics. Thus they give full electrical and optical characteristics of the examined solar cell (model) as well as an analysis of losses and/or gain options. Therefore they are suited for integration into a global system loss analysis, which uses a modular setup and has no feedback loops between the different system levels (cell – module – system), which is previously described as "WTS" and depicted in the waterfall diagram (Fig. 1). Also these three analysis methods are robust against non-standard test conditions as long as they stay in the definition boundaries of the applied simulation models (strong temperature deviations, e.g., may not be covered). For an application with OPA difficulties arise, when feedback loops should be applied due to strong interaction of components in the system level (i.e. inhomogeneous irradiance on different cells in a module).

The aforementioned types of loss analysis give results for global parameters. Another approach, which gives spatially resolved information, is the "Efficiency Limiting Bulk Recombination Analysis" (ELBA). The ELBA approach is based on actual measurements and uses photoluminescence (PL) images calibrated to lifetime to attain the excess carrier lifetime of surface passivated silicon samples which underwent all relevant high temperature steps of a solar cell production [13]. As j_{SC}, V_{OC} and FF of a solar cell are affected by the bulk lifetime τ_{bulk}; PL images at varying generation are used to gather an injection dependent τ_{bulk} for every pixel of the lifetime samples and are then combined with a simulation of a solar cell with a designated design in PC1D. A flat Shockley-Read-Hall (SRH) level is simulated using all relevant information about the cell concept which is then applied to every pixel to calculate V_{OC} and j_{SC}. The fill factor FF is approximated by simulating a Suns-V_{OC} curve which results in a pseudo fill factor pFF_{bulk} and all parameters together are used for the prediction of the spatially resolved solar cell efficiency η, an exemplary result is shown in Fig. 3. This approach is appropriate for the WTS model as the efficiency potential of a solar cell can be easily predicted via an ELBA analysis, with these parameters module performance at non-STC can be simulated. Unfortunately, ELBA is not suitable for OPA since it is not possible to use environmental conditions to simulate the performance of a solar cell at STC via ELBA analysis.

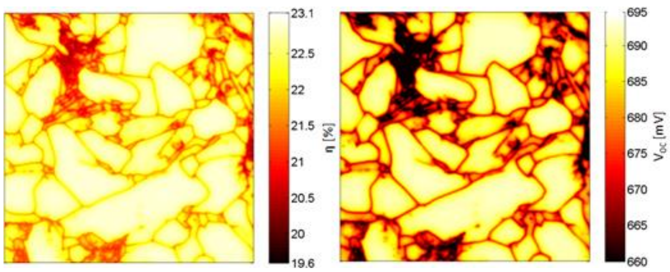

Fig. 3: Predicted local efficiency η and V_{OC} for a lifetime sample with designated cell design.

This list of cell analysis methods is by no means exhaustive and serves as example how to systematically approach cell losses which may then be integrated in an extended loss analysis of solar modules or systems. Relevant factors for choosing a sub-model are the required interfaces (i.e. STC / non-STC) and the necessity of feedback loops between the models.

IV. Photovoltaic Module Modelling

Gains and losses originating from the encapsulation of the solar cell within the photovoltaic module are commonly calculated at standard testing conditions STC [5, 7, 14] and consider optical, electrical and geometrical effects. Additional models are available for isolated physical effects or module components [6, 8, 14–18].

The WTS approach uses the interfaces cell and module power at STC as well as other well-established key figures (i.e. performance ratio [19]) and therefore provides the possibility to exchange models based on those interfaces. The OPA approach on the other hand, requires models explicitly capable of considering non-STC operation.

Cell and module power lead to the definition of the cell-to-module (CTM) ratio that has become a key figure describing effects of module integration [20]. While the CTM previously has been used to describe effects at STC only, results have been published lately also considering the influence of arbitrary conditions (non-STC) on cell and module power [21]. The CTM-ratio therefore is “non-STC compatible”.

The definition of CTM allows the display of power gains in the WTS model. Power gains from cell to module are possible since a solar cell at STC is used as an initial reference and module integration can improve the overall power of the encapsulated solar cell compared to the unencapsulated cell (i.e. using internal reflections within PV modules).

The (annual) performance of a module is the sum of the power at each operating point. Each module operating point can be described by a specific set of CTM-factors. It is possible to extend the CTM methodology and to bridge WTS interfaces. To achieve this, we keep the cell power at STC as the first interface but instead of calculating the module power at STC and performing an energy rating afterwards we condense the CTM-factors for each data point to CTM-factors summarizing for the complete dataset (Fig. 4). Using this, the rated energy can be described by a set of “annual CTM factors”. We call this approach “cell-to-system” as it describes the performance of a solar cell within a module under environmental conditions. The CTS-approach not only bridges interfaces within WTS, it also closes the gap between WTS and OPA due to the application of realistic environmental conditions and the loss analysis along the path of energy conversion within a module.

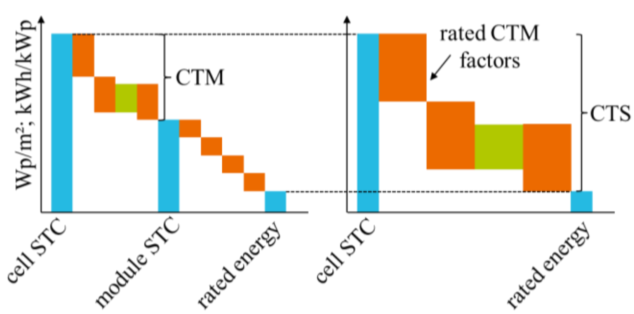

Fig. 4: concept of cell-to-system analysis

The CTM as well as the CTS analyses result in inputs for the extended environmental and system loss analysis.

V. Yield and System Modelling

When moving from a single PV module under a single set of ambient (or laboratory test) conditions to a full PV generator under varying real world meteorological conditions, a transition from instantaneous values to integrated values happens - the calculation of power values is extended towards energy values. Obviously, this is one of the major challenges when designing a full WTS model.

One possible approach starts from a defined set of module properties like STC power, temperature coefficients, angular dependency and others. These properties may be derived from CTM modeling or from laboratory measurements of module samples and are then fed into the different steps of a loss model chain for PV modules and systems. Such models are typically designed as time step models; they read meteorological time series data as input and predict device losses and component efficiencies for each time step [22, 23]. This is the industry standard when preparing yield certificates for PV power plant projects. The calculation of averaged loss factors can be done retroactively to achieve the values depicted in Fig. 1.

As operation conditions are not identical for all PV cells or modules of a PV system even within a single time step, a parallel calculation of several instances of certain loss model steps may become necessary. One prominent example is the partial shading of the module area, which most real world PV generators experience each day at least around sunrise and sunset. The frequency and amount of shading is determined by the system site and by its mounting geometry. Partial shading leads to inhomogeneous irradiance levels and consequently to cell mismatch losses. Even if the estimation of cell mismatch losses was already included in a CTM calculation at STC (with equal irradiance on all cells), it needs to be repeated for the shaded modules and for individual time steps.

Thus, the parallel approach starts from individual time series of meteorological and ambient conditions for each of the cells of a PV module. Then, the calculations described in the previous section are performed, leading to the values of f_i in (1) for each time step and to instantaneous values of output power for each step. In the end, the integration towards energy values is a simple task.

As another example, fixed or tracked mounting changes the direct and indirect plane of array irradiance and the distribution of incidence angles. Design optimizations of the Angle of Incidence (AoI) behavior for a given mode of operation may be away from optimum for another mode of operation. The OPA approach can easily deal with this dependency and allows for a quick assessment of design changes on cell or module level.

With any approach, PV system modeling will finally consist of four major steps,

- calculate module DC energy delivery (this is close to the approach of energy rating (ER) as defined in IEC 61853) [24],
- calculate the losses in the BOS components (fuses and switchgear, inverters, cables, transformers),
- assess the effects of deliberate design limitations (inverter vs. module power, power limitations at feed-in point),
- include long term effects as soiling and module or system degradation

and thus completes our full wafer to PV system model.

VI. Conclusion & Summary

We present a holistic approach to analyze power and performance losses in photovoltaic systems. Two models are discussed. The first one takes the power of solar cell at certain operating conditions and corrects the power output based on effects of module and system integration as well as changes based on shifts of the environmental and operational parameters compared to the initial operating conditions. We call this bottom-up model “Wafer-to-System”. It is based on the application of change factors to adjust the electrical output of the solar device for different effects along the integration from wafer to system.

The second approach analyzes the environmental conditions first and applies these conditions on the encapsulated cell. Due to the focus of the second approach on the operation of the solar cell at certain conditions we name this model “operational performance analysis” (OPA).

We discuss both models and show that both approaches can be combined. While they feature important differences regarding sub-models, interfaces or the implementation (i.e. necessity of feedback loops) they can also complement each other at some points. Especially the sub-models of the WTS-approach follow OPA with its loss analysis along the path of energy conversion.

V Acknowledgement

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