ELECTRICAL AND THERMAL MODELING OF JUNCTION BOXES

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ABSTRACT: The power of photovoltaic modules is the product of single gain and loss factors. These factors influence the cell-to-module (CTM) ratio and final power of modules. We extend an existing CTM-methodology by presenting a complete model to calculate the losses attributed to junction boxes and cabling. We find the total junction box losses to be small (< 1 W) compared to the power of common photovoltaic modules. Electrical losses in cabling are the dominant loss factor (> 80%) for junction boxes. We simulate the thermal behavior of a junction box using the finite element method and analyze the temperatures of bypass diodes. The model is verified using infrared thermography. We find the diode temperature in the analyzed setup to be below critical temperatures for a thermal runaway. From our FEM-model we find that diode temperatures can be reduced by 13K using potting material with increased thermal conductivity (0.8 W/m*K compared to 0.2 W/m*K). Electrical losses of the junction box increase with elevated temperatures but are still comparably low. We perform an economic analysis and consider costs of power loss as well as material costs for cabling. We find the optimal cable cross section to be 4 mm² at Standard Testing Conditions. At irradiations other than 1000 W/m² the optimal cross section is found to be different (6 mm² at 1200 W/m², 2.5 mm² at 600 W/m²).

Keywords: CTM, Cell-to-Module, Power Prediction, Junction Box, Diode, FEM

1 INTRODUCTION

The integration of solar cells into photovoltaic modules causes a change of power and reference area which defines the efficiency of solar devices. The cell-to-module power ratio (CTM) describes the ratio of the module power after integration of the solar cells relative to the sum of the power of the solar cells before integration [1]-[3]. Optimization and therefore detailed knowledge of the influence factors for CTM is necessary to further increase the power and efficiency of PV modules and to eliminate unnecessary losses.

A unified methodology was presented by Haedrich et al [4] summarizing previous work and offering a comprehensive toolbox to analyze the CTM ratio and its contributing factors. This model does not include losses in junction boxes. Thus parameters in CTM calculation models are unable to precisely evaluate commercially available photovoltaic modules and components.

2 METHOD

We extend the existing methodology by presenting a new loss factor for junction boxes and cabling. Cable dimensions, bypass diode losses, contact resistance in plugs and jacks as well as internal ohmic losses in the junction box itself are considered. Modeling is validated by measurements on several industrial available junction boxes.

We perform a cost analysis and calculate an optimal cable thickness for solar modules reducing the total costs (including power loss and material costs) of solar cables and junction boxes for different irradiations.

We simulate the thermal 3D profile of a junction box connected to a PV module by finite element modeling (FEM). We present a 3-dimendional FEM model, which is based on a detailed CAD model reproducing the junction box exactly. The FEM model is adjusted by thermographic measurements.

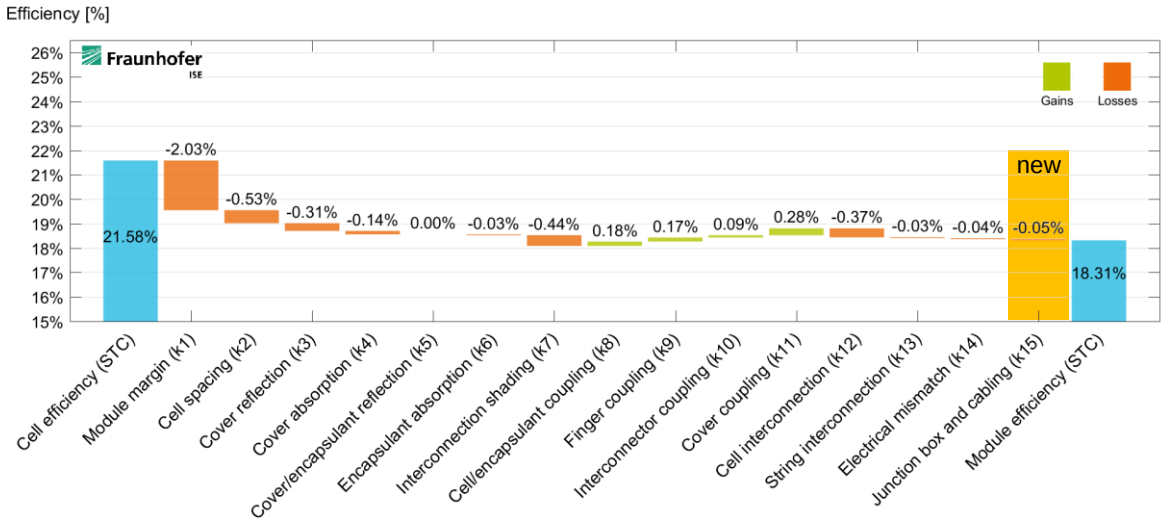

Figure 1: Improved Cell-to-module analysis [5][8][9] for a conventional solar module following the methodology of Haedrich [2]

Temperatures in the junction box and the bypass diode as a function of the module current and ambient temperature are evaluated. We analyze the temperature dependent electrical losses in the bypass diode and estimate their relevance for losses in the junction box. We use the FEM-simulation results to analyze the risk of elevated temperatures within junction boxes (risk of thermal runway) and validate our simulation with measurement results.

3 MODELING OF JUNCTION BOX AND CABLING LOSSES

Electrical losses in junction boxes and cabling are caused by the ohmic resistance of electrical conductive components at the I_{MPP} of the module. The total junction box loss comprises five different power loss mechanisms:

a) ohmic resistance of the cable
b) contact resistance between jack and plug of the junction box cables
c) ohmic resistance of the internal circuits of the junction box
d) contact resistance between the string interconnector ribbon and junction box connectors
e) reverse leakage current in bypass diodes

$$P_{loss} = P_{cable} + P_{plugs} + P_{internal} + P_{string\,connector\,joints} + P_{diode}$$

As shown in Figure 2 commonly used Schottky diodes have a reverse leakage current of around 5 µA at 25 °C. Depending on the number of strings, solar cells per string and the number of bypass diodes, losses of type a) vary significantly. Nonetheless the bypass diode losses are usually negligible for solar modules due to the small currents. At significantly elevated operating temperatures (120 °C) reverse leakage current increases to approx. 10 mA for Schottky diodes (Figure 2) and therefore losses in typical modules may reach 0.1% of the nominal power.

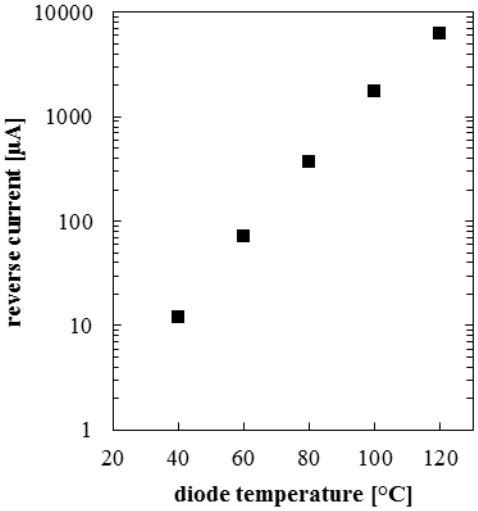

Figure 2: Measurement results of reverse current of a Schottky bypass diode

The ohmic losses in the connecting cables are dependent on the second power of the module current, on cable length, specific resistance and cross section. Commercially available cables are made by using tin coated copper (specific ohmic resistance of approx. 0.0175 Ω*m/mm²) and feature typical cross sections between 2.5 and 6 mm².

Common modules are equipped with two connecting cables that feature one jack or one plug each. Cables are connected to form module strings. Each jack is usually connected with one plug and therefore contact resistance of jack and plug can be measured together. We use a transfer length method (TLM) to measure the contact resistance [8]. Figure 3 shows the result of these TLM-measurements for two different jack-plug combinations. The measured resistance of jacks and plugs ranges around 0.3 mΩ. Results are in good accordance to datasheet specifications (< 0.5 mΩ).

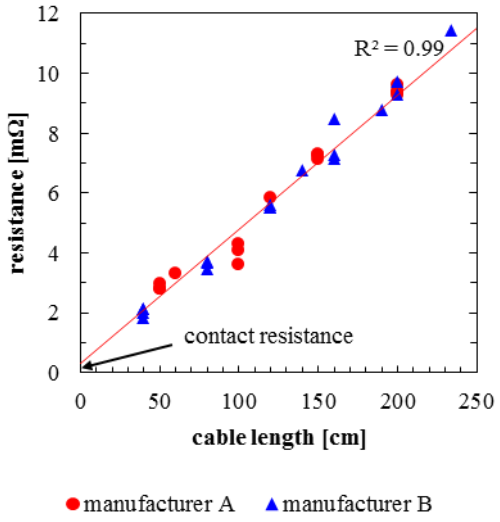

Figure 3: Resistance of two jack&plug combinations with cables of different lengths, linear fit for manufacturer A

Losses from contact resistance between the string interconnector ribbon and junction box connectors as well as the losses from the ohmic resistance of the internal circuits of the junction box are both measured together. Separating the measurement is possible but offers no advantage for practical applications. We measure the internal losses of different junction boxes by again using a transfer length method. String interconnector ribbons of variable length are connected with the junction box using soldering or plug-in connection. Figure 4 shows the results of resistance measurements on four different junction boxes. By doing a linear fit for every measured junction box, we obtain the sum of internal resistance and contact resistance between junction box and string connector ribbon. Resistances range from 0.27 mΩ to 1.5 mΩ.

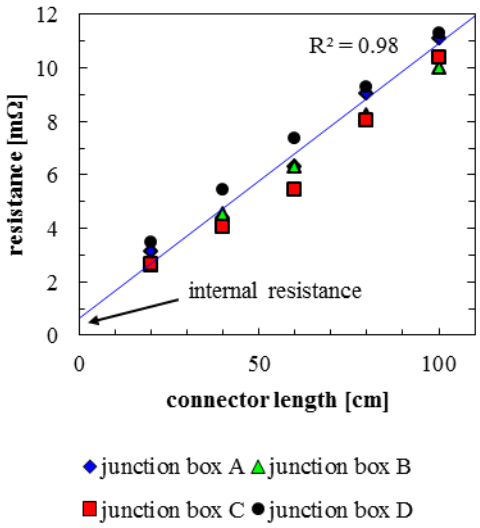

Figure 4: Internal **r**esistance of junction boxes with different string connector lengths, linear fit for box A

We implement all sub-models to calculate the complete junction box losses and combine all single factors. Calculation for a common module (9.1 A I_{MPP}, 303 Wp) with cables of 1 m length (4 mm², copper core) results in losses of approx. 0.84 W which represent 0.28% of the module power. Most important factor for junction box losses are the ohmic losses in the connecting cables (Figure 5).

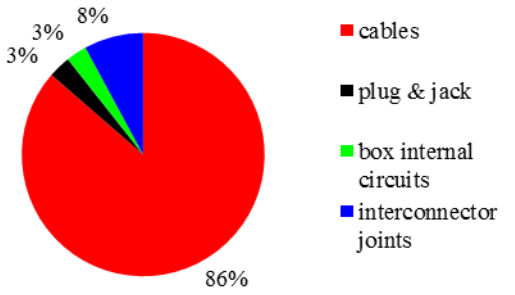

Figure 5: Share of different loss mechanisms for a common module and junction box setup

The junction box loss calculation model has been integrated into SmartCalc.CTM [7][9] by Fraunhofer ISE which is a software to analyze cell to module losses for photovoltaic modules.

4 ECONOMIC ANALYSIS OF JUNCTION BOX LOSSES

Assuming a module price of 0.40 €/Wp [10] the calculated losses (0.84 W at STC) caused by junction boxes equal 0.34 €. For other cable cross sections, the losses change and therefore their costs (Figure 6, red square). We assume the price of solar cable to be 0.50 €/m for 6 mm², 0.385 €/m for 4 mm² cross section and 0.265 €/m for 2 mm² based on market research. Calculating the junction box losses and using these cost information, we find a minimum of the total costs at STC (including cabling material and losses) for a cable cross section of 4.0 mm² (Figure 6, black circles). Other costs such as junction box material, plugs etc. are kept constant and are not included.

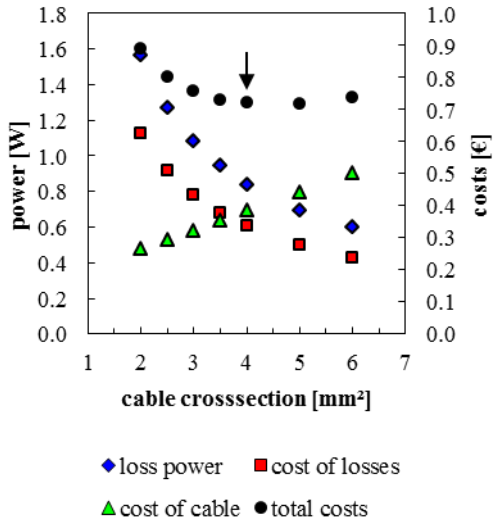

Figure 6: Power losses (@STC) and respective costs, cable and total costs

It is well known that laboratory testing at STC only provides limited information about outdoor performance. We therefore extend our model and calculate the total costs of power loss – including electrical losses as well as material costs for cabling – for different levels of irradiation. We assume a linear change of the current with irradiation. Results are displayed in figure 7. While at STC, a cable cross section of 4 mm² leads to minimal total costs, different cross sections are favorable at other irradiations. We therefore conclude that based on the environmental conditions a customized design of the junction box and cabling may reduce Levelized Costs of Electricity.

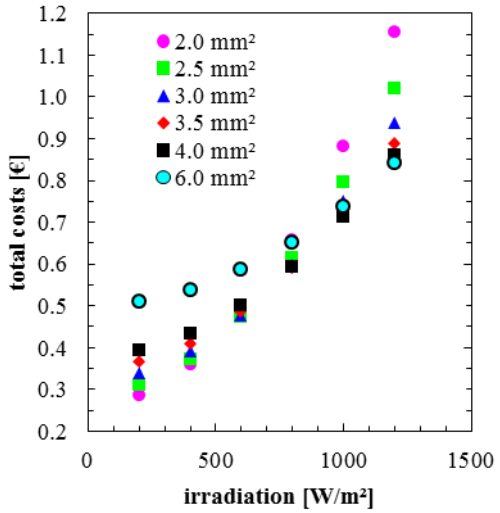

Figure 7: Total costs of junction box and cabling losses including costs for cables of various cross sections at different irradiation

5 INFLUENCE OF ELEVATED JUNCTION BOX TEMPERATURES ON LOSSES AND SAFETY

Since losses in junction boxes not only depend on module currents but also on temperature, we investigate the temperature profile of a junction box as a function of the current and thermal conductivity of potting materials. We also put particular interest in the temperature of the diode as the reverse current increases exponentially with increasing temperature (Figure 2).

We set up an electro-thermal FEM-model using CAD-files of the geometry of the junction box (Figure 8).

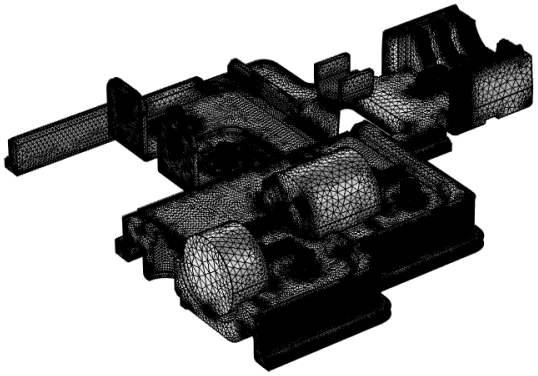

Figure 8: Symmetry element of a junction box with mesh for FEM-modelling

We perform measurements on the diodes of the junction box and find the forward voltage drop over the Schottky diodes to be approx. 0.45 V at 9 A (Figure 9). Using these values we are able to calculate the losses dissipated as heat during bypass operation to be 4 W per diode. A measurement of the temperature dependency of the threshold voltage (forward voltage drop) shows a decrease with higher temperatures (Figure 9).

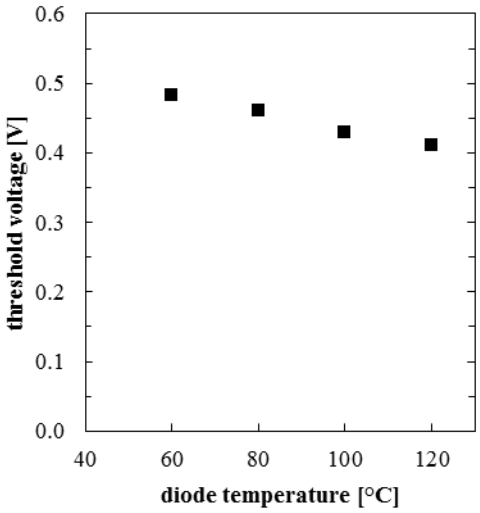

Figure 9: Temperature dependency of the threshold voltage of an exemplary Schottky diode

We feed the loss power of the bypass diode (4 W) as boundary condition into the FEM-model and simulate the heat spread within the junction box (Figure 10).

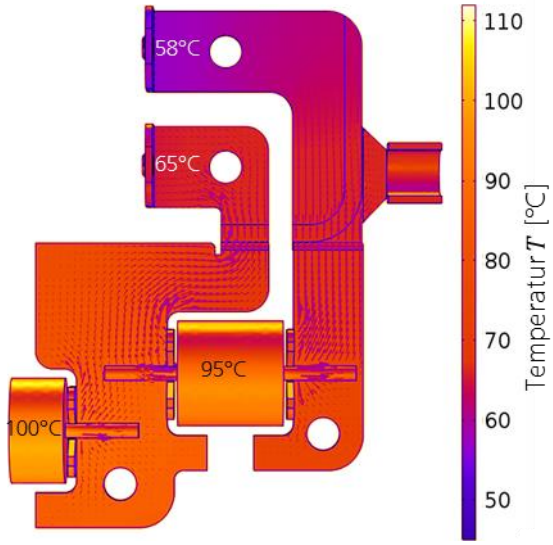

Figure 10: Temperature profile of the electrically active parts of the junction box

We balance the FEM simulation with infrared thermography measurements (Figure 11) and adapt the coefficient of convection to match the infrared-measurement results.

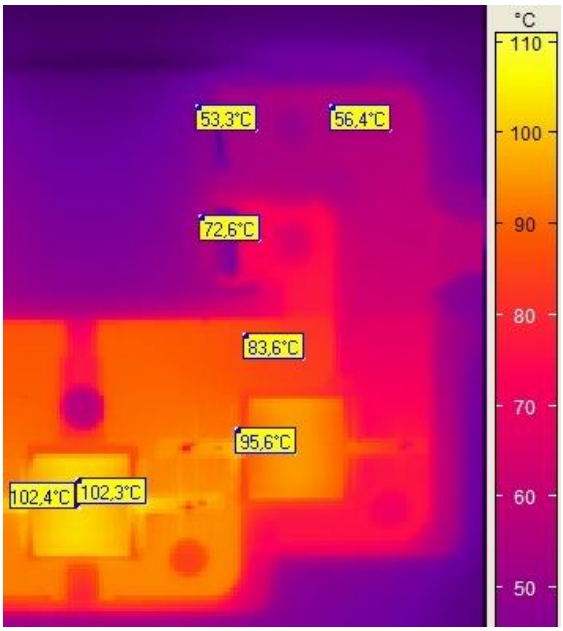

Figure 11: Infrared thermography image of the junction box of a module in failure mode at 9 A.

We find the highest temperature to be at the symmetry plane in the center diode and obtain a temperature of about 100 °C at a forward current of 9 A (failure mode of bypass diode).

When exceeding the stationary point, where the cooling capacity is equal to the dissipated heat of the diode, the thermal dependency of the reverse current is amplified by the so called thermal runaway effect which may lead to damage of junction boxes [11][12]. By simulating the heat spreading within the junction box using a FEM analysis, we obtain the diode temperature in dependency of the module current and are capable of evaluating the risk for thermal runaway as well as investigating electrical losses.

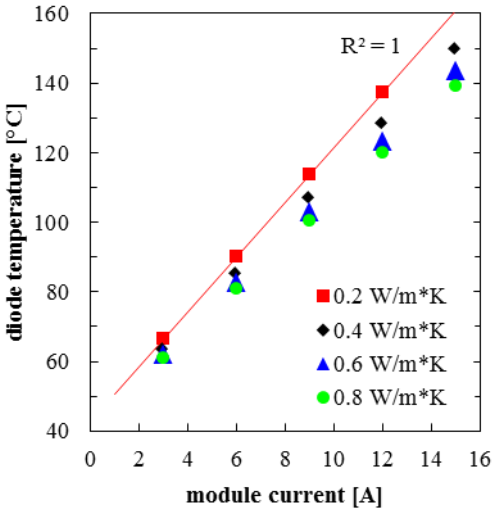

Figure 12: Simulated diode temperature versus module current for different thermal conductivities of the junction box potting material, linear fit for 0.2 W/m*K

The FEM model shows that the diode temperature increases linearly with increasing module current (figure 12). Assuming common solar cells and modules with currents below 10 A, we find the bypass diode temperature within the simulated junction boxes to be lower than the critical thermal runaway temperature (130 °C, depending on diode and manufacturer) [11]. Nonetheless risk of module and diode damage increases for solar cells with higher currents such as bifacial cells and elevated temperatures in general.

We vary the thermal conductivity of the potting material in the FEM simulation and evaluate the influence on diode temperature.
Improving the thermal conductivity from 0.2 to 0.8 W/(m*K) leads to decrease in diode temperature of 13 K (at 9 A). Improving the potting material therefore leads to lower temperatures of bypass diodes (Figure 12).

As shown in figure 2, the elevated temperature within the junction box increases the reverse current of the bypass diode. Even with a significantly increased reverse current (1.8 mA @ 100 °C compared to 5 µA at 25 °C) the bypass diode losses are small compared to other loss factors such as losses within cables.

Using the total junction box loss power (0.84 W) and the module current (9.1 A) we are able to calculate the total junction box resistance and find it to be 10 mΩ. Assuming the temperature coefficient of the resistance to be similar to copper ($\alpha = 3.93 \times 10^{-3}\ K^{-1}$) we are capable to calculate the junction box losses at elevated temperatures. Junction box losses of a module at 60 °C increase only slightly assuming the cables to have the same temperature as the junction box itself. We find the total junction box resistance to be approx. 1.5% higher at 60 °C compared to STC.

6 SUMMARY

We present a model to calculate the electrical losses in junction boxes and cabling and implement this model into the software SmartCalc.CTM [7][9] to calculate CTM-losses for crystalline photovoltaic modules. We find the total losses to be low compared to the total module power output (0.25 - 0.30% at STC) and the losses within the cable to be the most important single loss factor regarding junction box losses (> 80%).

A cost calculation and a sensitivity analysis are performed showing an optimal cross section of module connection cables to be at 4.0 mm² to reduce total costs at STC. At irradiations different from 1000 W/m² or for modules with currents significantly different from common module technologies other cable cross sections are favorable.

We present a detailed electro-thermal FEM model of a junction box. The model is adjusted by a thermography measurement and simulates the thermal profile of the junction box. We calculate the diode temperature in dependency of the PV module current. A diode temperature of approx. 100 °C is obtained for a module in failure mode at 9 A.

We find the electrical losses in bypass diodes to be insignificant at normal operation for STC and elevated temperatures. The losses in connection cables and internal wiring within the junction box increase with elevated temperatures but are still low (< 1 W) compared to the power output of common photovoltaic modules.

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