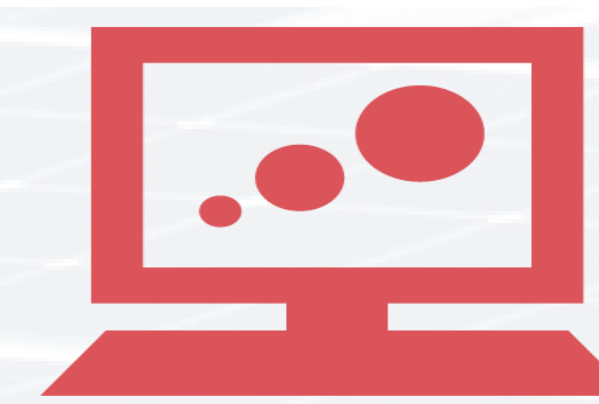




Multi-Scale, Multi-Physics Model

Integrating SPICE and pvlib for Advanced Modeling of PV String Power Losses

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Contributing to DuraMAT Consortium Goals

This work will develop **open-source simulation methods** to simulate real world impact on power loss of cell defects. Using a **quantitative inspection of large EL datasets** cell parameters are estimated for each cell on a string level. These are then used with a integrated circuit simulation tool to **assess the power loss** on a string level.

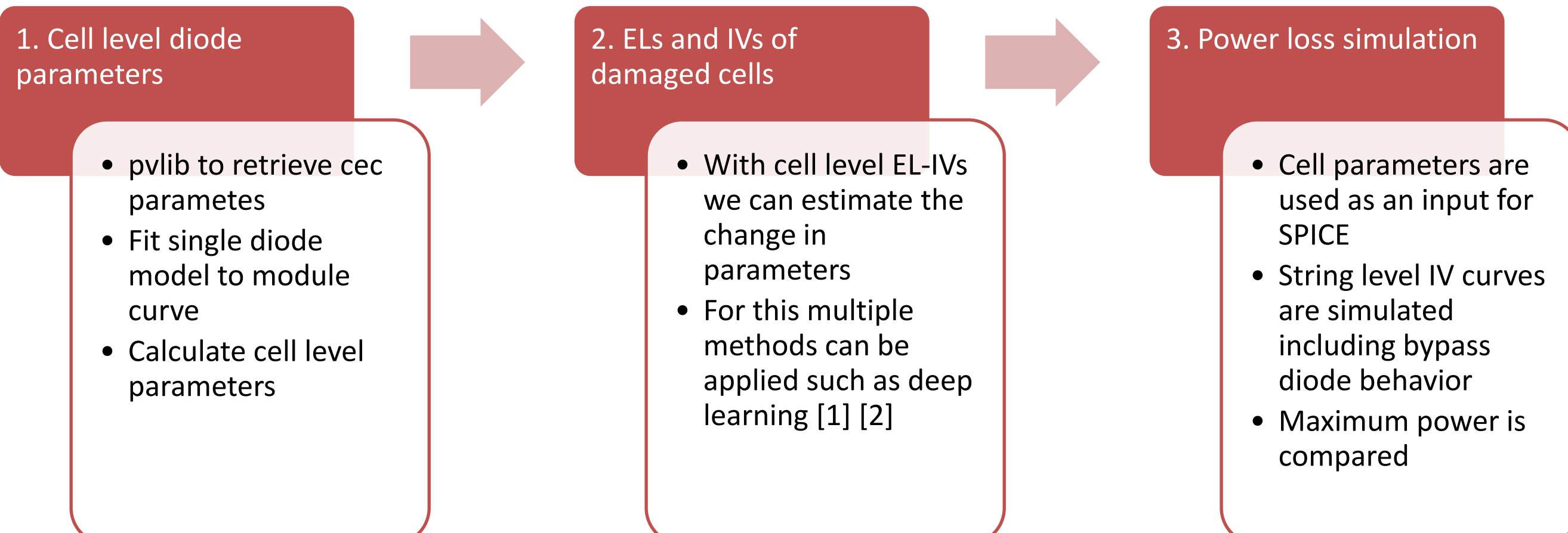
Advanced Modeling of PV String Power Losses

Project Overview

Multiple simulation tools for power modeling are available as open-source or commercial software. The level of detail these tools simulate varies by provider but is mostly limited to string the solar module level. Their goal is to simulate generic normal operation on the plant level. Very generic degradation rates are used for estimating losses. We are working on a tool which is based on electrical circuit simulation (SPICE) to simulate on a solar cell level (diode model) and build the modules and consecutive strings using a python code. Simulating on such a level of detail allows us to modify the diode parameters of each cell according to defects observed in EL images or other sources such as simulated degradations (DuraMAT:pvdeg). A good example is after hail damage occurs, we can use EL images to detect cell cracking in local cells and modify the parameters to simulate the consequences of these damages. These detailed simulations also allow us to incorporate bypass diode behaviors and complex non-uniform shading.

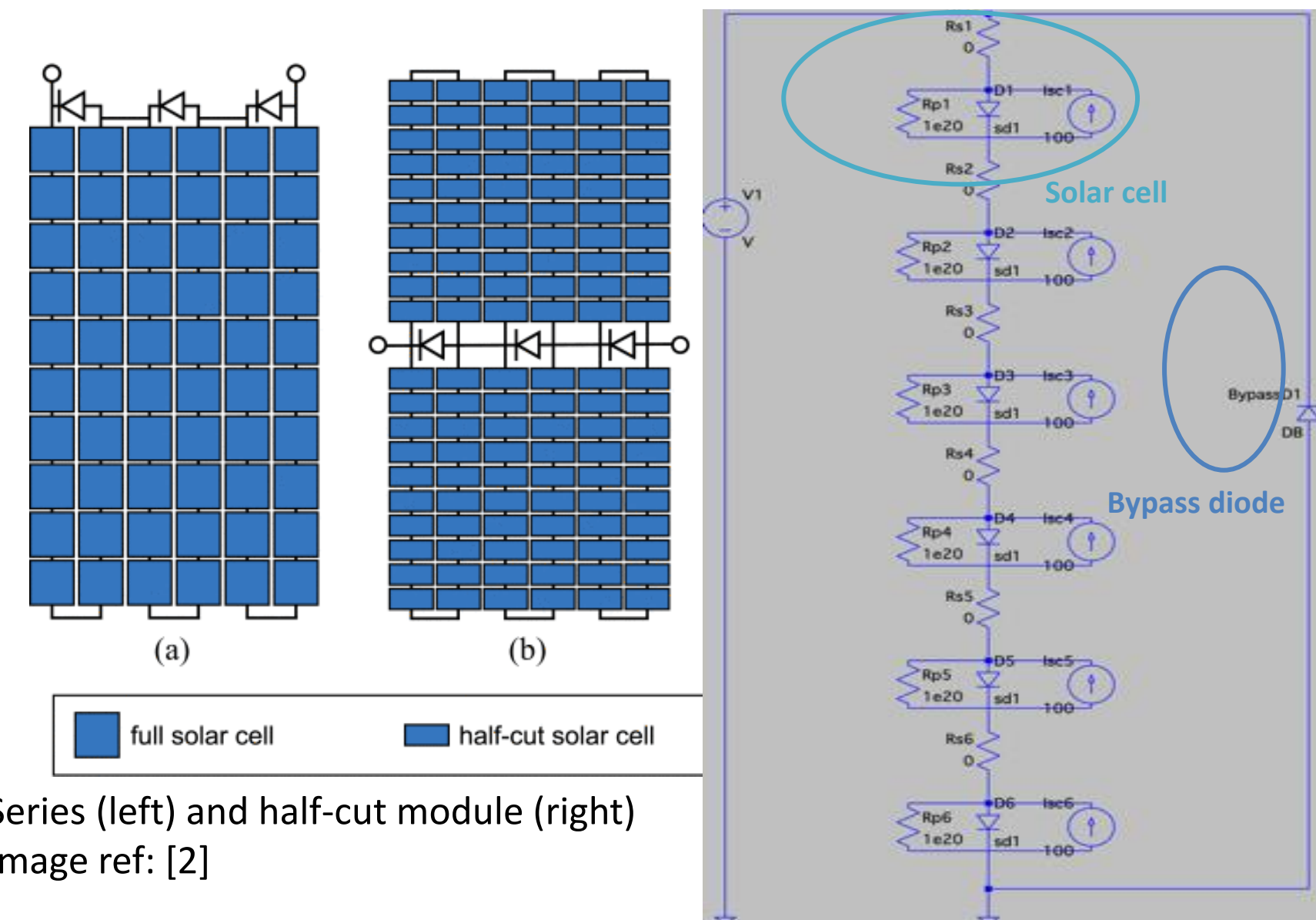
Workflow for string power loss simulations

1. Define initial cell level diode parameters, using pvlib or SPICE
2. From EL images estimate the change of these parameters due to cell damages, observe the distribution of these defects
3. IV curve simulation on a string level by varying statistical and spatial distribution of defects



pvspice

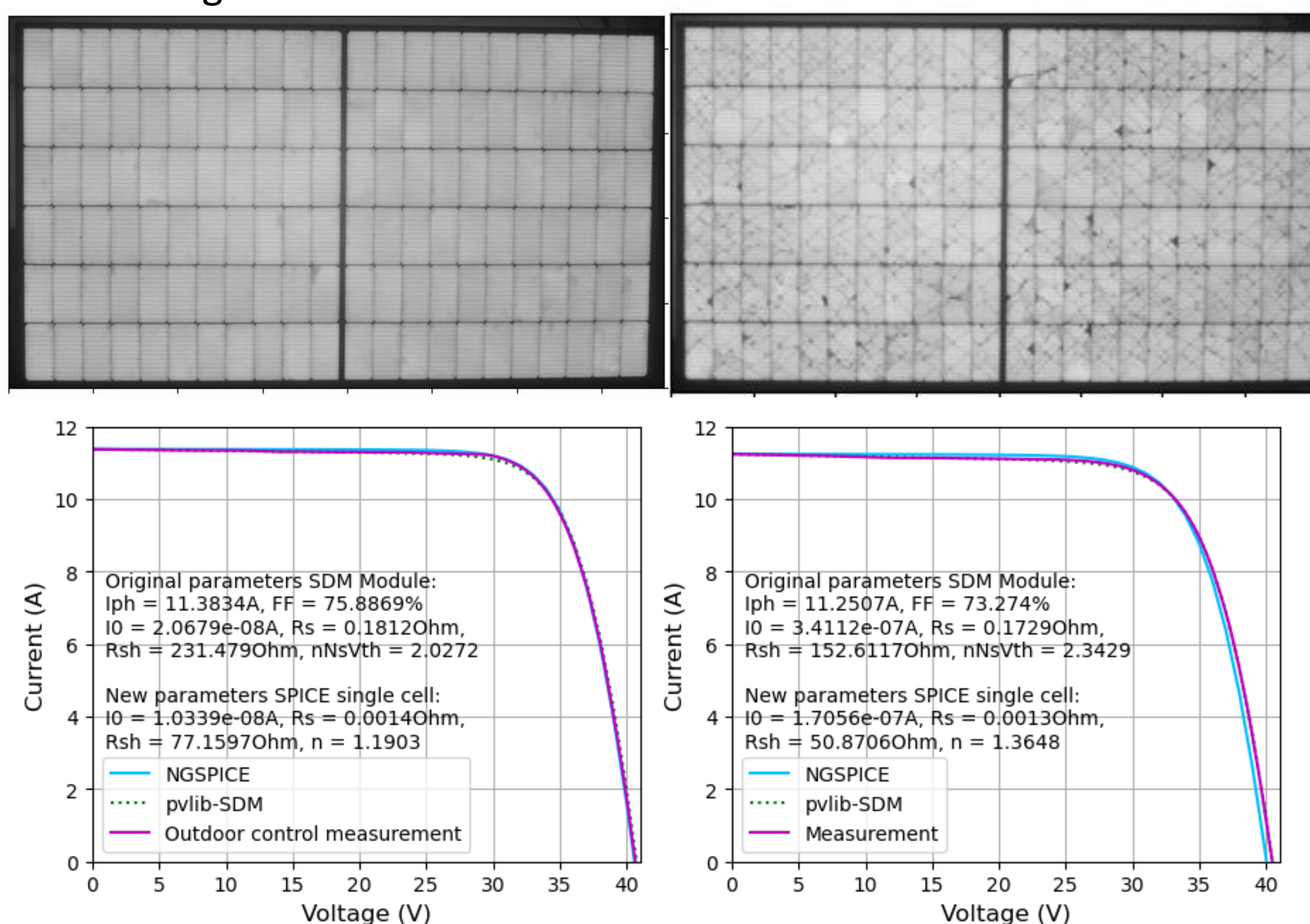
- Based on electrical circuit simulation SPICE
- We start off with the elementary diode model (single diode or two diode) and build the modules and string of modules
- This approach gives us the possibility to change diode parameters on a cell level
- We also have the flexibility to simulate different module architectures like half-cut



SPICE schematic for a 5 solar cell module with bypass diode. For this example LTSpice was used. The single diode model is composed of a diode with saturation current (I_0) and ideality factor (n), a current source with I_{ph} , the series resistance (R_s) and shunt or parallel resistance (R_p , R_{sh}).

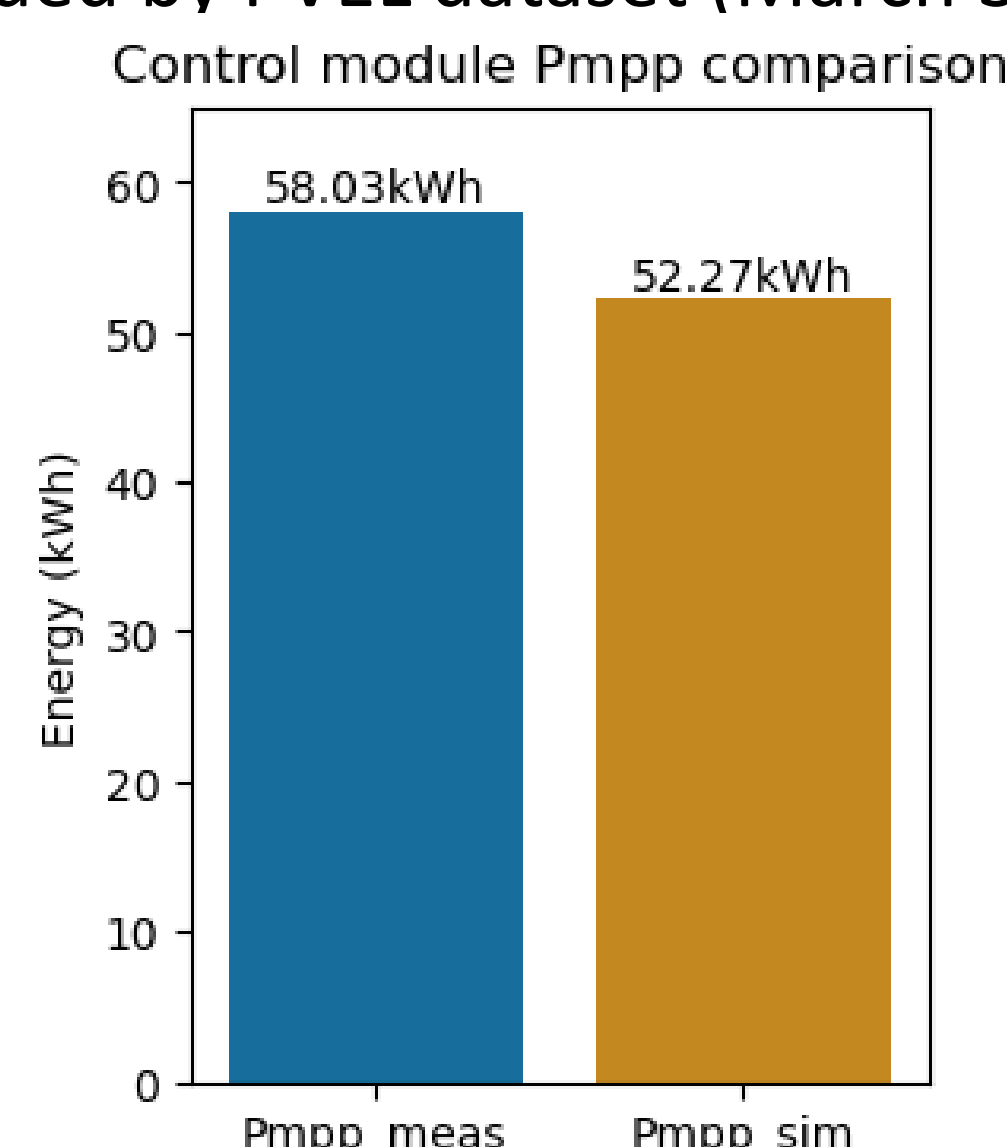
Damaged module parameters

- Cracked half-cut modules made available from Kiwa PVEL as part of their DuraMAT project help us validate the SPICE model
- Solar module IV curves are fitted with the pvlib.sdm model, the parameters are translated to single cell parameters for SPICE modeling



Control module (left) and module with all solar cells showing cracks (right) of the same bill-of-materials. Source: Kiwa PVEL

- High amount of busbars account for just a small loss in FF caused by cracking
- To further validate the simulation we simulate all the timeseries values provided by PVEL dataset (March 30th – April 11th 2024)

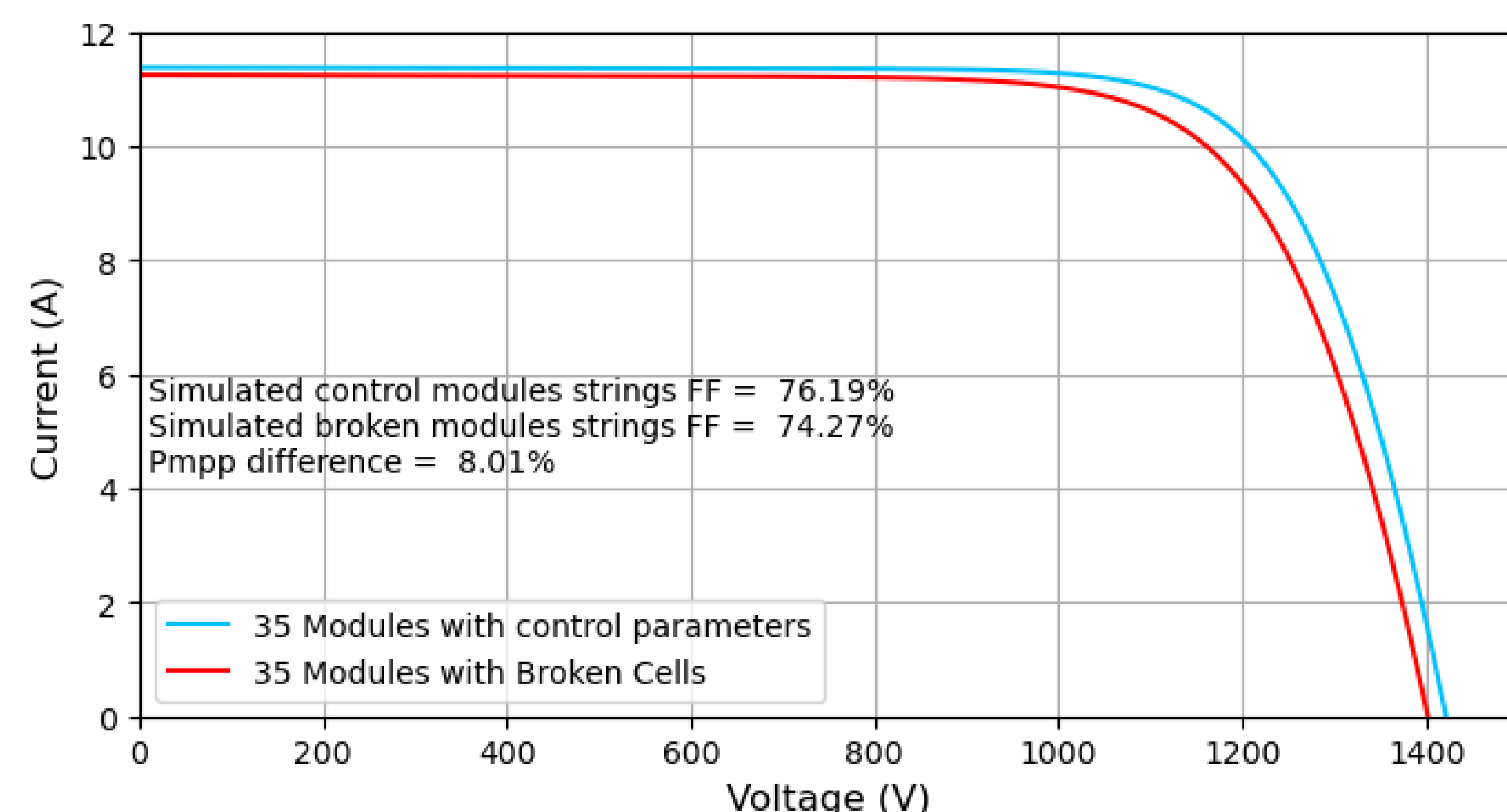


Time series measured module power (Pmp) vs with SPICE simulated power (Pmpp_sim). For the control module on the right and the damaged module on the left.

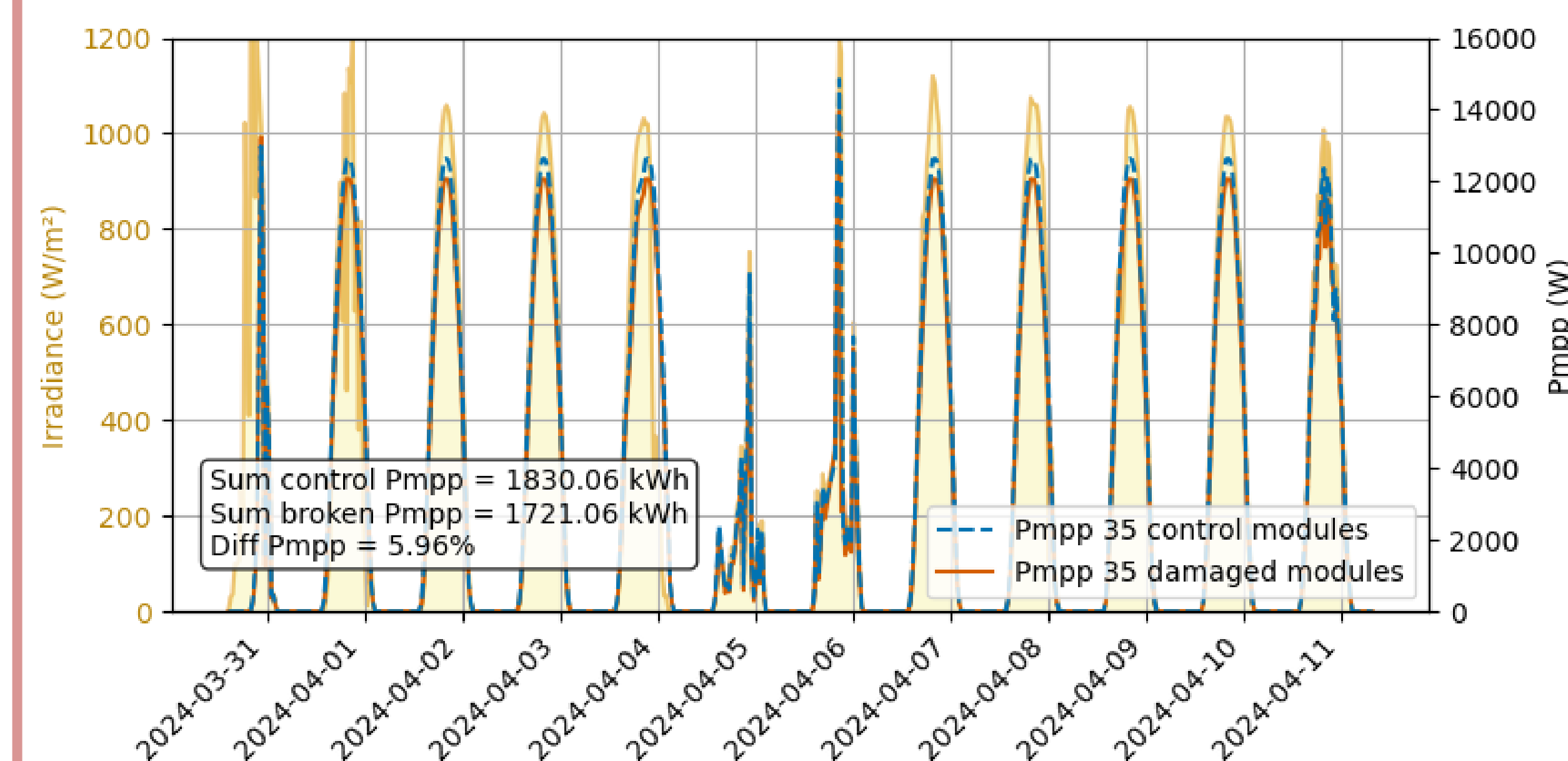
- Looking at the sums we currently have a error of ca. 10% for the control module and 8% for the damaged module
- The error is likely due inaccurate diode parameters and not including the thermal coefficients for voltage and current

Simulating String-Level Power Loss

- We simulate 35 modules in series using the same parameters as from the PVEL modules shown beside. The control module and the module with all broken cells is simulated for ideal conditions. All cells have the same parameters



- The fill factor (FF) of the whole 35 module string reduces ca. 4% and the P_{MPP} difference is 8%
- We proceed with the full time series simulations on a 35 module string level



- **Outlook:** It is important to quantify these differences as the MPP tracking from the inverters could cause further power losses due to the string voltage and current not being the tracking range
- **Next steps:**
 - Currently we do not have any string level data with cracked solar cells to validate
 - Simulate different distributions of defects
 - Defining the SDM parameters must be improved by improving the fits for single cell and module IV curves

References

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- [2] B.K. Byford *et al.*, DOI: 10.1109/IPHOTOV.2025.3562931
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