Limits of the single diode model in view of its application to the latest PV cell technologies

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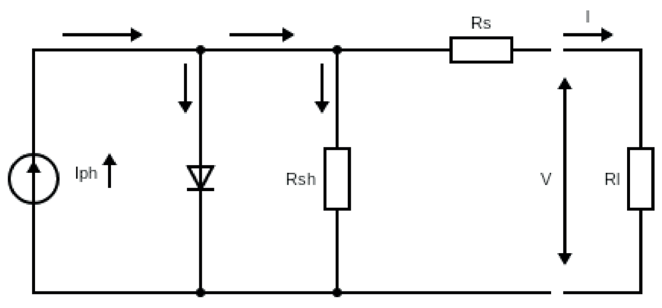
Abstract

The single diode model has been used for PV performance modeling since many years. It can be applied to many different PV technologies, describing accurately the I-V behavior of PV cells and modules as function of irradiance and temperature. The single diode model was validated in the past for many types of PV technology, including crystalline silicon and thin film.
The most recent high efficiency PV modules get to the limits of what the single diode model can describe accurately. The HIT, TOPCon and IBC cells have very high fill factors, which need extreme parameters for the model.
In this study we explore the limits of the single diode model to describe the I-V behavior of PV cells with very high fill factors, which translates to an elevated V_{mpp}/V_{oc} ratio.

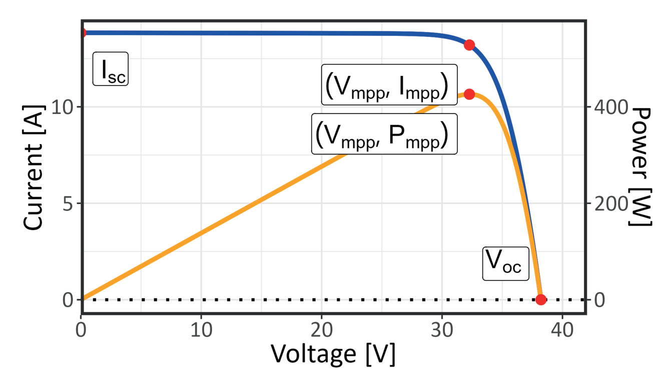
Single diode model



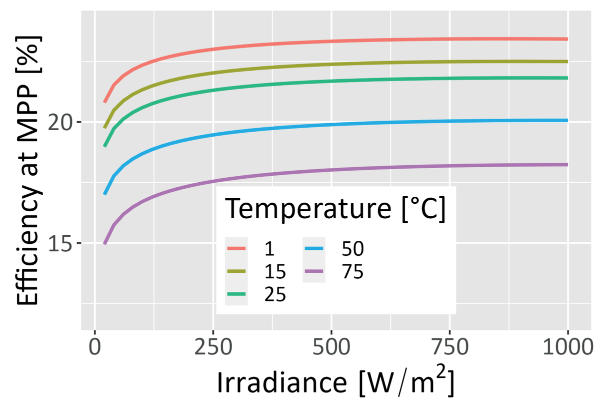
$$I = I_{ph} - I_0\left(e^{\left(\frac{V+I\cdot R_s}{N_{cells}\cdot n\cdot V_{th}}\right)} - 1\right) - \frac{V + I\cdot R_s}{R_{sh}}$$

- I, V : current and voltage in the load
- I_{ph} : photocurrent
- I_0 : diode saturation current
- N_{cells} : no. of cells in series
- R_s : series resistance
- R_{sh} : shunt resistance
- n : diode ideality factor
- V_{th} : Thermal voltage kT/q

Output of single diode model



The model parameters allow to describe IV and PV curves with their characteristic points for I_{sc}, V_{oc} and V_{mpp}, I_{mpp}

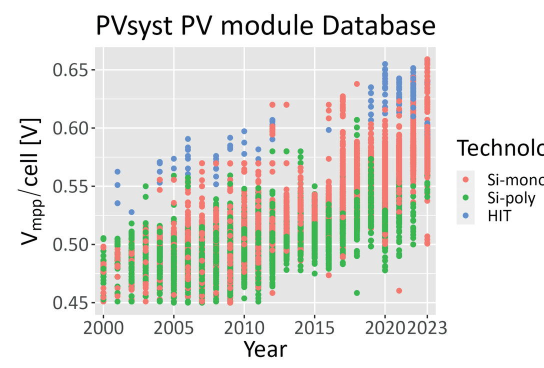


The single diode model describes the PV module behavior at all temperatures and irradiances.

Historical trend of V_{mpp}/N_{cells}

Over time,
- Fill Factor, FF = $(I_{mpp}\cdot V_{mpp}) / (I_{sc}\cdot V_{oc})$ has been increasing,
- I_{mpp}/I_{sc} has been stable,
- V_{mpp}/N_{cells} has been inscreasing faster than V_{oc}

➔ V_{mpp}/V_{oc} increased, but there is an inherent limitation to this ratio in the SDM



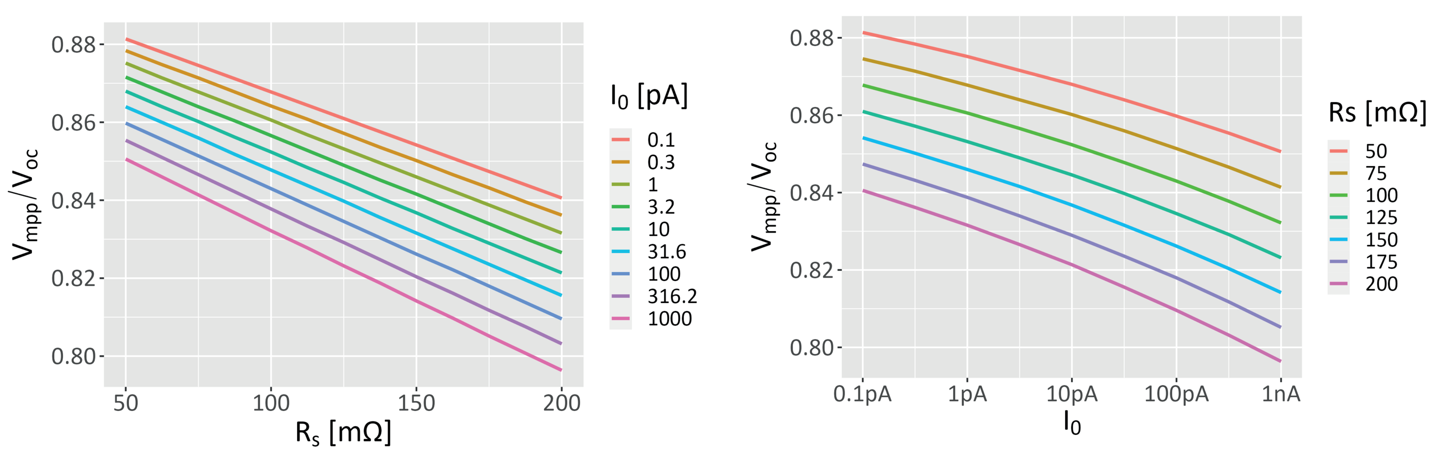
Parameter ranges and constraints

For this study, we vary the single diode model parameters around values corresponding to a typical monocrystalline 426 Wp PV module.
I_{ph} and N_{cells} set the global power of the PV module.
The other parameters will have an impact on the detailed shape of the IV and PV curves.

Example PV module	
I_{ph}	13.84 A
I_0	15 pA
N_{cells}	54
n	1
R_s	120 mΩ
R_{sh}	800 Ω

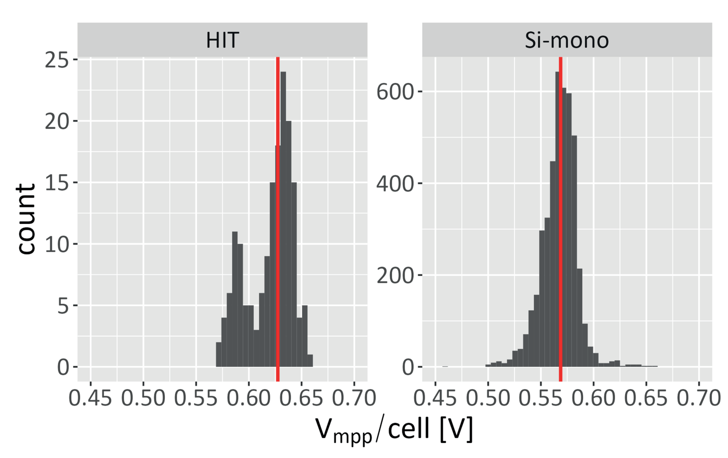
V_{mpp}/V_{oc} dependence on R_s and I_0

In the single diode model, the ratio V_{mpp}/V_{oc} increases with falling R_s and I_0
The dependence is logarithmic for I_0 and almost linear for R_s.



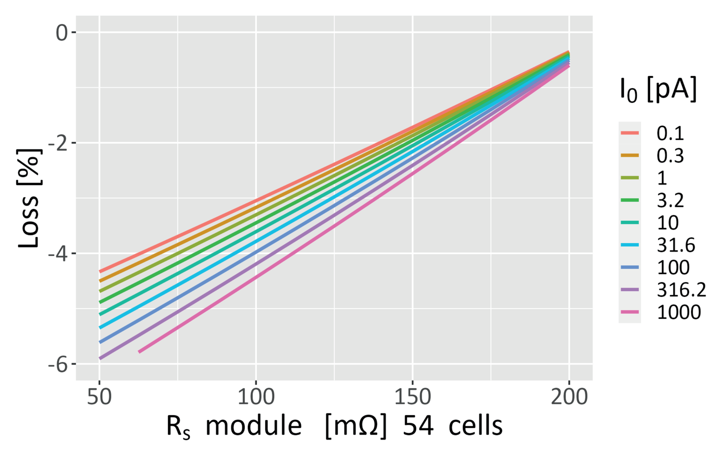
However, changing R_s and I_0 impacts on other results of the one diode model, like V_{mpp}/N_{cells} and the low light efficiency.
A realistic description of a PV module, should make sure that these quantities stay within typical limits.

V_{mpp}/V_{cells}



The value V_{mpp}/N_{cells} does not change much for a given PV module technology. It lies between 0.55V and 0.60 V for monocrystalline Si and between 0.60V and 0.65V for HIT modules.

Low light efficiency

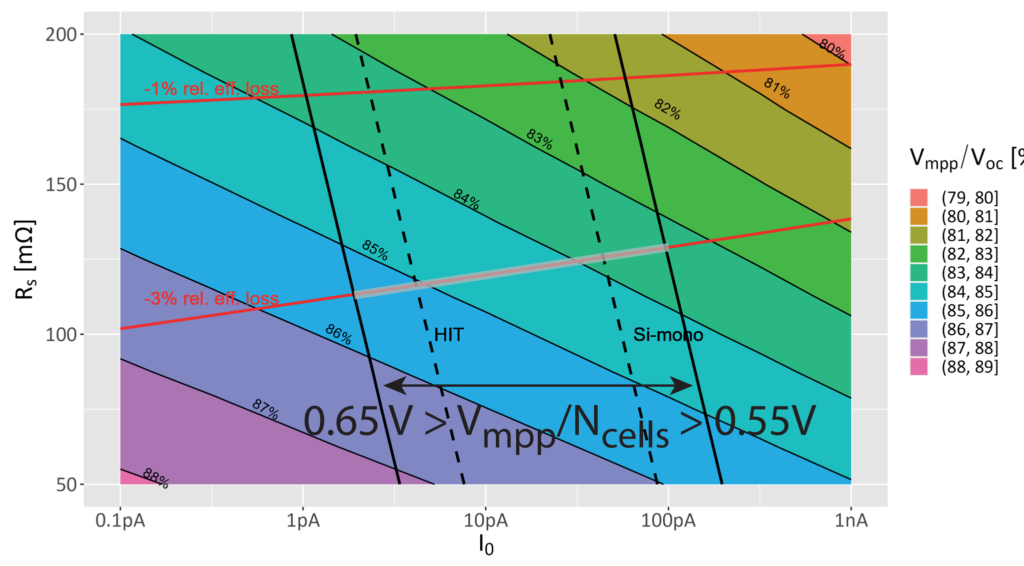


Low light efficiency is driven by R_s.
Typically observed behavior:
- At 200W/m² relative efficiency drops by 3%.
- R_{sh} (200W/m²) = 4 · R_{sh} (STC)

Limits for the ratios V_{mpp}/V_{oc} and I_{mpp}/I_{sc}

Limiting V_{mpp}/N_{cells} and the low light efficiency, to a range of typically observed values, leads also to a limited range for V_{mpp}/V_{oc} and I_{mpp}/I_{sc}

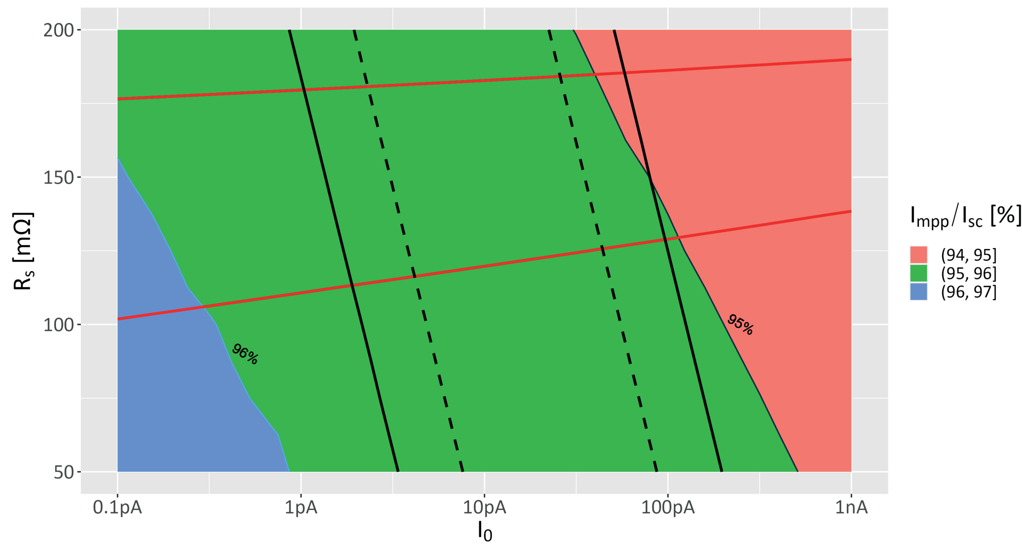
V_{mpp}/V_{oc} | **Important / critical**



For V_{mpp}/N_{cells} between 0.55V and 0.65V and a relative efficiency loss of 3% at 200 W/m2 the ratio V_{mpp}/V_{oc} is limited to values between 83% and around 85%.

The limit at 85% implies very small saturation currents I_0 of a few pA at 25°C. This leads to extremely small saturation currents at low temperatures (around -10°C).

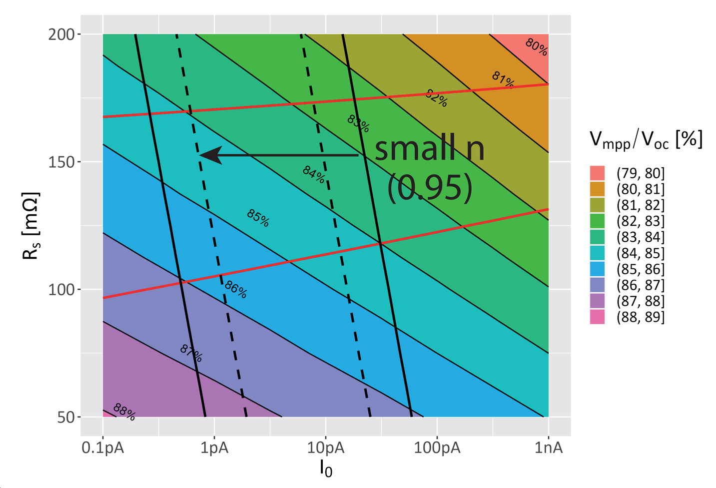
I_{mpp}/I_{sc} | **Not sensitive**



The ratio I_{mpp}/I_{sc} is mainly constrained by V_{mpp}/N_{cells}.
For typical values of V_{mpp}/N_{cells}, the ratio I_{mpp}/I_{sc} stays between 95% and 96%.
This means that I_{mpp} and I_{sc} can have only a marginal impact in increasing the fill factor.

Discussion and perspectives

- Increasing R_{sh} only marginally increases the range to higher V_{mpp}/V_{oc} and I_{mpp}/I_{sc} ratios.
- A small R_s leads to large V_{mpp}/V_{oc} ratios at the cost of a higher efficiency loss at low irradiance.
- The range of possible V_{mpp}/V_{oc} ratios could be increased by choosing values for the ideality factor n <1 and much smaller values for I_0.
  But it is not evident to give a physical interpretation to this.
- In the PVsyst Database, the V_{mpp}/V_{oc} ratio sometimes has to be limited by increasing the V_{oc} values. This ensures a description of the MPP that is consistent with the data sheets.



Summary and Outlook

The single diode model could mathematically describe any fill factor up to unity. However, keeping the behavior of the model within certain physical bounds, limits the achievable V_{mpp}/V_{oc} ratio and thus the fill factor.

Assuming the constraints that V_{mpp}/N_{cells} is limited to values between 0.55V and 0.65V, and that the relative efficiency loss at 200 W/m² is around 3%, the values of V_{mpp}/V_{oc} have un upper limit around 85%. In principle the range of possible V_{mpp}/V_{oc} ratios could be increased by choosing values for the ideality factor n, that are significantly smaller than one. But this becomes difficult to interpret in terms of physics. Increasing R_{sh} only marginally increases the possible range for V_{mpp}/V_{oc} to higher values. A lower R_s leads to a larger V_{mpp}/V_{oc} ratio at the cost of a significant efficiency loss at low irradiance.