Open-source photovoltaic model for early building planning processes: Modeling, application and validation

Laura Maier¹, Michael Kratz², Christian Vering¹, Philipp Mehrfeld¹, Dirk Müller¹
¹RWTH Aachen University, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate, Aachen, Germany
²currently studying at ETH, Zurich, Switzerland

Abstract
Over the last years, interconnected building energy systems (BES) have gained importance. In this context, photovoltaic (PV) systems play an important role as they enable local electricity generation. Their proper sizing is crucial for a sustainable and economically reasonable building operation. Here, simulation models can support practitioners to estimate electricity generation depending on PV plant design. However, there is still need for validated, modular and easy-to-use open-source PV models. We close this gap by developing an open-source Modelica model and validating it with measurement data. Results prove that the model accurately calculates DC power output. The estimation of Ohmic losses would even increase model accuracy. Yet, their integration raises model complexity, which is why they are neglected.

Key Innovations
- Model development with focus on easy handling and accurate results during the planning process
- Validation of open-source PV model with measurements by the National Institute of Standardization (NIST)

Research Implications
When utilizing the PV simulation model at an early planning stage, consider that it tends to overestimate DC power output. Also, always encourage simple model parameterization based on manufacturer data to raise models’ usefulness in practice.

Introduction
Within buildings, a great potential to reduce CO₂ emissions exists. One common solution is to integrate renewable energy sources (RES) into BESs which are called interconnected systems. In this regard, PV systems are a promising technology as they enable sector coupling on the one hand and support local electricity generation on the other hand. In order to exploit the full potential of PV systems, they have to be systematically integrated into the local control system. In this context, the proper sizing of PV modules plays an important role. This decision is made at an early planning stage. However, the optimal sizing of PV systems is challenging due to dynamic boundary conditions such as weather and its interdependencies with the whole BES, i.e. mounting’s influence. In this context, simulation models facilitate the process of estimating future operation of PV modules.

For interconnected BES, Modelica is a promising language, as it is suitable for describing the physical behavior of both thermal and electrical systems. In addition, Modelica enables modular modelling. Yet, none of the researched Modelica PV models cover all of the following aspects:
- Open-source access
- Parameters based on manufacturer data only
- Integration of the mounting’s influence
- Validation based on measurement data

To close this gap, we contribute to a more simplified planning process by applying the following steps:
1. We develop an open-source Modelica PV model for wafer-based cells, which is based on manufacturer data only and is suitable for early stage design.
2. We validate the model with measured data to prove mounting’s influence.

Method
To estimate the PV module’s DC power output, the I-V-characteristic has to be modelled. It describes the position of the maximum power point. This characteristic depends on boundary conditions such as the solar radiation and the cell temperature. Consequently, a simulation model should include a method for calculating the cell temperature, the I-V-characteristic and solar radiation.

I-V-characteristic calculation methods
Empirical as well as physics-based methods exist to calculate the I-V-characteristic. The latter ones are based on physical equivalent circuits and can be further distinguished into single- and double-diode models. For this study, we decide against empirical methods as they are not based on manufacturer data only. Among the physics-based models, numerical and analytical methods exist. The latter lead to slightly less accurate but more robust models. For the physics-based models, the 5p-model is promising. The name arises from the number of unknown variables, which are the photo- and saturation current, series and parallel resistance and a correction factor. The approach represents a reasonable compromise of accuracy, computational effort and simplicity. As the developed model intends to facilitate the early planning process, a quick model with easy parameterization is necessary. This is why we choose the analytical 5p-modelling approach. (Batzelis et al. (2016))
Cell temperature calculation methods
There are several methods to estimate the cell temperature PV modules. Some assume no load conditions only and neglect the influence of wind speed on the convective heat transfer. The wind speed’s influence on DC power output varies with the mounting type. To incorporate different mountings, we implement two cell temperature calculation methods. The first one is a physics-based method by Duffie et al. (2013) and represents a module that is installed open rack. The second approach is empirical and based on studies by King et al. (2005). It corresponds to a mounting close to ground.

Open-source model library
The developed model is integrated into the open-source Modelica model library AixLib (Müller (2016)).

Validation
In order to validate the model, one-minute measurements of the year 2016 by the NIST are taken as a basis (Boyd (2015) and (2017)). The data includes measurements of the DC power, global radiation, ambient temperature and wind speed for two module mountings. Both plants are oriented towards south and consist of mono-silicon modules. The first plant (1152 modules) is installed on the ground (20° tilt) while the second (312 modules) is mounted on a roof (10° tilt).

Results and Discussion
In order to evaluate the model accuracy, we compare the simulated electrical energy of selected days with the measured one. Figure 1 illustrates the simulation’s relative error and root mean square relative error (RMSRE) of 5 representative days. Here, the cell temperature calculation is adapted to the respective module’s mounting. The simulation mostly overestimates the electricity generation. This is caused by effects such as ageing, Ohmic losses (OL) or staining, which are neglected. Apart from that, the highest relative error is observed for the roof system (Sep. 12th) at around 16%.

To understand higher model errors, we compare the roof system’s simulated (blue) and measured (red) DC power for Sep. 12th (see Figure 2). The absolute difference between the data sets increases with rising power output. When also taking into account the OL (red), the model error is decreased to 7%. Here, we estimate the OL using the simulated cell temperature and measured current.

For a simulative OLs estimation, the detailed interconnection of the implemented PV modules has to be known. This information is not necessarily given at an early planning stage and complicates the parameterization. As the plants’ modules’ number and tilt differ and results are accurate overall, we assume model scalability and transferability to comparable installations.

Conclusions
This study presents the validation of a Modelica model for PV modules, which supports practitioners in building planning. A comparison with measured data proves that the model leads to accurate results for two mounting types although it overestimates the power. The integration of OL increases model accuracy. However, their estimation requires detailed information on module connections. As this contradicts the model’s aim to be simple and used at an early stage of planning, OLs are neglected.

Acknowledgement
We gratefully acknowledge the financial support by Federal Ministry for Economic Affairs and Energy (BMWi), promotional reference 03ET1619B.

References