Solar Energy Materials and Solar Cells 181 (2018) 38–45

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Modelling of flexible thin-film modules for building and product integrated photovoltaics

N. Bednar[a,*], A. Caviasca[b], P. Sevela[c], N. Severino[a], N. Adamovic[a]

[a] Technische Universität Wien, Institute of Sensor and Actuator Systems, Gusshausstrasse 27-29, A-1040 Vienna, Austria
[b] SIARQ Advanced Solar Design, Avenida Diagonal 523, 08029 Barcelona, Spain
[c] University of Innsbruck, Technikerstraße 13, A-6020 Innsbruck, Austria

ARTICLE INFO

Keywords:
Thin-film
Flexible modules
Modelling
BIPV
PIPV

ABSTRACT

In this work we present a simulation of performance of curved thin-film modules for building and product integrated photovoltaic applications. Flexibility of design and possibility of achieving irregular shapes is important feature in these markets. The photovoltaic module model presented in this work is based on a coupled two-step model. The first 1D model describes the technology and outputs device current density in dependence of voltage, temperature, illumination, etc. The second 3D model uses this data as one of its inputs, and describes size, shape and interconnection of the individual cells within the curved flexible module. In this way power production of such photovoltaic system can be assessed in reasonable time and computing resources. Two study cases are presented: a dome shaped solar street lamp and a conic shaped active rooftop shading for a skylight.

1. Introduction

The demand for aesthetically and flexible integrated photovoltaic (PV) materials is increasing steadily in many industries. Developing markets such as sustainable housing, temporary building structures, outdoor activities, electro-mobility and mobile computing will drive the demand for decentralized energy solutions.

Although the crystalline silicon PV still has a dominant market share, there are some applications in which the use of thin-film PV technology is preferable. These applications mostly exploit the flexibility of the design of thin-film PV modules (such as arbitrary shapes and sizes, as well as bendability), which provides better integration possibilities.

Rectangular shaped modules are unmatched in achieving the highest efficiency, but the possibility of having PV module of different shapes is desirable for the applications in products from creative industry, such as building integrated photovoltaics (BIPV) and product integrated photovoltaics (PIPV), where besides the pure efficiency one must take care of the overall product design and visual appeal [1].

There are only few papers describing simulation of curved PV modules. These works include triangular parametrization and optimization of curved modules [2,3] and a recent analytical model using geometric parameters of curvature and sun positions [4].

This work we present a simulation of performance of curved thin-film modules used in BIPV and PIPV applications. Two study cases are presented: a solar street lamp and an active shading for a skylight.

2. Approach and techniques

In this work we use a combined 1D/3D model of a photovoltaic module (Fig. 1) [5]. The one-dimensional material (device) level model describes the physical processes in solar cell, such as generation, transport and recombination of carriers. The three-dimensional module level model describes the geometry and bending shape of the whole solar module and enables the estimation of power generation. The simulations based on the two models are run sequentially, as the resulting J-V curve of the 1D model is used as an input data in 3D model. In this way it is possible to simulate much larger surfaces than with one 3D model which would describe both material and module level.

Simulations based on the 1D material model were carried out using SCAPS-1D simulation software [6]. It is a widely used simulation software, which provides a good agreement between simulated and experimental data [7,8]. Dark and illuminated J-V curves, as well as external quantum efficiency, fill factor and other key cell performance attributes were obtained by the simulation using solar spectra calculated upon positions of the Sun and module in particular times of day.

The baseline set of parameters used for the simulations was based on $Cu(In,Ga)Se_2$ (CIGS) technology with the following stack of layers: Mo (800 nm) / CIGS (2000 nm) / CdS (70 nm) / ZnO: i (100 nm) / ZnO:Al (330 nm) on a flexible polyimide substrate. The baseline

* Corresponding author.
E-mail address: nikola.bednar@tuwien.ac.at (N. Bednar).

https://doi.org/10.1016/j.solmat.2017.12.035
Received 30 August 2017; Received in revised form 20 November 2017; Accepted 19 December 2017
Available online 06 January 2018

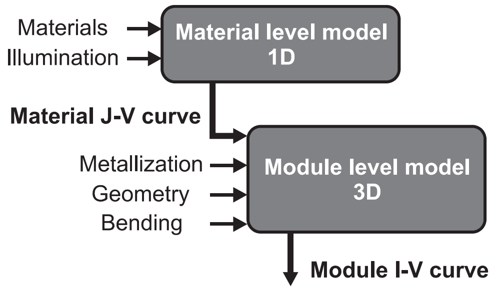

Fig. 1. Diagram of simulation flow based on the hybrid model.

parameters of all the cell layers are taken from the literature [9–12]. Additionally, an encapsulation barrier was considered on top of the device layers stack. The encapsulation was modelled by application of a spectral filter on the illumination levels reaching the device.

This CIGS technology with lower performance has been chosen to prove that it is satisfactory to use it in the intended applications. Also in BIPV and PIPV applications it is often necessary to satisfy the appearance demands. Therefore, encapsulants with embedded color particles could be used [13], which on the other hand reduce the efficiency of solar cells by filtering out a portion of incoming photons. However, the chosen technology is not the limiting factor since other thin-film technologies could be simulated using this model.

In the second step, the simulations on the module level were carried out using finite element method (FEM) COMSOL Multiphysics software package [14]. This step is used to simulate the lateral electrical current flow (in the plane parallel to the surface of the cell), which causes addition of serial resistances in the solar cell. The geometry of the model consists of two layered top electrode, as presented in Fig. 2. The first layer is transparent conductive oxide (TCO), here combination of ZnO: i and ZnO: Al, which possesses good transparency in the visual spectrum [15], but with limited conductivity. The conductivity of the top electrode is increased by adding an opaque metallic grid, which on the other hand creates shading losses by reflecting a number of incoming photons. One of the uses of this simulation step is to optimize the metallic grid in order to find the compromise between electrical and shading losses which results in the highest cell efficiency [5].

The simulation of curved PV cells is enabled by introduction of a scaling factor to an equivalent flat module with the same dimensions, which is then applied on the transversal photo-current, scaling it in dependence of the illumination level of each point along the curved PV module's surface. The tilt and azimuth angles of the equivalent flat module are chosen to be median values of the curved module (or of the part of the module, if the module model is divided in several parts).

Sun positions and insolation levels were calculated using the procedure described in [16]. The incoming light intensity on a module with an arbitrary tilt and orientation can be calculated as

$$S_{MODULE} = S_{INCIDENT} \cos\gamma = S_{INCIDENT} \cdot \vec{S} \cdot \vec{N}, \quad (1)$$

where γ is the angle between the unit vector towards the Sun (***S***), and the unit vector normal to the surface of the module (***N***). Also it can be

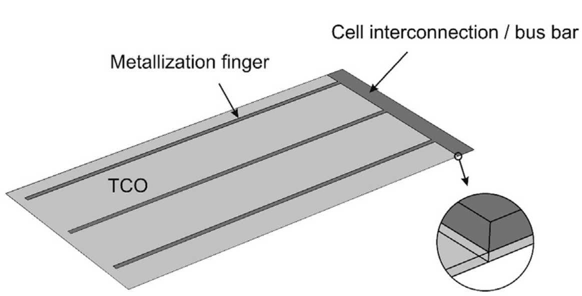

Fig. 2. Geometry of the 3D model – TCO and metallization lines.

written

$$S_{MODULE} = S_{INCIDENT} [\cos\alpha \sin\beta \cos(\Psi - \Theta) + \sin\alpha \cos\beta], \quad (2)$$

where S_{MODULE} and S_{INCIDENT} are the light intensities on the module and of the incoming light, α is the Sun elevation angle, β module tilt angle ($\beta = 0^\circ$ for module flat on the ground, and $\beta = 90^\circ$ for vertical module), Θ is the Sun azimuth angle ($\Theta = 0^\circ$ corresponds to North) and Ψ is module azimuth angle.

Flexible modules are exposed to higher mechanical stress, compared to rigid ones. Straining of modules due to mechanical stress in a bent shape could cause degradation of photovoltaic device. The main reason for mechanical stress induced degradation could be explained by damaging of contacting layers, which leads to increase in the series resistance of the device [17]. It was found out that degradation of efficiency caused by bending is much less pronounced in the CIGS cells fabricated on polyimide substrate, than in the devices on ultra-thin glass substrates due to better matching coefficients of thermal expansion of the substrate and CIGS layer [18]. The straining of materials in a bent shape is also related to the position of the neutral axis of the structure (the line along the structure profile where neither compressive nor tensile strain is induced) [19]. Therefore, the strain in the thin-film photovoltaic device can be greatly reduced by choosing front and back sheets of appropriate thickness in order that the thin-film cell itself is as close as possible to the neutral axis of the laminated device.

This work presents simulation of two study cases with the integrated curved PV modules: a solar street lamp “Solar Hub” and a shading for a skylight “Innsbruckoid”. Both study cases demonstrate the implementation of flexible photovoltaic panels in real-life products.

2.1. Solar street lamp “Solar Hub”

The first prototype presents a highly energy-efficient compact solar street light for urban environments. The lamp possesses a dome-like structure (Fig. 3), with PV modules covering the whole dome (except the top). The diameter of the dome is 82 cm. LED lighting system is embedded on the bottom of the device, and all the rest of the components (battery, electronics, etc.) are concealed within the dome. This design enables the power generation during the whole daytime period and also utilizes the diffused light. The shape of the lamp favors lower Sun positions, while the power collection is more critical in wintertime.

The presented simulation approach was used to estimate the daily power yield of the prototype in order to design the system to be fully self-sufficient.

A battery intended to be used in this application could provide

Fig. 3. Solar street lamp – “Solar Hub” (designed and developed by SIARQ Advanced Solar Design).