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PERFORMANCE OF DIFFERENT PHOTOVOLTAIC MODELS IN *ENERGYPLUS* ENVIRONMENT

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Abstract*:* *Zero net energy building uses photovoltaic (PV) panels for electricity generation from solar energy. To calculate the annual electricity generation, the EnergyPlus software is used. The EnergyPlus software contains three models of PV panels: Simple, Equivalent One-Diode and Sandia. It is important to determine behavior of these models during calculation at different conditions. The objective of this paper is to compare the PV energy output of these models in EnergyPlus environment.*

Keywords*:* *PV panels, models of PV panels, software EnergyPlus*

1. INTRODUCTION

Photovoltaic energy conversion is widely considered as one of the more promising renewable energy technologies which has the potential to contribute significantly to a sustainable energy supply and which may help to mitigate greenhouse gas emissions. Commercial PV materials commonly used for photovoltaic modules include mono-crystalline silicon, multi-crystalline silicon, amorphous silicon and thin film technologies, such as cadmium-telluride (CdTe) and coper indium diselenide (CIS). A typical PV system consists of the PV module and the balance of system (BOS) structures for mounting the PV modules and converting the generated electricity to alternate current (AC) electricity of the proper magnitude for usage in the power grid [1].

Photovoltaic performance models are used to estimate the power output of a photovoltaic system, which typically includes PV panels, inverters, charge controllers and other BOS components. The PV arrays with their support are located at the house roof and connected to the national electricity network and/or the house. From solar energy, the PV array produces the DC electricity sent to the inverter where it becomes AC electricity. This AC electricity is either spent by the house and/or purchased by the national electricity network. In each moment, different amounts of the electricity are produced by the PV array and consumed by the residence and/or by the national electricity network. These models create a generation profile based on a specific geographic location which helps determine how much solar irradiance is available for harvesting. The meteorological inputs for any given location vary by latitude, season and changing weather patterns; being able to accurately determine the generation profile due to these changing variables results in better matching of system load with expected generation. Some models make general assumptions about system components and ratings while other more complex models take into account manufacturer parameters, derived parameters and empirically derived data [2].

From an electrical point of view, PV modules are characterized by their current vs. voltage curve, commonly called I-V curve. The power delivered by the module is the product of its voltage and current, so it has to be known the operating point (i.e. voltage and current) of the module to determine the energy produced. The modeling of PV module primarily involves the approximation of the non-linear I–V curves. Throughout the years, a number of models were developed [2,3,4].

EnergyPlus is a whole-building energy analysis software program being developed by the U.S. Department of Energy. This softver is a very useful tool to investigate the behavior of the net-zero energy buildings. It offers three different models for predicting the electricity produced by photovoltaics. The simple model allows the user to input arbitrary conversion efficiencies. The other two models use empirical relationships to more accurately predict PV operating performance based on conditions such as incident radiation and cell temperature [5].

This paper analyzes different photovoltaic models, and their behavior in EnergyPlus environment.

2. SIMULATION SOFTWARE - *ENERGYPLUS*

In this study, the simulation software EnergyPlus (Version 7.0) was used. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA [5]. Its development began in 1996 on the basis of two widely used programs: DOE-2 and BLAST. The software serves to simulate building energy behavior and use of renewable energy in buildings. The renewable energy simulation capabilities include solar thermal and photovoltaic simulation. Other simulation features of EnergyPlus include: variable time steps, user-configurable modular systems, and user defined input and output data structures. The software has been tested using the IEA HVAC BESTEST E100-E200 series of tests [6].

The EnergyPlus PV module includes three different models referred to as “Simple”, “Equivalent One-Diode” and “Sandia” and the choice will determine the mathematical models (and input data) used to determine the energy produced by solar/electric conversion panels. The EnergyPlus photovoltaic array models are called one at a time at the HVAC system timestep along with other electrical generation components such as gas turbines and diesel engines.

3. MATEHEMATICAL MODEL

EnergyPlus offers three different models for predicting the electricity produced by photovoltaic. Energy production is based on the assumption that the quasi-steady power prediction is constant and continuous over the simulation timestep. The choice of model determines the mathematical algorithm used to calculate electric energy production. The Simple model allows the user to input arbitrary conversion efficiencies. Equivalent One-Diode and Sandia model use empirical relationships to more accurately predict PV operating performance based on conditions such as incident radiation and cell temperature.

4.1 Simple model

This model is the simplest one for predicting photovoltaic energy production. In this model the user specifies the efficiency with which surfaces convert incident solar radiation to electricity. In the other models this efficiency is determined as part of the model. The full geometric model for solar radiation is used, including sky models, shading, and reflections, to determine the incident solar resource. The model accepts arbitrary conversion efficiencies and does not require actual production units be tested to obtain empirical performance coefficients.

The electrical power produced by a PV surface is calculated using:

$$P = A_{surf} \cdot f_{activ} \cdot G_T \cdot \eta_{cell} \cdot \eta_{invert} \qquad (1)$$

where A_{surf} is net area of surface in m^2, f_{activ} is fraction of surface area with active solar cells, G_T is total solar radiation incident on PV array in W/m^2, η_{cell} is module conversion efficiency and η_{invert} is DC to AC conversion efficiency. On the right hand side of this equation, only GT is calculated by EnergyPlus and the rest are user inputs. Power levels are assumed constant over the timestep to arrive at energy production.

4.2 Equivalent One-Diode Model

The equivalent one-diode model is a four-parameter empirical model to predict the electrical performance of crystalline (both mono and poly) PV modules. The model was developed largely by Townsend (1989) and is detailed by Duffie and Beckman [7]. Originally developed as a component for the TRNSYS program by Eckstein [8], it was ported to EnergyPlus in Version 1.1.1 by Bradley (UIUC & LBNL 2004). The model simulates a PV module with an equivalent circuit consisting of a direct-current source, diode, and one or two resistors. The strength of the current source is dependent on incident solar radiation. The current-voltage characteristics of the diode depend on the temperature of the solar cells: the hotter the module, the lower its electrical output. The model determines current as a function of load voltage. Other outputs include current and voltage at the maximum power point along the current-voltage curve, open-circuit voltage, short-circuit current as well as electrical load met and unmet. The EnergyPlus implementation employs the Eckstein model for crystalline PV modules, using it whenever the short-circuit current-voltage slope is set to zero or a positive value as modified by Ulleberg [9]. The model automatically calculates parameter values from commonly available data, such as short-circuit current, open-circuit voltage, current at maximum power, etc.

The four-parameter equivalent circuit is shown in the following figure:

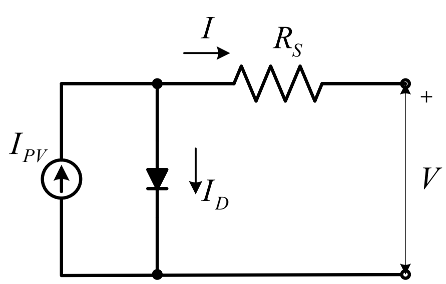

Fig. 1. Equivalent circuit with series resistance

The output current can be derivate as:

$$I = I_{PV} - I_0 \left[\exp\left(\frac{V}{aV_T} \right) - 1 \right] \qquad (2)$$

where I_{PV} is the current generated by the incidence of light, I_0 is the reverse saturation current, $V_T = N_S\, kT/q$ is the thermal voltage of the PV module having N_S cells connected in series, q is the electron charge (1.60217646×10^{-19} C), k is the Boltzmann constant (1.3806503×10^{-23} J/K), T is the temperature of the p-n junction in K, and a is the diode ideality factor.

4.3 Sandia model

The third model available in EnergyPlus for predicting the electricity generated by photovoltaics is referred to as the Sandia model. This model is based on work done at Sandia National Lab, Albuquerque, NM by David King [10] with the help of many others. The model consists of a series of empirical relationships with coefficients that are derived from actual testing. Once the coefficients for a particular module are available, it is straightforward matter to use the model equations to calculate five select points on the current-voltage curve. Although the implementation in EnergyPlus assumes that the module only operates at the maximum power point, four other points on the current-voltage curve are calculated and reported so that data are available for analyses outside of EnergyPlus. Since performance depends on cell temperature, there are two modes for predicting the back-of-module temperature. One is appropriate for most rack-mounted PV installations and calculates the cell temperature in isolation. The other mode is appropriate for building integrated applications and obtains the back-of-module temperature from the exterior surface heat balance and is discussed below. Like the equivalent one-diode model, the Sandia model predicts the performance of a single PV module. The performance of an array of identical modules is assumed to be linear with the number of modules in series and parallel. Inverter efficiency can be applied to derate the energy production. An inverter capacity forms a limit for power production from a PV system. The implementation in EnergyPlus is also based on work done by Greg Barker [11] for the National Renewable Energy Lab who implemented the Sandia model in FORTRAN77 as a custom type (Type101) for the TRNSYS computer program. There are several climate and solar orientation inputs to the model that are managed elsewhere in EnergyPlus including: incident beam solar, incident diffuse solar, incidence angle of beam solar, solar zenith Angle, outdoor dry bulb, wind speed, and elevation.

5. RESULTS AND DISCUSION

5.1 Research object

The analyzed building is a residential family house shown in Fig. 2. The building is designed for one family and has a living area of 190.08 m^2. The envelope of the building is made of 190 mm porous brick, 50 mm thermal insulating layer and 20 mm lime mortar. The U-value is 0.57 W/(m^{2}K). The windows are double glazed with U-value of 2.72 W/(m^{2}K). The overall ratio of glass to the exterior walls is 7.32%, where the total area of exterior walls is 264.35 m^2 and area of windows 19.36 m^2.

The PV system is installed in a residential house, [12]. The house has the south-oriented roof with the angle 37.5°. The roof has total area 119.6 m^2 and it is divided in two segments – first one with the possibility of PV array installation (total area of 82 m^2) and the other one with total area of 37.6 m^2.

The house location is in Kragujevac, so the weather file used in simulation is for Kragujevac, Serbia.

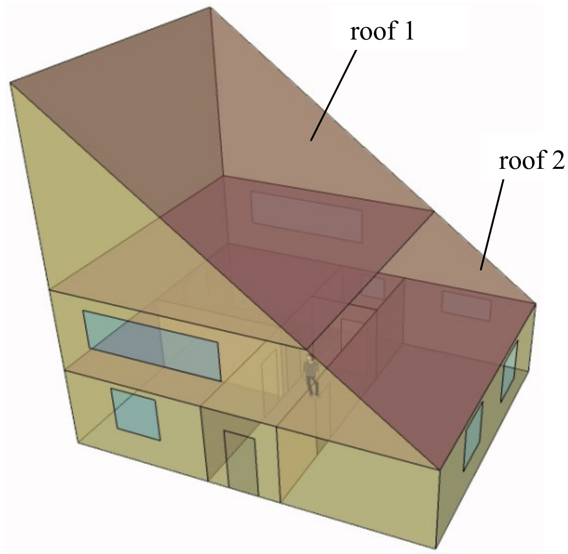

Fig. 2. Modeled residential house

5.2 Simulation results

Three different models of PV panels are analyzed - Simple, Equivalent One-Diode and Sandia.

Performance for Simple model considered in this study is presented in Table 1.

Table 1. *PV performance for Equivalent Simple Model*

Net area of surface	82 m^2
Fraction of surface area with active solar cells	0.0077
Cell efficiency	14.5 %
DC/AC conversion efficiency	1

DC/AC conversion efficiency is selected with maximum efficiency, because only PV performances are analyzed in this paper.

Performance for Equivalent One-diode model and for Sandia model considered in this study, are presented in Table 2 and Table 3 respectively. Detailed list of coefficients and Database parameters for these models is given in [5].

Table 2. *PV performance for Equivalent One-Diode Model*

Cell type	CrystallineSilicon
Number of cells in series	36
Active area	0.63 m^2
Transmittance Absorptance Product	0.9
Semiconductor Bandgap	1.12 eV
Shunt resistance	1000 KΩ
Short circuit current	4,75 A
Open circuit voltage	21,4 V
Reference Temperature	25^o C
Reference Insolation	1000 W/m^2
Module current at Maximum Power	4.45 A
Module voltage at Maximum Power	17 V

Table 3. PV performance for Sandia Model	
Name	BP Solar BP275
Number of cells in series	36
Number of cells in parallel	1
Active area	0.63 m^2
Short circuit current	4,75 A
Open circuit current	21,4 V
Module current at Maximum Power	4.45 A
Module voltage at Maximum Power	17 V
Diode Factor	1.38

In this paper PV energy outputs of three different models are compared in EnergyPlus environment. Total Electric Energy Produced represents the total photovoltaic electricity produced on-site for the entire model.

Fig. 3 represents the total electric energy produced, in MJ, for different types of PV models, calculated by EnergyPlus for each month in the year. Obtained results for models considered in this study are very similar, with small differences from month to month. Total electric energy produced for each model of photovoltaic array rapidly increases from March to august, and after that it decreases, from September to February.

Fig. 4 shows the yearly total electric energy produced, in MJ, for different types of PV models, calculated by EnergyPlus. According to the previous figure, Simple PV model and Sandia model give the little higher values for total electric energy produced, than Equivalent one-diode model.

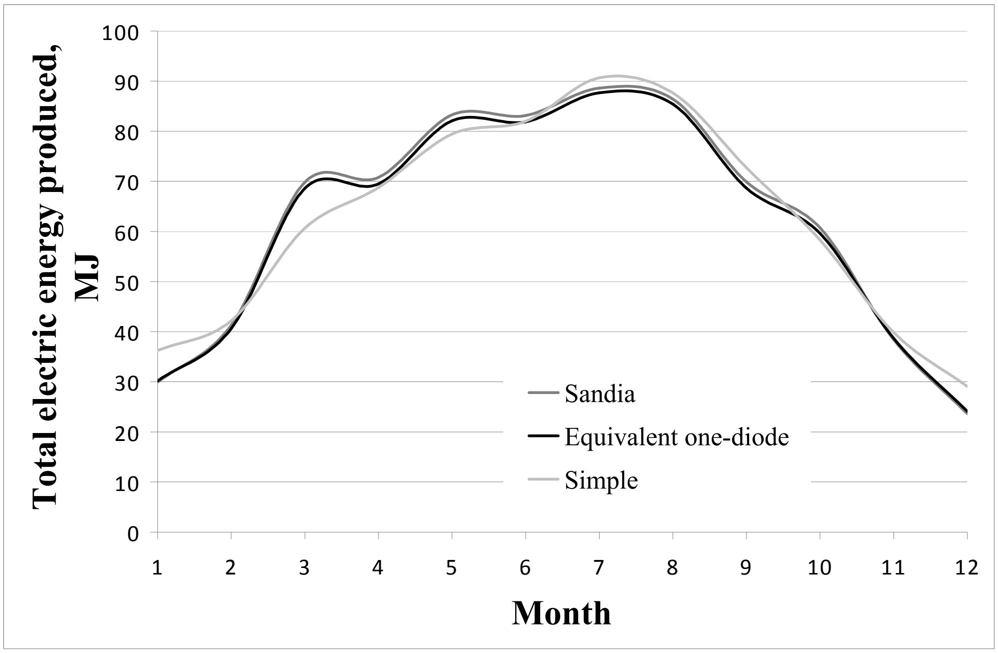

Fig. 3. Total electric energy produced for different PV models, calculated by EnergyPlus for each month in the year

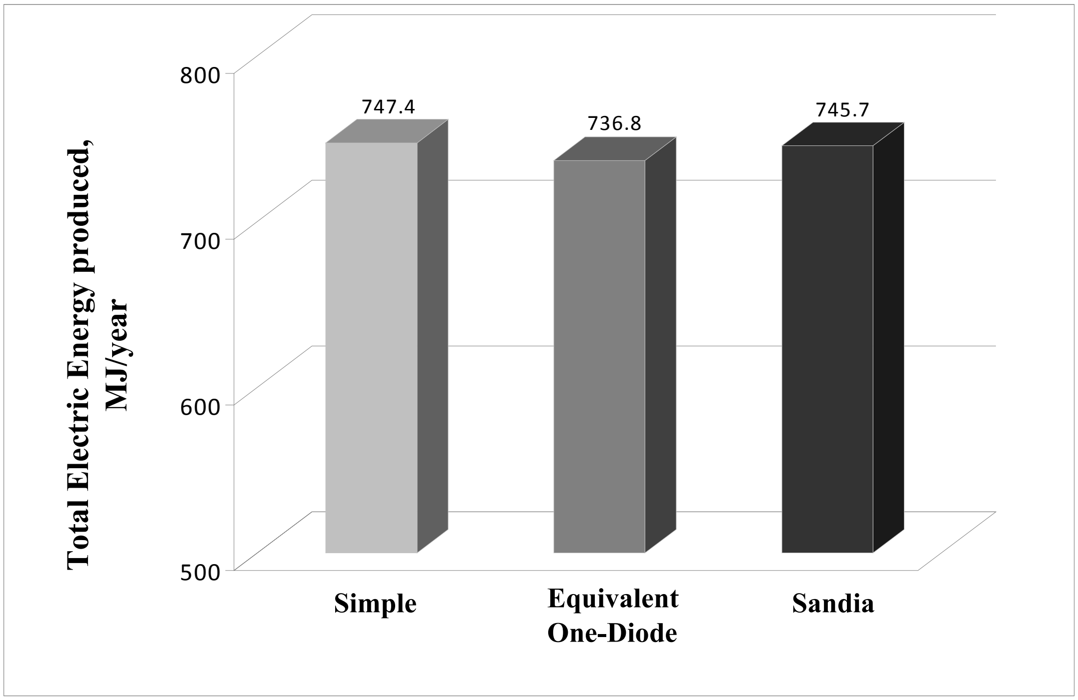

Fig. 4. Yearly total electric energy produced for different PV models, calculated by EnergyPlus

6. CONCLUSION

This paper compares the energy output of three different types of PV panels (Simple, Equivalent One-Diode and Sandia) in EnergyPlus environment. Obtained PV energy outputs for these models are quite similar. This software has great capabilities for modeling buildings energy behavior and use of renewable energy in buildings. By using the EnergyPlus software with it outputs, the building designers can define the optimal value of PV panels for every building, according to the electric consumption.

LITERATURE

[1] Radulovic, J. J., M., Bojic, J., Skerlic, D., Nikolic, D. Taranovic, Energy generation and CO_2 emissions of PV systems, 6th International Quality Conference, Faculty of Engineering, University of Kragujevac (2012) 802–808.

[2] Klise, G. T., J. Stein, Models Used to Assess the Performance of Photovoltaic Systems, Sandia report, SAND2009-8258, Sandia Nacional Laboratory(2009) 1–61.

[3] Thevenard, D., Review and Reccommendations for improving the modeling of Building Integrated Photovoltaic Systems, Ninth International IBPSA Conference Montréal**,** Canada August 15-18, (2005), 1222-1228.

[4] Kashif, I., Z., Salam, An improved modeling method to determine the model parameters of photovoltaic (PV) modules using differential evolution (DE), Solar Energy, 85 (2011) 2349–2359.

[5] EnergyPlus Engineering Document: The Reference to EnergyPlus Calculations, Lawrence Berkeley national laboratory, 2009.

[6] Henninger, R.H., M.J. Witte, D.B., Crawley, Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100-E200 test suite, Energy and Buildings 36 (8) (2004) 855–863.
[7] Duffie, J. A., W. A. Beckman, Solar Engineering of Thermal Processes, Second Edition. New York: Wiley-Interscience, 1991.
[8] Eckstein, J., Helmut, Detailed Modeling of Photovoltaic Components. M. S. Thesis Solar Energy Laboratory, University of Wisconsin, Madison, 1990.
[9] Ulleberg, Ø., HYDROGEMS Component Library for TRNSYS 15 User Manual, Institute for Energy Technology, Kjeller, Norway, 2000.
[10] King, D.L., W.E., Boyson, J.A., Kratochvil, Photovoltaic Array Performance Model. Sandia National Laboratories, Albuquerque, NM 87185, 2003.
[11] Barker, G., (unknown). Predicting Long-Term Performance of Photovoltaic Arrays. Submitted as deliverable for NREL subcontract LAX-1-30480-02, 2003. Currently in DRAFT
[12] Bojic, M., D., Bigot, F., Miranville., A. Parvedy-Patou., J., Radulovic., Optimizing performances of photovoltaics in Reunion Island—tilt angle, Progress in Photovoltaics: Research and Applications, DOI: 10.1002/pip.1159, (2011) Online ISSN:1099-159X.

Acknowledgment: This paper is a result of two project investigations: (1) project TR33015 of Technological Development of Republic of Serbia, and (2) project III 42006 of Integral and Interdisciplinary investigations of Republic of Serbia. The first project is titled “Investigation and development of Serbian zero-net energy house”, and the second project is titled “Investigation and development of energy and ecological highly effective systems of poly-generation based on renewable energy sources. We would like to thank to the Ministry of Education and Science of Republic of Serbia for their financial support during these investigations.