

Real-Time Irradiance Simulation for PV Products and Building Integrated PV in a Virtual Reality Environment

Anton J. Veldhuis and Angele H. M. E. Reinders

Abstract—This paper describes a new software tool named “VR4PV,” which has been developed for real-time simulation of irradiance for photovoltaic (PV) products in a virtual 3-D environment. This tool offers the possibility for product designers and architects to evaluate the distribution of irradiance on surfaces with an arbitrary geometry that can be covered with PV cells. In addition, the energetic performance can be estimated during the design process of PV products and building integrated PV (BIPV). The software allows for irradiance calculations on multiple arbitrarily oriented surfaces at the same time. It includes shadow simulation for multiple surrounding objects with various shapes and can handle movements of the 3-D objects during the simulation, which might be useful for the design of moving PV-powered products like boats, cars, and portable handhelds. A validation is carried out based on 1-min outdoor measurements of irradiance on two different locations in Italy and in California.

Index Terms—Building integrated photovoltaics (BIPV), irradiance, PV products, shading, simulation, virtual reality.

I. INTRODUCTION

DURING design processes of product-integrated photovoltaics (PV) and building integrated PV (BIPV), it is desirable to analyze the availability and intensity of solar irradiance on surfaces of these products and buildings in order to optimally position PV cells or PV modules while including 1) variable irradiance due to curvature, 2) (self-)shading effects, and 3) effects of movement of the PV product. This can be partly done in computer-aided design (CAD) software in which most products and buildings are designed in the Netherlands. However, previous studies in the field of irradiance simulations in CAD environments [1]–[3] used software based on the ray-tracing technique, which gave accurate results, but required a lot of processing time. The rendering of a model would take about 30 min to a couple of hours per scene, depending on the

complexity of the geometry, using ray tracing in 3-D Studio Max, which is a typical render tool for industrial designers.

Ray tracing is an algorithm that traces the paths of light rays from a light source until it eventually reaches the eye (i.e., camera). From a computational point of view, the algorithm is mostly implemented as backward ray tracing: Starting at the position of the eye, rays are traced until eventually a light source is reached. Ray tracing enables special effect such as reflections, refractions, shadows, and indirect lighting [4].

A study of Kovach and Schmid [1] uses the software tool RADIANCE to calculate the shading losses in PV systems by applying the ray-tracing technique. However, this software is less suitable during a design process, because it is not integrated in a CAD environment. This in contrast with the studies of Reich *et al.* [2], [3], where irradiance simulation is carried out within a CAD tool, based on the ray-tracing algorithm. However, it is found that both methods do not match well with the designers’ needs during the design process [2], [3] because rendering of a scene takes too much time, and handling of the software is complicated.

There have been several attempts to evaluate shadows caused by obstacles from the environment. Some studies estimate the shadow geometry by (fisheye) photographs [5], [6], others determine irradiance losses due to shadowing by a space-angular approach [7]. These methods require optical measurements at the particular location of a PV system and transformation of lens coordinates. Since the space angular approach is valid for one specific position on a PV module only, it is mainly suitable for rough estimations [7]. Various software programs to simulate these shadows are available; however, some of these programs lack the option to import 3-D CAD models into the tool, which makes this modeling step complicated and time consuming [8]. Furthermore, some software tools are able to import complex 3-D CAD models, but in general, these tools are quite extensive and more suited for detailed design [8]. Moreover, the energetic performance of PV systems is not included.

To decrease the processing time, this study explores a new method based on the rasterization algorithm. Rasterization is the process of decomposing computer graphics into smaller fragments corresponding to pixels on the screen. These fragments consist of a window coordinate, color, and other attributes, such as the normal and texture coordinate. The values associated with each fragment are interpolated between the points (i.e., vertices) of the polygon of a 3-D mesh that is processed [9]. This method is less accurate and does not allow for special effects like reflection and refraction; however, it demands less calculation time

Manuscript received August 3, 2011; revised February 7, 2012; accepted February 27, 2012. Date of publication April 17, 2012; date of current version June 18, 2012.

A. J. Veldhuis is with the Department of Design, Production and Management, Faculty of Engineering Technology, University of Twente, Enschede 7522NB, The Netherlands (e-mail: a.j.veldhuis@utwente.nl).

A. H. M. E. Reinders is with the Department of Design, Production, and Management, Faculty of Engineering Technology, University of Twente, Enschede 7522NB, The Netherlands, and also with the Department of Design for Sustainability, Faculty of Industrial Design Engineering, Delft University of Technology, Delft 2628CN, The Netherlands (e-mail: a.h.m.e.reinders@utwente.nl).

Digital Object Identifier 10.1109/JPHOTOV.2012.2189937

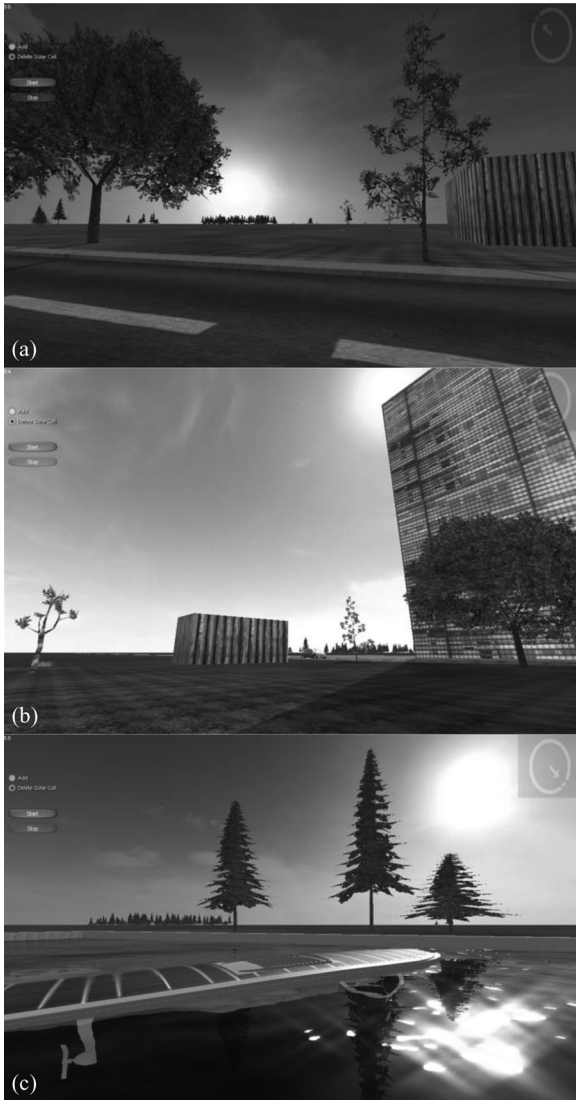


Fig. 1. Three screen shots of the VR4PV during simulation of one day from different viewpoints. Showing (a) sunrise, (b) clear sky at noon, and (c) a PV powered boat in the afternoon of a day in July in the Netherlands.

than ray tracing. Depending on several factors [e.g., complexity of the 3-D object(s), the central processing unit (CPU), and the graphics processing unit (GPU)], estimated processing time is a factor 0.01, compared with ray tracing. Therefore, one can produce real-time results, actually a sequence of simulations of subsequent scenes can be interpreted like a movie, which is important during the design phase. In Fig. 1, three screen shots during the simulation of one day are shown.

The VR4PV has the ability to calculate the irradiance, shading, temperature, and the electrical performance of the PV cell. This study focuses on the irradiance component of the tool, since this is the largest contributor to inaccuracy and directly influences the temperature and electrical performance of the PV cell. The goal of this study is to validate a tool based on rasterization in order to classify the accuracy of the simulation when using hourly averaged irradiance data as input for the calculation of irradiance per minute.

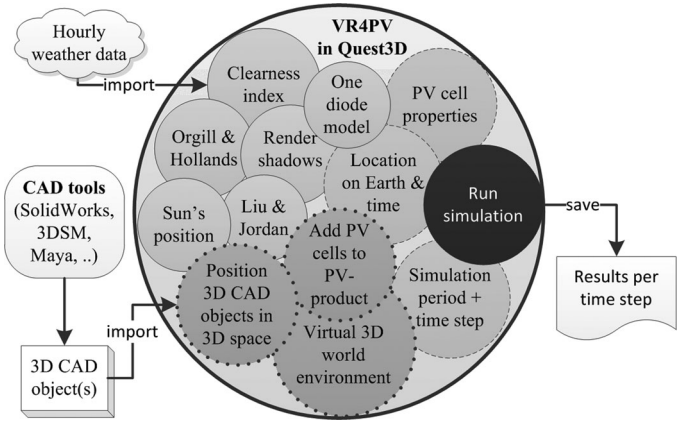


Fig. 2. Schematic overview of the VR4PV.

The structure of this paper is as follows. First, the project will be introduced in more detail. Then, the various models regarding (tilted) irradiance, diode modeling, cell temperatures, and shadow algorithms, which are found in literature and implemented in the VR4PV, are presented and evaluated. Subsequently, the simulation steps of the tool will be described, followed by the results of a modest validation. The paper will finish with a discussion and conclusion.

II. PROJECT DESCRIPTION

The software tool presented in this study is meant to play a role during the design process of PV products and BIPV and to support the selection of a preliminary layout of PV cells and PV modules in the total design. Besides, the VR4PV can be used to evaluate the product and (self-)shading in a scenario, i.e., in a situation that changes in course of time and in which positions of objects can change. The tool is currently in the R&D phase and not commercially available. A schematic overview of the VR4PV is shown in Fig. 2. The circles with a solid border indicate models implemented inside the tool which cannot be adjusted by the user, the circles with a dashed border indicate input fields, and the ones with a dotted border indicate functions to adjust 3-D objects.

As shown, 3-D CAD objects are imported into VR4PV together with the hourly weather data of a specific location. Inside the tool, it is possible to add PV cells to the imported CAD object, representing the PV product. By clicking on this product, a PV cell is added to the product at the position of the mouse cursor and will be oriented normal to the surface. The PV cell itself has a flat surface. Subsequently, the irradiance model calculates the irradiance received by the PV cells, taking direct shadows of the surroundings and the product itself into account.

This approach aims to reduce the time as well as the costs involved in the development of PV products leading to better and cheaper PV products. Instead of producing different prototypes and carrying out expensive measurements to determine the difference yields of the PV cells of each prototype, this process can be carried out in a virtual environment. Another benefit of the opportunity to simulate the yield for various scenarios is

that it will probably lead to better PV products in a market with various users and different environments of use.

A. Quest3D

In this study, Quest3D [10] is used as the software environment to develop the VR4PV. Quest3D is a real-time software environment based on the rasterization algorithm that has been used so far to create software for internet, simulators, and virtual reality applications. Quest3D is an object-oriented programming environment, but instead of writing lines of code, programs in Quest3D are constructed on the basis of building blocks containing methods and related algorithms. These building blocks—so-called channels—are connected to each other to form a channel graph. Because of this structure, the software is highly modular. Quest3D is suitable for the use of time-based scenario-based evaluations of PV products. In such an evaluation, the product is analyzed taking into account, among other things, the surroundings and different modes of use or application in the course of time. This creates the opportunity to evaluate a product in its real-life environment, which is often indicated as virtual reality.

B. Simulation

To be able to execute a simulation, first, a surrounding with 3-D objects must be created in which a product or building with PV cells will be evaluated. This product or this building has to be created using a CAD tool as well, and it has to be imported in the 3-D surroundings. To be able to calculate time dependent variables, such as solar irradiance, the time period and the time step has to be set, as well as the location on earth. Besides, the corresponding weather data have to be imported. In addition, the electrical and geometrical PV-cell parameters can be adjusted to the PV cells that will be investigated.

After the calculations of each time step, the tool outputs the results into an ASCII data file that can be further processed. Fig. 3 shows a flow chart of the simulation steps inside the VR4PV.

C. Irradiance on Tilted Surfaces

To compute the irradiance received by a surface with an arbitrary tilt angle, various irradiance models can be found in literature that can be distinguished in two categories: isotropic and anisotropic sky models. The Perez model [11] is a widely accepted anisotropic sky model. The Liou–Jordan model [12] is the most commonly used isotropic sky model. The VR4PV converts global horizontal irradiance H_h to direct H_{bh} and diffuse H_{dh} horizontal irradiance by applying the clearness index k_r combined with the Orgill–Hollands relationship [13].

The eccentricity factor E_o is calculated by Spencer's Fourier series [14] and is used to calculate the extraterrestrial irradiance based on the solar constant of 1367 W/m^2 .

Subsequently, the Liou–Jordan model is applied to calculate the irradiance on a tilted surface. This approach can be easily implemented in the simulation tool and requires less input data. To estimate the consequences of using the Liou–Jordan

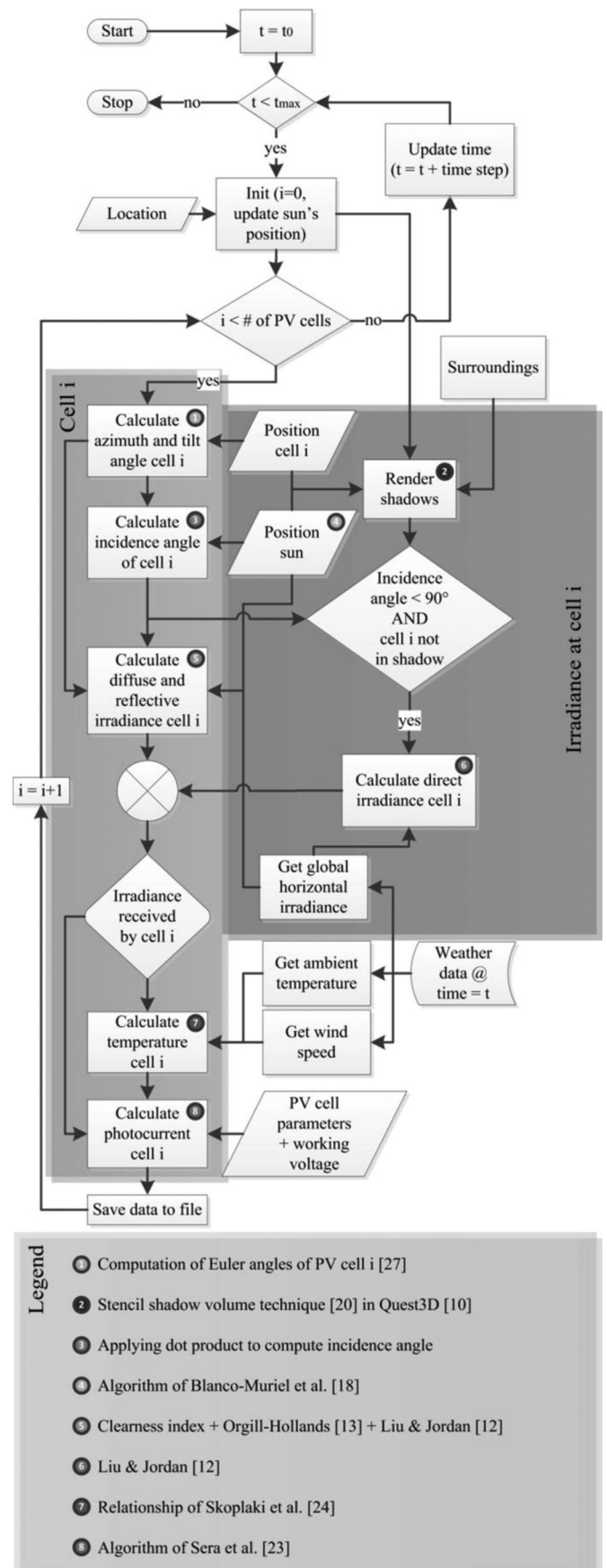


Fig. 3. Simulation procedure in the VR4PV.

model versus the Perez model, we refer to a study by Santamouris *et al.* [15]. Eleven isotropic and anisotropic models were evaluated over a period of two years (1984–1986) with measurement data from Cyprus. It was found that the Perez model overestimates and the Liu–Jordan model underestimates measured irradiance values. The average difference between both the models is only 5%, which is less than the accuracy of outdoor measurements of irradiance.

The Liu–Jordan model has a good accuracy for low intensities ($<300 \text{ W/m}^2$), such values being associated with overcast skies which is quite common in the North West of Europe. As skies become clearer, the validity of the isotropic sky model reduces due to the presence of circumsolar and horizon brightening anisotropic effects [16]. The Liu–Jordan model slightly underestimates irradiance at clear and partly cloudy conditions [17].

Additionally, the position of the sun is calculated in the VR4PV. The model of Blanco-Muriel *et al.* [18] is implemented, which determines the position of the sun with an accuracy of 0.5 min of arc for the period 1999–2015. This model is applied because of its ease of use and its accuracy.

D. Shadows

Shaded objects receive less radiation; hence, the tool calculates shadows. To compute the shadows, various computer algorithms can be found in the literature. The two most common techniques, for software based on the rasterization algorithm, are shadow mapping [19] and the stencil shadow volume technique [20].

The stencil shadow volume algorithm defines a region of space that is in the shadow of a particular occluder with a given light source. It requires knowledge of the polygonal meshes in the scene to calculate the silhouette of each shadow-casting object [21]. The basic concept of the stencil shadow algorithm is to use the stencil buffer of the GPU as a masking mechanism to prevent pixels in shadow from being drawn during the rendering pass for a particular light source. This is accomplished by rendering an invisible shadow volume for each shadow-casting object in a scene. Subsequently, only pixels outside these shadow volumes are illuminated [22].

The stencil shadow volume algorithm is implemented in the presented tool to add shadows to the environment, since it is more accurate and the feature is already built-in in Quest3D.

By applying simplified objects for the generation of shadows, the influence of the stencil shadow volume algorithm on the CPU performance is minimal [21].

To have a clear view on the shape of shadows on PV cells that is not affected by the camera angle of a scene, a user interface is built in the scene viewer which shows PV cells on top. As an example, in Fig. 4(a), a screenshot of the tool is shown, the little numbered white squares on top of the figure represent the solar cells in the object at the front, and the gray areas in these white squares indicate the shadows received by each PV cell.

If the pixel in the center of a PV cell is gray, thus in shadow, the direct irradiance part of the Liu and Jordan model is excluded from the calculation for this particular cell.

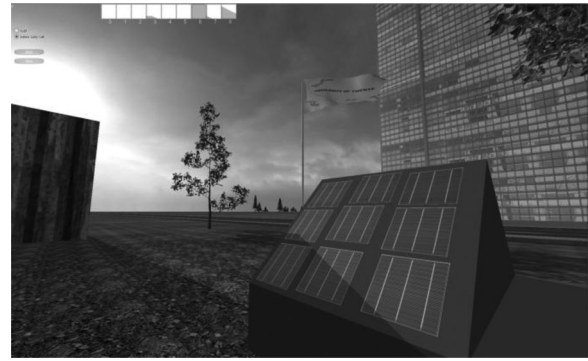


Fig. 4. Screenshot of the tool with, at the top left, all PV cells seen as white squares; gray indicates a shaded area.

E. Time Step

The time step of the simulation can be adjusted to the needs of the user. It is possible to simulate each minute or even each second; this way, the shadows will move slightly in every frame according to the small adjustment of the Sun's position.

In order to get the irradiance at these time steps, a moving average is used, based on the hourly irradiance data.

Because small time steps are allowed, the Liu and Jordan model—which is based on hourly irradiance—will be used on a per-minute basis. This will introduce an error, which will be investigated as well.

F. Cell Temperature

The VR4PV accounts for the irradiance and temperature dependences of the cell according to [23]. The relationship used in this study computes the cell temperature based on the irradiance G_t received, the ambient temperature T_a , and the wind speed V_f , based on a simple semiempirical correlation proposed by Skoplaki *et al.* [24]

$$T_c = T_a + \omega \left(\frac{0.32}{8.91 + 2.0V_f} \right) G_t \quad (1)$$

where ω is a mounting coefficient.

The selected models found in the literature are combined in the VR4PV to evaluate the yield of PV cells for different orientations and tilt angles in an arbitrary 3-D environment. With input of time series of local global horizontal irradiance, ambient temperature, and wind speed, it will be possible to evaluate a PV product at a random location on earth.

III. EXPERIMENTAL SETUP

For the validation of the tool, 1-min irradiance measurements of two different locations are used. The first dataset is achieved from the Measurement and Instrumentation Data Center from the National Renewable Energy Laboratory [25]. The location is in Los Angeles, CA (Latitude 33.97 North, Longitude 118.42 West), and the measurements of the global horizontal irradiance cover the month of June 2011. A rotating shadow band radiometer is used as a measurement device; the data sample rate is every 3 s with 1-min average output.

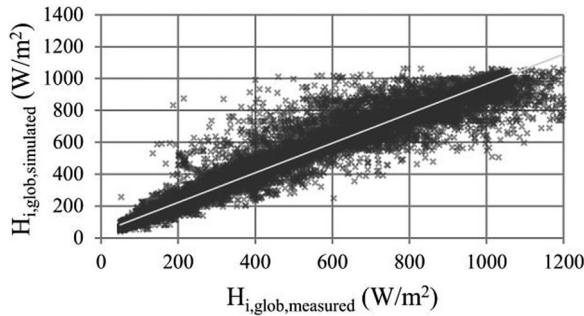


Fig. 5. Measured versus simulated minutely horizontal irradiance for Los Angeles; simulation 1.

The second dataset is from the European Solar Test Installation from the Joint Research Center as part of the European Commission [26]. The measurements of the global horizontal irradiance and irradiance on a fixed 30° tilted plane oriented 8.5° west from south are carried out in Bolzano, Italy (Latitude 46.46° North, Longitude 11.33° East). The sampling frequency is once per minute. The validation is based on a period from April 6 to April 30, 2011.

Two PV cells, one horizontal and the other 30° tilted and orientated corresponding to the plane in Bolzano, are simulated on the basis of hourly irradiance originating from these datasets, in order to validate the tool.

The errors of the results can be related to three factors:

- the assumption of constant irradiance between the average hourly irradiance points;
- the use of Orgill–Hollands and Liu–Jordan model;
- the use of these hourly irradiance models for the calculation of irradiance per minute.

To evaluate these errors, four simulations are carried out. The investigated error factor(s) are mentioned inside the brackets.

- measured hourly averaged horizontal irradiance $\xrightarrow{\text{VR4PV}}$ minutely horizontal irradiance for Los Angeles (a);
- measured hourly averaged horizontal irradiance $\xrightarrow{\text{VR4PV}}$ minutely horizontal and 30° tilted irradiance for Bolzano (a, b, and c);
- measured minutely horizontal irradiance $\xrightarrow{\text{VR4PV}}$ minutely 30° tilted irradiance for Bolzano (b and c);
- measured hourly averaged horizontal irradiance $\xrightarrow{\text{VR4PV}}$ hourly averaged 30° tilted irradiance $\xrightarrow{\text{interpolated}}$ minutely 30° tilted irradiance for Bolzano (a and b).

The measured hourly averaged horizontal irradiance is based on the minutely measurements. All the simulation results are compared with the actual measurements per minute.

IV. RESULTS

In Fig. 5, the results of the first simulation with the VR4PV are shown. The simulated global horizontal irradiance is plotted against the measured global horizontal irradiance per minute for the location of Los Angeles for the range of 50 – 1200 W/m^2 . As can be seen, most simulated irradiance points correlate as expected with the measured global horizontal irradiance. Because

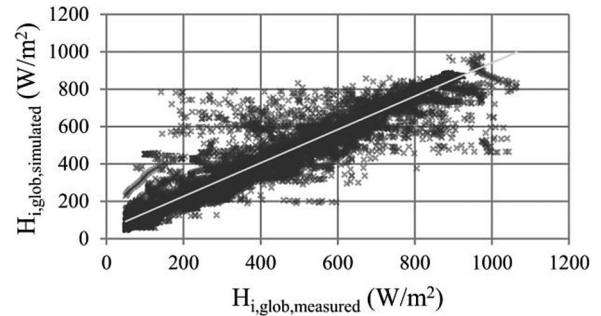


Fig. 6. Measured versus simulated minutely horizontal irradiance for Bolzano; simulation 2.

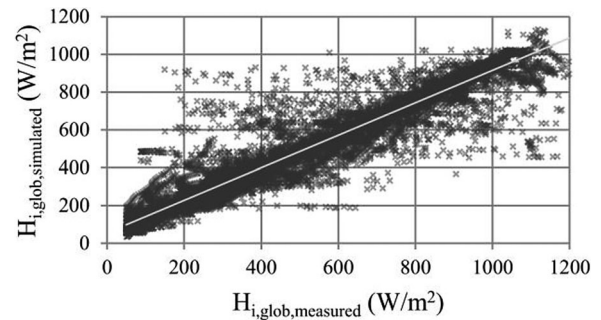


Fig. 7. Measured versus simulated minutely 30° tilted irradiance for Bolzano; simulation 2.

of the average hourly irradiance used as input, the extreme irradiance values above 1050 W/m^2 correlate less well.

In Fig. 6, the results of the horizontal irradiance of the second simulation are shown. Again, most simulated values are in good line with the measurements, although large errors exist, especially for lower irradiance values. Irradiance values above 850 W/m^2 correlate less well, because of the averaged hourly irradiance used as input. Compared with Fig. 5, irradiance values from 600 W/m^2 correlate better. As can be seen, some simulated values differ a lot from the measured values, especially for low irradiance values.

In Fig. 7, the results of the 30° tilted irradiance of the second simulation are shown. Compared with Fig. 6, the shape of the results is the same, but they are spread over a larger region.

This can be seen in Fig. 8 as well, where the average relative error of the simulated irradiance compared with the measurements is shown for the same location per range of 50 W/m^2 .

In addition, for each of these ranges the root-mean-squared error (RMSE) is plotted in the figure. The RMSE is calculated by

$$\text{RMSE} = \left[\frac{1}{n} \sum_{i=1}^n (H_{i,s} - H_{i,m})^2 \right]^{1/2} \quad (2)$$

where n is the number of measurements, and $H_{i,s}$ and $H_{i,m}$ are, respectively, the simulated and measured irradiance.

The RMSE percentage is obtained by dividing the RMSE of the specific range by the average value of the range.

For low irradiance levels, the relative errors are quite large, and the number of measurements peaks in this region. However,

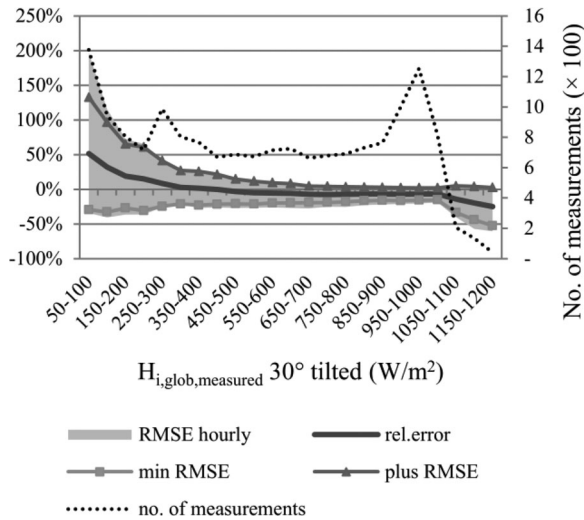


Fig. 8. Average relative error of the simulated minutely 30° tilted irradiance for Bolzano per range of 50 W/m^2 ; simulations 3 and 4.

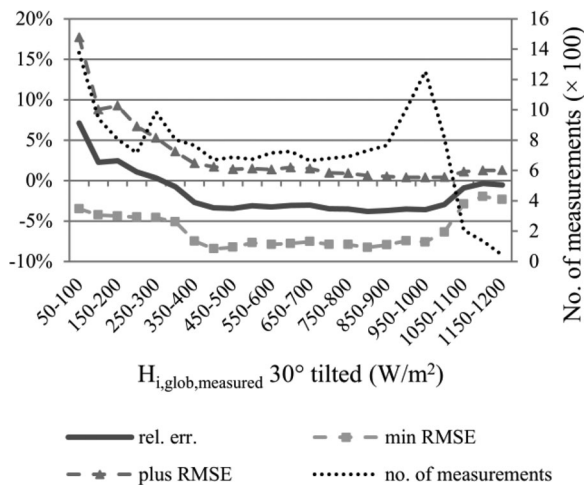


Fig. 9. Average relative error of the simulated minutely 30° tilted irradiance for Bolzano per range of 50 W/m^2 ; simulation 3.

the absolute error of this area is in the same range compared with irradiance levels around 1000 W/m^2 . The same can be said about the higher irradiance levels. The absolute errors are quite large in this region (around 500 W/m^2), but the number of measurements in this area is very small compared with the total number of measurements. Therefore, the influence of these larger errors on the total simulation is minor. The average relative error and RMSE for irradiance values between 450 and 1050 W/m^2 are, respectively, -6% and 85 W/m^2 on a minute scale.

In Fig. 8, the RMSE results of the fourth simulation are shown as well, indicated by the gray area. These values are in the same order as the values from simulation 2, as can be seen.

In Fig. 9, the results of the third simulation are shown. From the figure, it follows that the average relative error of the use of the Liu–Jordan model in combination with the Orgill–Hollands relationship on a minutely basis is in the order of -3% for irradiance levels between 300 and 1050 W/m^2 for a tilt angle of 30° . The average RMSE for this range is 29 W/m^2 .

V. DISCUSSION AND CONCLUSION

In this study, a new concept of a software tool that can simulate irradiance in real time is presented. The tool, which is called VR4PV, is faster than the previously developed tools, which makes it very useful during the design process. Besides, due to the highly modular program structure, it is quite simple to replace implemented models by others. For instance, the Liu–Jordan model can be replaced by the Perez model.

In this study, a validation of the tool for two locations is carried out. For both locations, 1-min measurements of irradiance are compared with the simulated irradiance per minute which are interpolated between the hourly averaged global horizontal irradiance used as input in the tool.

Most of the simulated irradiance values correlate well to the measurements. At the higher irradiance levels (500 – 1000 W/m^2), the correlation is better compared with lower levels. For a 30° tilted surface, the average RMSE and relative error for irradiance levels between 450 and 1050 W/m^2 are, respectively, 85 W/m^2 and -6% . The errors due to the tilt conversion by the Orgill–Hollands and Liu–Jordan model are, respectively, 29 W/m^2 and -3% for the same range and under the same conditions. For irradiance levels between 50 – 450 W/m^2 , the RMSE and the average relative error are, respectively, 85 W/m^2 and 16% . The use of the Orgill–Hollands and Liu–Jordan model on a minutely basis corresponds to the results on an hourly basis, as shown in Fig. 10. The average RMSE for the conversion of hourly to minutely horizontal irradiance is 62 W/m^2 for irradiance levels between 300 and 850 W/m^2 . Therefore, the largest error is caused by the assumption of constant irradiance between the hourly averaged irradiance values (i.e., the fluctuation of the actual irradiance during an hour).

Although the tool is quite flexible, future work should focus on a good graphical user interface (GUI), which, at present, is lacking. The GUI is an essential element to let designers and architects adjust parameters during runtime and make successful use of the VR4PV. The rasterization technique applied lacks the possibility to account for complex reflections and transparent materials, which might be of interest for glazed surroundings like in interior spaces.

Summarizing the first version of the tool shows promising results. In the forthcoming period, the tool will be validated for different components, which will give directions to future improvements. In addition, the use of the tool in a designer setting will be tested for various products and buildings, leading to recommendations for an easily accessible GUI.

ACKNOWLEDGMENT

The authors would like to thank W. Zaaiman and A. Coli from the JRP for providing us with the monitoring data from Bolzano and NREL for the solar resource data from Los Angeles.

REFERENCES

- [1] A. Kovach and J. Schmid, "Determination of energy output losses due to shading of building-integrated photovoltaic arrays using a ray-tracing technique," *Sol. Energy*, vol. 57, no. 2, pp. 117–124, 1996.

- [2] N. H. Reich, W. G. J. H. M. van Sark, W. C. Turkenburg, and W. C. Sinke, "Using CAD software to simulate PV energy yield—The case of product integrated photovoltaic operated under indoor solar irradiation," *Sol. Energy*, vol. 84, no. 8, pp. 1526–1537, 2010.
- [3] N. H. Reich, W. G. J. H. M. van Sark, A. H. M. E. Reinders, and H. de Wit, "Using CAD software to simulate PV energy yield: Predicting the charge yield of solar cells incorporated into a PV powered consumer product under 3D-irradiation conditions," in *Proc. 34th IEEE Photovoltaic. Spec. Conf.*, 2009, pp. 001291–001296.
- [4] S. R. Buss, *3-D Computer Graphics: A Mathematical Introduction With OpenGL*. Cambridge, U.K: Cambridge Univ. Press, 2003, p. 234.
- [5] H. Matsukawa, P. S. Pimentel, T. Izawa, S. Ike, H. Koizumi, and K. Kurokawa, "An integrated design software for photovoltaic systems," in *Proc. 3rd World Conf. Photovolt. Energy Convers.*, 2003, vol. 2, pp. 1930–1933.
- [6] T. Tomori, K. Otani, K. Sakuta, and K. Kurokawa, "On-site BIPV array shading evaluation tool using stereo-fisheye photographs," in *Proc. 28th IEEE Photovoltaic. Spec. Conf.*, 2000, pp. 1599–1602.
- [7] A. Woyte, J. Nijs, and R. Belmans, "Partial shadowing of photovoltaic arrays with different system configurations: Literature review and field test results," in *Proc. 28th IEEE Photovolt. Spec. Conf.*, 2000, pp. 217–233.
- [8] M. C. Dubois and M. Horvat, "State-of-the-art of digital tools used by architects for solar design," IEA SHC, 2010.
- [9] G. Hasle, K. A. Lie, and E. Quak, *Geometric Modelling, Numerical Simulation, and Optimization: Applied Mathematics at SINTEF*. New York: Springer-Verlag, 2007, p. 132.
- [10] Quest3D. (Jul. 2011) [Online]. Available: <http://quest3d.com>
- [11] R. Perez, R. Stewart, C. Arbogast, R. Seals, and J. Scott, "An anisotropic hourly diffuse radiation model for sloping surfaces: Description, performance, validation, site dependency evaluation," *Sol. Energy*, vol. 36, no. 6, pp. 481–497, 1986.
- [12] B. Y. H. Liu and R. C. Jordan, "The interrelationship and characteristic distribution of direct, diffuse, and total solar radiation," *Sol. Energy*, vol. 4, no. 3, pp. 1–19, 1960.
- [13] J. F. Orgill and K. G. T. Hollands, "Correlation equation for hourly diffuse radiation on a horizontal surface," *Sol. Energy*, vol. 19, no. 4, pp. 357–359, 1977.
- [14] J. W. Spencer, "Fourier series representation of the position of the Sun," *Search*, vol. 2, no. 5, p. 172, 1971.
- [15] M. Santamouris, I. Tselepidaki, and N. Dris, "Evaluation of models to predict solar radiation on tilted surfaces for the Mediterranean region," *Sol. Wind Technol.*, vol. 7, no. 5, pp. 585–589, 1990.
- [16] D. T. Reindl, W. A. Beckman, and J. A. Duffie, "Evaluation of hourly tilted surface radiation models," *Sol. Energy*, vol. 45, no. 1, pp. 9–17, 1990.
- [17] T. Muneer and G. S. Saluja, "A brief review of models for computing solar radiation on inclined surfaces," *Energy Convers. Manage.*, vol. 25, no. 4, pp. 443–458, 1985.
- [18] M. Blanco-Muriel, D. C. Alarcon-Padilla, T. Lopez-Moratalla, and M. Lara-Coira, "Computing the solar vector," *Sol. Energy*, vol. 70, no. 5, pp. 431–441, 2001.
- [19] L. Williams, "Casting curved shadows on curved surfaces," in *Proc. Int. Conf. Comput. Graphics Interactive Tech.*, 1978, vol. 12, no. 3, pp. 270–274.
- [20] F. C. Crow, "Shadow algorithms for computer graphics," in *Proc. Ann. Conf. Comput. Graphics Interactive Tech.*, 1977, vol. 11, no. 2, pp. 242–248.
- [21] M. Haller, S. Drab, and W. Hartmann, "A real-time shadow approach for an augmented reality application using shadow volumes," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2003, pp. 56–65.
- [22] E. Lengyel, *Mathematics for 3D Game Programming and Computer Graphics*, Connecticut: Cengage Learning, 2004.
- [23] D. Sera, R. Teodorescu, and P. Rodriguez, "PV panel model based on datasheet values," in *Proc. IEEE Int. Symp. Ind. Electron.*, 2007, pp. 2392–2396.
- [24] E. Skoplaki, A. G. Boudouvis, and J. A. Palyvos, "A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting," *Sol. Energy Mater. Sol. Cells*, vol. 92, no. 11, pp. 1393–1402, 2008.
- [25] (Jul. 2011). [Online]. Available: <http://www.nrel.gov/midc/lmu/>
- [26] W. Zaiman and A. Colli, "Single axis tracking and fix-tilt performance of c-SI systems in the Italian Alpine region," in *Proc. 37th IEEE Photovolt. Spec. Conf.*, 2011.
- [27] G. G. Slabaugh. (Jul. 2011). Computing Euler angles from a rotation matrix. [Online]. Available: <http://gregslabaugh.name/publications/euler.pdf>

Authors' photographs and biographies not available at the time of publication.