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Impact of atmospheric aerosols on photovoltaic energy production Scenario for the Sahel zone

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Abstract

Photovoltaic (PV) energy is one option to serve the rising global energy need with low environmental impact. PV is of particular interest for local energy solutions in developing countries prone to high solar insolation. In order to assess the PV potential of prospective sites, combining knowledge of the atmospheric state modulating solar radiation and the PV performance is necessary. The present study discusses the PV power as function of atmospheric aerosols in the Sahel zone for clear-sky-days. Daily yields for a polycrystalline silicon PV module are reduced by up to 48 % depending on the climatologically-relevant aerosol abundances.

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Keywords: energy meteorology; photovoltaic; aerosol; irradiance; Sahel zone

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1. Introduction

The 7th goal of the United Nation's Sustainable development goals "Ensure access to affordable, reliable, sustainable and modern energy for all" [1], mandates a shift away from the traditional fossil-fuel powered energy system towards renewable energy. PV energy is one option to serve the rising global energy demand at low environmental impacts [2,3]. Building an energy system, with a considerable share of PV power, requires long-term investment and a careful investigation of potential sites. Therefore, understanding the influence of varying regional and local atmospheric conditions on PV energy production is crucial for energy yield projections. Specifically, the incoming solar radiation is modified in the atmosphere due to absorption and scattering on trace gases, aerosol and cloud particles

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[4,5]. However, information about these parameters is not easily available in a reasonable spatiotemporal resolution. In attempts to counter this absence of local measurements, different approaches have been estimating solar radiation at the ground by using simple models that are based on scaling long term averages [6], numerical radiative transfer (RT) models [7,8], or simulations relying on satellite data and weather models [9,10].

Modeling PV power requires considering the direct and diffuse solar radiation in the module plane, reflection losses and cell temperature [11]. Furthermore, determining the cell temperature requires the knowledge of ambient temperature and wind speed. PV cell performance models usually use either inputs from ground-based measurements, satellite data and/or numerical weather simulations for the solar radiation at the ground [12–15]. In atmospheric science, detailed RT models, using information of the atmospheric state as input, are used to calculate the radiative flux profiles in the atmosphere [16]. However, these models do not support PV power calculations. In this study, we combine various tools known in the atmospheric- and PV-community by coupling a multi-layer RT model with a two-diode based PV power model. Thereby we take into account the variation of radiation due to aerosols, the transformation of horizontal radiation to the tilted plane of the module, reflection losses on the module front and cell temperature behavior. The PV power model is designed to simulate a representative PV module, i.e., a polycrystalline Solar World silicon module, with a maximum power at standard test conditions (STC) of 235 Wp (in brief a SW 235 poly) [17].

In the present study, we use the combined model chain to assess the PV potential in the Sahel region for several reasons. First, it is a region suffering from the lack of energy infrastructure. Second, local solutions for power production based on PV are attractive due to the high solar insolation year around. Third, the region is characterized by its diversity in land use and its large seasonal changes due to the influence of the West African monsoon. In the dry season conditions are arid and dusty while the wet season is moister and cloudier. Finally, the deployment of the Atmospheric Radiation Program (ARM) Mobile Facility (AMF) in Niamey, Niger (13.5 N, 2.2 E) throughout 2006 [18,19] offers detailed data sets to investigate atmospheric effects on solar radiation. With less than 10 % cloud fraction observed during the AMF observational period [20,21] the major variability of solar radiation is caused by the presence of atmospheric aerosols [19].

The effect of aerosols on solar radiation strongly depends on their physical, i.e., aerosol size distribution and particle shape, their chemical composition, and land surface conditions [22–24]. Depending on their optical properties, aerosols reduce the direct solar radiation component and modify the direction of the diffuse component, compared to aerosol-free atmospheric conditions. To investigate the aerosol effect on PV power in detail, we select 69 clear-sky-days observed by AMF for our model calculations.

After this brief introduction, the model chain is described in section 2. Its calibration is performed in Sankt Augustin using collocated meteorological data and PV power measurements (in section 3). The fourth section shows the prediction of the impact of aerosols on daily PV yields in Niamey, using the model chain with a theoretically mounted module. Our results are then discussed in section 5, and the study is concluded with our main findings in section 6.

2. Model description

For estimating aerosol impact in Niamey, PV yields are simulated for an aerosol-free and an aerosol-loaded atmosphere using the model chain depicted in Fig. 1. Based on the atmospheric state as an input (see section 4 for detailed parameters) we use the library of RT programs and routines (libRadtran) [8,25] to calculate the direct and diffuse solar radiation for a horizontal surface. The modelled libRadtran irradiances and radiances are used to calculate the effective radiation on the tilted PV module. This is determined in two steps. First the radiation is transformed to the tilted plane and second reflection losses on the module front are taken into account. Furthermore, the cell temperature is simulated from ambient temperature and wind speed. Based on this input, depending on atmospheric parameters, and subsequently using PV module characteristics (provided by manufacturer) as additional input for the two-diode model, PV power calculations are undertaken. For all simulations we use hourly data.

The main libRadtran function uvspec can compute radiances, irradiances and actinic fluxes for pre-described atmospheric states. In our model chain the RT equation is numerically solved by using the DISORT (DIScrete Ordinates Radiative Transfer solver) algorithm [26]. The irradiance is calculated using 6 streams while radiances are calculated using 16 streams. The radiation is integrated over the wavelength interval from 290 nm to 2600 nm, covering the total spectral range relevant for PV cells. For the molecular absorption a correlated k method developed by Kato et al. [27]

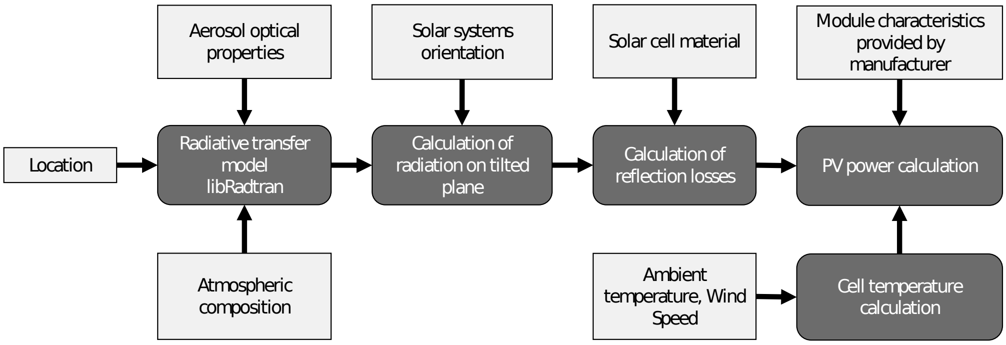

Fig. 1. Schematic overview on the model structure (input data light grey, single model steps dark grey).

is applied to reduce the computing time. Local measurements of trace gases and aerosol optical properties are used to define the atmospheric state. Missing parameters are included by using a standard tropical atmosphere and a typical desert aerosol composition defined by the Optical Properties of Aerosols and Clouds (OPAC) library by Hess et al. [24].

The effective radiation used from the PV cell is calculated by transforming the single components of the radiation to the tilted plane and considering reflection losses on the modules surface. Direct radiation I_{dir} can be analytically transformed to the tilted plane I_{dir}^{tilt} using an Eulerian transformation with the solar zenith being γ and α the solar azimuth angle as well as the PV modules orientation (azimuth α_{PV} and tilting angle Φ)

$$I_{dir}^{tilt} = I_{dir}\frac{cos(\Phi)\,cos(\gamma) + sin(\Phi)\,sin(\gamma)\,cos(\alpha-\alpha_{PV})}{cos(\gamma)}. \tag{1}$$

The diffuse radiation on the tilted plane I_{diff}^{tilt} is determined from the calculated spatial distribution of the incoming diffuse radiation $I_{diff}(\gamma, \alpha)$. LibRadtran allows explicit modelling of the diffuse radiance distribution over the whole sky dome. However, this is computationally costly. The computing time is reduced by using the horizontal component of diffuse radiation calculated by libRadtran and by deriving its spatial distribution using a parametrized model. In general, several models for the spatial distribution of diffuse radiation are documented in literature [28,29]. The different models for the effective diffuse radiation received on the tilted plane are tested by using the diffuse radiation calculated by libRadtran. The different streams are analytically transformed to the tilted plane (using Equation 1) before integrating them over all azimuth and zenith angles. The model which shows the least difference to the libRadtran results is then taken in our model chain. For this study, one isotropic model developed by Liu and Jordan [30] and two three-component models [31,32] are compared assuming an aerosol load typical for deserts. The three-component models take one isotropic, one circumsolar and one horizontal brightening component into account. The model of Reindl et al. [31] uses the transmittance to determine the fraction of each diffuse component, while the model by Perez et al. [32] uses empirical parameters. Diffuse radiation is calculated for solar zenith angles from 0° to 75° in 15° steps, a solar azimuth angle of 180° and tilt angles of the PV module between 0° and 90° in 5° steps for a south orientated module. For each tilt angle of the PV module the percentage bias and root mean square error (RMSE) are calculated for each single model using the analytically transformed radiation as a reference (Fig. 2). Among all tested models, the Perez model performs similarly well as the libRadtran calculation for tilt angles of the PV module around 15°, with a bias of 2 % and a RMSE of 13 W/m^2. Therefore, we use the Perez model to calculate the effective diffuse radiation on the tilted plane.

Reflection losses in the surface layer of the PV cell are calculated by using the incidence angle modifier (IAM) described in De Soto et al. [33]. For the calculation a glazing extinction coefficient of 4 m^{-1} (water white glass), a glazing thickness of 2 mm and a refractive index of 1.526 (glass) is used, which are typical parameters for PV modules [33]. Reflection losses of the direct radiation can be calculated by using the incidence angle on the module and Snells law. For the diffuse radiation an isotropic, horizon and reflective IAM are calculated. The isotropic IAM is the mean over IAMs from all directions of the sky dome in azimuthal steps of 2° and elevation steps of 0.5°. The horizon IAM is assumed to be the mean over all IAMs of radiation coming from the horizon (with azimuthal steps of 2°). The reflective IAM is calculated similar to the isotropic IAM, but for radiation received from the ground.

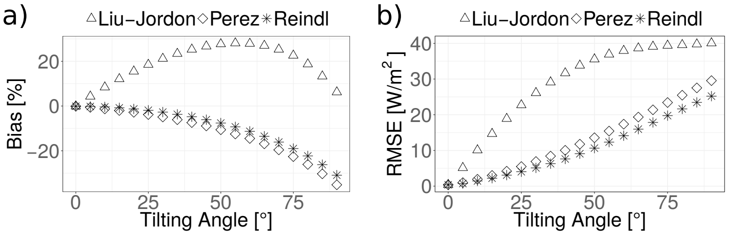

Fig. 2. Bias (a) and RMSE (b) of various diffuse radiation models, namely Lui-Jordon (triangle), Perez (diamond) and Reindl (star) using the libRadtran calculations of radiances for varying tilting angles in a desert aerosol regime as a reference.

Considering the PV cell temperature is important because rising cell temperatures reduce the efficiency of PV modules [34]. The cell temperature can be derived using different model approaches [35]. Each model approach has been developed for a certain mounting option, building geometry and module material. For the model calibration calculations (see section 3) a model accounting for the closed mounting system on the measuring site in Sankt Augustin is used. The model has been developed by King et al. [12] from the Sandia National Laboratory, allowing to account for different mounting options. It is able to predict the cell temperature within 5 °C with a minimum amount of input, if the correct mounting option is assumed [35,36]. Parameters for the closed roof mount option and the required input for ambient temperature and wind speed are employed.

Modeling PV power requires the estimation of a non-linear I-U curve. One simple approach is to assume the electrical behavior of a PV module as a single diode. This model approach is in good agreement to outdoor measurements for polycrystalline silicon modules [14]. However, for low irradiance calculations it comes with high uncertainties [37,38]. The two diode model allows improved I-U calculations especially suited for low irradiances [39]. In this study the simple model approach designed by Ishaque et al. [37] is applied. It requires four parameters to describe the current equation, which makes it fast compared to other models using seven parameters [40] and still brings reliable results. For different temperatures, relative errors for the maximum power point are smaller than 1 % as compared to measured data for all tested modules [37].

3. Model calibration at the measurement site in Sankt Augustin

Since the beginning of 2015 we have been continuously measuring global, diffuse and direct normal radiation as well as PV power of a polycrystalline silicon module at the University of Applied Science Bonn-Rhein-Sieg in Sankt Augustin, Germany (50.7 N, 7.2 E) (Fig. 3). These measurements are used to calibrate our PV power model. The skylight radiation has been measured using a SOLYS 2 sun tracker with two CMP 11 pyranometers and a CHP 1 pyrheliometer from Kipp & Zonen, and the PV power is from the SW 235 poly [17]. The module is orientated at 191° azimuth and 14° tilt angle. Furthermore, detailed local meteorological parameters have been measured, e.g. ambient temperatures and wind speed. The PV power model, designed for a SW 235 poly, is validated with running the model using hourly measured data of the global and diffuse radiation, ambient temperature and wind speed. The model output is compared to the SW 235 PV power measured in Sankt Augustin on an hourly resolution for ten clear-sky-days during 2015/2016. The ten days are distributed over all seasons to cover a wide range of celestial and atmospheric conditions. An albedo of 0.18 is assumed because of gravel in the near environment of the measurement site [41]. Hourly measured and simulated PV power is shown in Fig. 4. For zenith angles < 75°, percentage bias and RMSE between simulated and observed PV power is deter-

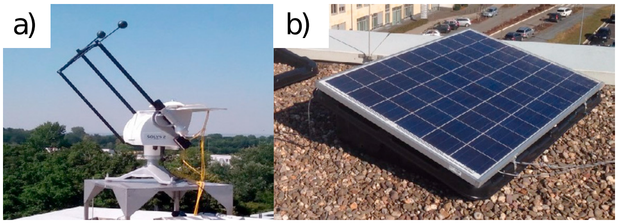

Fig. 3. Equipment for measuring global, diffuse and direct normal radiation (a) and PV yields of a SW 235 poly module (b) at University of Applied Science Bonn-Rhein-Sieg in Sankt Augustin, Germany (50.7 N, 7.2 E).

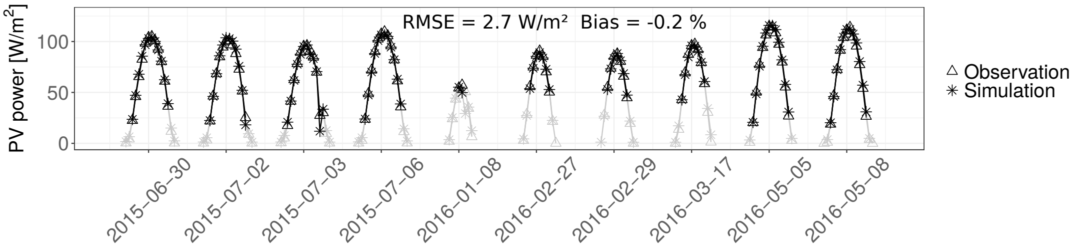

Fig. 4. Comparison of measured PV yields in Sankt Augustin, Germany (triangles) and those modelled using the novel developed PV power model (stars) on an hourly basis for ten clear sky days in 2015/2016. Biases and RMSEs are calculated for zenith angles below 75°, the used points are marked in black.

mined. We discarded measurements at high solar zenith angles because of disturbing reflections from the roof fringe in early morning and late evening hours. The PV power model performs well with a relative bias of -0.2 % and a RMSE of 2.7 W/m^2 compared to the PV power measurements on clear-sky-days.

4. Impact of desert aerosols on PV energy in Niamey, Niger

After having calibrated our PV power model with measurements performed in Sankt Augustin, Germany, we apply the model to a prospective plant located at Niamey airport (13.5 N, 2.2 E). From there excellent solar irradiance data are available from the ”Radiative Divergence using AMF, GERB and AMMA (African Monsoon Multidisciplinary Analysis) Stations” (RADAGAST) campaign in 2006 [18,19,42]. Within the framework of the campaign, the U.S. AMF as a mobile base deployed a set of instruments to collect atmospheric and climate data [43]. The instrumentation provides measurements of optical properties of aerosols, trace gas concentration, broadband radiation, etc. The locally measured data are used to first simulate direct and diffuse radiation using libRadtran and second to project PV power of a theoretically mounted SW 235 poly module, orientated at 191° azimuth and 14° tilt angle, similar to the measurement set-up in Sankt Augustin.

The whole model chain (see section 2) is applied to simulate 69 clear-sky-days in Niamey that occurred in 2006. Eight of the analyzed days lie in the wet season between May and September while the remaining days were in the dry season. Atmospheric data from the RADAGAST campaign and the Monitoring Atmospheric Composition and Climate (MACC) reanalysis data base by European Centre for Medium-range Weather Forecasts [44] are used as input for the libRadtran simulations (Table 1).

Table 1. Data implemented in libRadtran with indicating the data base, the data format and the way of implementation.

Parameter	Data base	Description	Implementation
Water vapor	ARM	Column value	Scaled for atmospheric layers
Ozone	MACC	Column value	Scaled for atmospheric layers
AOD	ARM	At 500 nm	Scaled for all wavelength and atmospheric layers
Angstrom exponent	ARM	Using AOD at 500 nm and 870 nm	Used for scaling of AOD
Angstrom coefficient	Calculated	From angstrom exponent and AOD at 500 nm	Used for scaling of AOD
SSA	ARM	At 550 nm	Scaled for all wavelength and atmospheric layers
Surface albedo	Calculated	From up- and down-welling global radiation	Averaged value is implemented

For the calculation, measured total atmospheric water vapor, ozone, aerosol optical depth (AOD) at 500 nm and single scattering albedo (SSA) at 550 nm are used. Angstrom exponent inferred from the measured AOD at 500 nm and 870 nm, Angstrom coefficient are subsequently calculated from the Angstrom exponent and AOD at 500 nm. Down- and up-welling total radiation is applied for calculating the ground albedo. Furthermore, we assume a desert aerosol composition profile from the OPAC data base [24]. The data base contains typical mass concentration and aerosol optical properties like AOD, SSA and asymmetry parameter, which are used for missing values or parameters which were not measured [24].

The atmospheric RT simulations are compared with the broadband down-welling solar radiation observed during the RADAGAST campaign (Fig. 5). The simulations agree well with the measurements with a slight underestimation during high aerosol loads and an overall relative bias of -0.3 % and RMSE of 29 W/m^2. Especially without knowing the aerosol characteristics, e.g. size distribution, shape, chemical composition, over the full vertical profile it is impossible to improve the simulations. The simulation including aerosols is called ”aerosol-loaded” scenario in the following. A second set of calculations address the aerosols-free case, which will be called the ”aerosol-free” scenario. For this purpose, the simulations are repeated as described above with the only difference that no aerosols are included in the atmospheric RT calculations. The down-welling radiation from both scenarios is then used for all further steps of the modeling chain (see section 2) to calculate PV power.

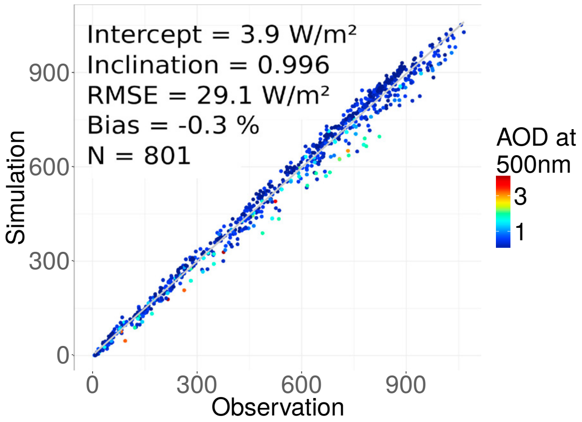

Fig. 5. Comparing hourly simulated values of global radiation with hourly observed global radiation during 69 clear-sky-days in 2006 in Niamey using the whole daily data set. The color scale shows the observed value of aerosol optical depth at 500 nm.

Fig. 6 shows modeled PV power for all 69 days at 1200 UTC noon and diurnal variations for three exemplary days with different aerosol loads. March 8, 2006 comprises a day with a sand storm when the AODs went up to 4. In contrast, on December 27, 2006 the aerosol load was low, with an AOD of about 0.1. On March 17, 2006 the AOD was about 0.5, typical for an average aerosol load on clear-sky-days in 2006. It can be clearly seen, that on an hourly basis for the ”aerosol-free” scenario higher PV power is obtained compared to the ”aerosol-loaded” scenario for all

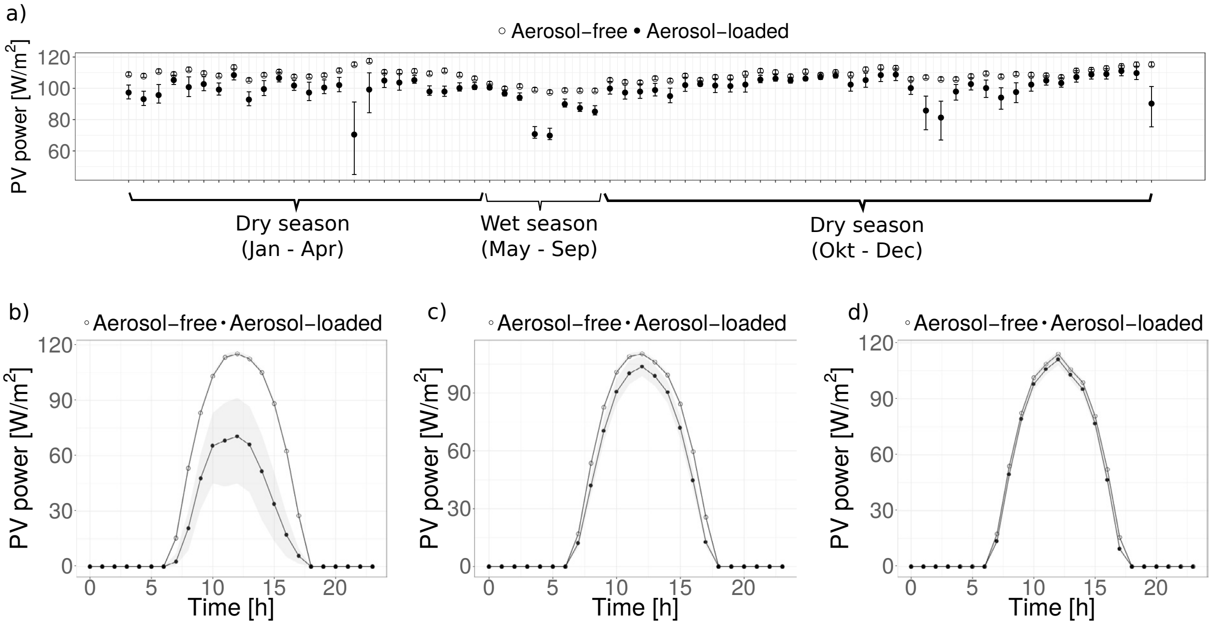

Fig. 6. Modeling PV power in an aerosol-free (blanc circle) and an aerosol-loaded (filled circle) scenario at 1200 UTC noon on 69 clear-sky-days (a) and for three special days, with an extreme (b), an averaged (c) and a low aerosol impact (d) on March 8, March 17 and December 27 respectively in 2006 in Niamey.

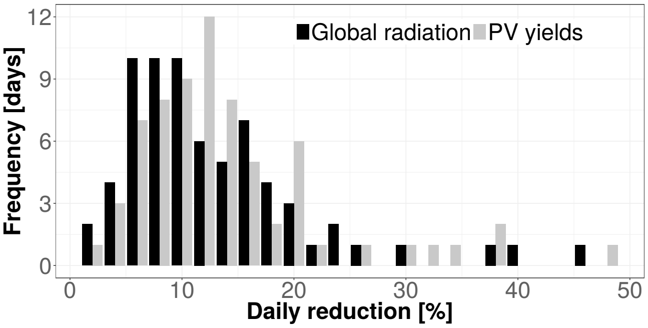

Fig. 7. Frequency of occurrence of daily reduction due to the presence of aerosols for daily global radiation (black) and PV yields (grey) on clear-sky-days in 2006 in Niamey.

aerosol loads. In a next step, the daily reduction of PV yields and global radiation due to the presence of aerosols is computed as the percentage difference between the two scenarios as a day integral for each day (Fig. 7). The mean daily reduction of PV yields and global radiation for all 69 days is 14 % and 13 %, respectively. However, during extreme events, i.e., dust storms, daily reduction in PV yields are as large as 48 %.

5. Discussion

We show that due to the presence of aerosols on average daily global radiation and daily PV yields for a poly-crystalline module are reduced by 14 % and 13 % respectively in Niamey on otherwise mostly clear sky days (see Fig. 7). These reductions in global radiation and PV yield are calculated using a coupled RT model for global radiation (libRadtran) and a subsequent PV power model (two-diode model) (see section 2), comparing "aerosol-free" and "aerosol-loaded" scenarios. In our model chain, we consider cell temperature, effective radiation on the tilted plane and reflection losses. The modeled global radiation on the horizontal plane is validated with measured data collected during the RADAGAST campaign in 2006. In contrast, simulated PV power are purely theoretical estimates since no data is available for this location and time period. However, the applied model chain combines knowledge from the atmospheric- and PV-community, assesses different characteristics of PV modules and considers all relevant factors, namely projecting the effective radiation on the tilted plane, reflection losses and cell temperature. Considering the difference of daily reduction in global radiation and PV yields (Fig. 7), the importance of details in such model chains is evident.

Apparently, the results of RT calculations largely depend on the atmospheric composition (e.g. trace gases and aerosols) in each atmospheric layer [25]. However, the knowledge of all relevant input parameters for each specific location is limited. In Niamey simulations, detailed measurements of the relevant input parameters are used which are not available for most locations. The used data sets for Niamey are total column amounts measured on the ground. While information on atmospheric gases are obtained from reanalysis or measurements with reasonable accuracy the situation is more difficult for aerosol. Here we consider measured aerosol optical properties combined with the assumption of a standard desert aerosol distribution profile [24]. Thus, uncertainties due to the spreading of column values over all atmospheric layers, the scaling to all wavelengths (Table 1), and the accuracy of measurements themselves are evident. All of these effects may cause sizable differences between measured and simulated radiation. Maximal errors due to measurement uncertainties are calculated by considering a scenario with lowest and highest global radiation. In order to span the maximal range of uncertainties, minima and maxima for AOD, water vapor, ozone, SSA and surface albedo are used in these simulations, depending on their effect on global radiation. Consequently, our simulations indicate mean daily reduction of PV yields ranging from 8 % to 20 % providing an uncertainty estimate of the mean of 14 %. Our calculations thus demonstrate that due to the presence of aerosols PV yields are reduced on average of at least 8 % in Niamey on clear-sky-days.

The PV power model includes a two-diode model for the I-U relation proposed by Ishaque et al. [37]. This approach is validated for three different module types, namely multi crystalline, mono crystalline and thin film. The simulation of all modules show relative errors of the power yields below 1 % for the relevant temperature range from -25 °C to 75 °C compared to measurements [37]. Our model chain also includes an effective cell temperature model and a model to derive effective radiation on the tilted plane depending on the direction of diffuse radiation. Cell temperature consideration highly depends on the mounting option of the module [35] as investigated by Kurnik et al. [45]. As open rack mounting is frequently used for PV installations [12], they compared open rack and roof integrated mounting options. In particular, Kurnik et al. [45] found that due to the reduced cooling, roof integrated modules suffer more from temperature related reduction in the PV power than open frame systems. Therefore, when considering the cell temperature, the knowledge of the mounting option of a module is necessary. For our PV power calculations in Niamey, we assume a close roof mounting, because of the comparability to our measuring site in Sankt Augustin (see section 3). However, to generalize the model approach different mounting options should always be considered systematically when analyzing and predicting PV yields. The effective diffuse radiation is calculated using the Perez model [32]. In literature studies comparing diffuse radiation models do not recommend the same models [29,46,47]. Here the different diffuse radiation models are compared to simulations of the RT model libRadtran. For low tilt angles (e.g. of 14°) the different models predict similar diffuse radiation (Fig. 2).

One further factor important for PV power calculations but not yet considered in the present model chain is the variation of the atmospheric spectrum due to e.g. the varying near infrared absorption of water. Here we consider a polycrystalline silicon module, for which the uncertainties due to spectral effects only lie between 1 % and 4 % [48,49].

6. Conclusion

Accurate modelling of PV power is one key element for the development of a renewable energy based power system, especially in developing countries with high solar insulation. In this study, a model chain is set-up which couples an atmospheric RT model with a PV power model. This newly developed model chain is used to investigate the impact of aerosols on PV power for a polycrystalline silicon module over the course of the year in a sub-Saharan region i.e., Niamey, Niger. PV power is predicted based on detailed meteorological information for 69 clear-sky-days there during 2006. Daily reductions in PV yields due to the presence of aerosols are found to range from 2 %, 48 % with a mean of 14 %. A maximum reduction of 48 % is predicted during a sand storm event. Decreasing daily PV yields with increasing atmospheric aerosol load is of particular concern in the light of anthropogenic impacts on atmospheric aerosol concentration [50]. In semi-arid regions like the Sahel zone ongoing desertification might be caused by land use changes [51]. For system operators and project planners the related changes are important to know especially in light of strong seasonal and regional variability of dust storm frequency [52].

It is worth noting that daily global radiation does not directly relate to PV yields (Fig. 7) implying the necessity of the full modelling chain. By using both, meteorological and PV engineering knowledge, we are able to model PV yields involving cell temperature consideration, radiation on the tilted plane and reflection losses on the modules front. However, to generalize the model further research is needed to include different mounting options and spectral effects. Furthermore, a detailed analysis of diffuse radiation models using different solar zenith angles and module tilting angles in comparison to measured data has to be undertaken.

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