Impact of atmospheric aerosols on solar power

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Abstract

Atmospheric aerosols affect the power production of solar energy systems. Their impact depends on both the atmospheric conditions and the solar technology employed. By being a region with a lack in power production and prone to high solar insolation, West Africa shows high potential for the application of solar power systems. However, dust outbreaks, containing high aerosol loads, occur especially in the Sahel, located between the Saharan desert in the north and the Sudanian Savanna in the south. They might affect the whole region for several days with significant effects on power generation. This study investigates the impact of atmospheric aerosols on solar energy production for the example year 2006 making use of six well instrumented sites in West Africa. Two different solar power technologies, a photovoltaic (PV) and a parabolic trough (PT) power plant, are considered. The daily reduction of solar power due to aerosols is determined over mostly clear-sky days in 2006 with a model chain combining radiative transfer and technology specific power generation. For mostly clear days the local daily reduction of PV power (at alternating current) (PV AC) and PT power (PTP) due to the presence of aerosols lies between 13 % and 22 % and between 22 % and 37 %, respectively. In March 2006 a major dust outbreak occurred, which serves as an example to investigate the impact of an aerosol extreme event on solar power. During the dust outbreak, daily reduction of PVAC and PTP of up to 79 % and 100 % occur with a mean reduction of 20 % to 40 % for PVAC and of 32 % to 71 % for PTP during the 12 days of the event.

Keywords: energy meteorology, solar power, West Africa, atmospheric aerosol

1 Introduction

To “ensure access to affordable, reliable, sustainable and modern energy for all”, as proposed in the 7th goal of the United Nation’s sustainable development goals (UNITED NATIONS, 2015), a shift away from the use of fossil-fuel based to renewable energy is necessary. Solar power systems are one option to feed the rising global energy demand in a sustainable way (e.g. HAEGER et al., 2017; SOLANGI et al., 2011). Especially in regions prone to high solar irradiance a power system with a considerable share of solar sources is worthwhile. However, meteorologically caused local variability of solar irradiance needs to be investigated carefully in system planning and sizing to ensure long-term investments.

In West Africa electrification rates are still below 50 % (ECOWAS, 2017) while global horizontal irradiance (GHI) is high with an average annual sum of up to 2400 kWh/m² (SOLARGIS, 2017). Furthermore, direct normal irradiance (DNI) shows annual sums of over 2000 kWh/m² in the northern parts of Niger and Mali (SOLARGIS, 2017). With low cloudiness, sunshine durations of about 6.6 to 9 hours per day can be reached (KOTHE et al., 2017). This leads to a high potential of solar power production. However, seasonal and local variability of solar resources needs to be considered. In south and central West Africa a typical annual cloud cycle exists because of the West African Monsoon (WAM) and its associated dry and wet seasons. Clouds occur predominantly during the wet season between June and September and reduce solar irradiance. In the dry season between October and May cloud cover is low, which in principle would lead to high solar transmission in the atmosphere. However, the frequent presence of dust in the dry season (dust emission frequencies go up to 15 % over the whole year (COWIE et al., 2014)) causes a strong variability of irradiance. Thus, the development of a solar power system in West Africa brings challenges even under low cloudiness conditions.

While solar power outputs are sensitive to meteorological parameters, such as temperature and wind speed, atmospheric conditions are the main contributor to their variability. In particular, aerosol and cloud particles as well as trace gases scatter and absorb the incoming solar irradiance (e.g. WENDISCH and YANG, 2012; WALLACE and HOBBS, 2006). Though clouds are a more efficient
modulator of solar radiation than aerosols here we only focus on aerosol effects that can become the decisive factor limiting the availability of solar energy during the dry season, which represents more than half of the year in the Sahel. In a cloud-free atmosphere, aerosols are the main driver for atmospheric extinction. The effect of aerosols on solar irradiance strongly depends on their physical and chemical composition (e.g. *BOUCHER*, 2015; *KAUFMAN* et al., 2002; *HESS* et al., 1998). Depending on their optical properties, aerosols reduce GHI by modifying both of its components. Thereby, DNI is strongly reduced while diffuse horizontal irradiance (DHI) increases to some maximum. Different solar power technologies use different components of solar irradiance. While non-concentrating technologies exploit global radiation, concentrating solar power (CSP) plants only use DNI. For CSP plant yields aerosols are also responsible for changes in sun shade and atmospheric extinction between the mirrors and the receiver (HANRIEDER et al., 2017; WILBERT, 2014). In addition to atmospheric aerosol, soiling (the deposition of subsiding aerosols on solar panels and collectors), which occurs especially during dust events, causes an additional solar power reduction. Depending on the cleaning cycle and the amount of dust transport, soiling may cause a power reduction of up to 90 % after one week as shown by SARVER et al. (2013).

Different studies, going beyond case studies, were undertaken to quantify the aerosol impact on solar power at single locations (e.g. *RUZ-ARIAS* et al., 2016). *LI* et al. (2017) predicted the annual average reductions of aerosols on photovoltaic (PV) power in China to 20 %–25 % by using GHI from satellites and a PV power model. *POLO and ESTALAYO* (2015) showed a 2 %–16 % difference in CSP power (single days showing effects of up to 95 %) in two desert regions – Tamanrasset, Algeria and Sede Boquer, Israel – using ground-based and satellite observations of DNI as input for power calculations. The aerosol optical depth (AOD) going beyond 2 is in a similar range than in this study. However, these results cannot easily be extrapolated to other regions, as local aerosol loads vary and are strongly connected to aerosol sources and wind conditions.

One tremendous aerosol source are frequent Saharan dust outbreaks (TAYLOR et al., 2017) persisting several days and being able to reach regions far away from the Sahara (e.g. *RIEGER* et al., 2017). In extreme cases, DNI is reduced to 0, which means that GHI only consists of DHI. The impact of a 5-day Saharan dust outbreak in 2015 on solar power in the eastern Mediterranean was quantified to 40 %–50 % for PV and 80 %–90 % for CSP using the relative impact on GHI and DNI, but no detailed solar power model was considered (KOSMOPoulos et al., 2017). Only a few studies analyze the aerosol effect on solar irradiance or solar power in West Africa because relevant meteorological observations are lacking (e.g. *SLINGO* et al., 2006). Using measurements from a dedicated instrument deployment in 2006, the contribution by NEHER et al. (2017) quantified the daily impact of atmospheric aerosols on a PV module at a single location (Niamey) on average to 14 % during clear-sky days and up to 48 % during a dust outbreak. However, a systematic investigation of aerosol impacts on solar power generation in West Africa considering different technologies and a wider regional spread is missing.

To quantify the impact of atmospheric aerosols on solar power the ideal aerosol-free and the aerosol-loaded atmosphere need to be compared. This can only be achieved via a modeling approach, which explicitly considers the impact of aerosols on solar irradiance. Solar irradiance based on long-term averages, numerical weather prediction models, reanalysis or satellite data are often used as input for solar power models (e.g. *SEN Gupta* et al., 2017; *RICHARDSON and ANDREWS*, 2014; *HAMMER* et al., 2003; *GUEYMARD*, 2003). A detailed treatment of aerosols is only considered in a few studies for these models (FOUNTOUNIKIS et al., 2018; *GUEYMARD and JIMENEZ*, 2018), none of them focusing on West Africa. In atmospheric science, however, more sophisticated multi-layer radiative transfer (RT) models have been developed to derive radiative fluxes from information on atmospheric composition (e.g. *CLOUGH* et al., 2005; *MAYER AND KYLLING*, 2005). The solar energy community has developed accurate models for solar power. PV power can be modeled, e.g., using a two-diode model with an accuracy of more than 99 % (ISHAQUE et al., 2011b). In these models, DNI and DHI as well as the ambient temperature and wind speed are needed as inputs. To estimate the power of a parabolic trough (PT) plant, various factors, such as the characteristics of mirrors, absorber tube and thermal power plant, need to be considered, in addition to DNI. When simulating solar power an accurate energy production model and highly reliable irradiance input data are required. For the latter, sophisticated RT models are needed to take the aerosol effect into account. To our best of knowledge a coupling of multi-layer atmospheric RT models with state-of-the-art PV power models has only been performed by NEHER et al. (2017) and RIEGER et al. (2017). However, RIEGER et al. (2017) used the model chain to improve the forecast of PV power by considering aerosols in numerical weather models (NWM) and not to analyze the local impact of aerosols on solar power. Due to computational constraints NWP models need to employ fast RT routines, which use simplified parametrizations.

In this study, we use the library of RT programs and routines (libRadtran) by MAYER and KYLLING (2005) to simulate the irradiance. The model chain, “Solar Power modeling including atmospheric Radiative Transfer” (SolPaRT) combines libRadtran with a PV power model (NEHER et al., 2017) and a PT power model (QUASCHNING et al., 2001a). We use a PTPP instead of a solar tower power plant for our analysis. Therewith, we exclude the larger additional aerosol impact in the latter power plant between the mirrors and the receiver (HANRIEDER et al., 2017), which is not the focus of this study. SolPaRT is used to assess the impact of aerosols
on both, a PV power plant (PVPP) and a PT power plant (PTPP) for six different locations in West Africa. For this purpose we compile a one-year data set for 2006 of meteorological parameters at these locations, covering different climate and land use zones throughout West Africa. To quantify only the aerosol effect the impact of clouds on solar irradiance has to be excluded. Hence, predominantly clear-sky days (named ‘clear days’ in the following) are selected (covering 20% to 46% of the year, see Section 2) for each location and the daily reduction of solar power due to aerosols is determined using SolPaRT. We analyze the aerosol effect on a daily scale. This day-to-day analysis enables us to detect the variability over the course of one year and during extreme events like dust outbreaks lasting several days.

The goal of this study is two-fold. First, we quantify daily average impacts of aerosols on different solar power technologies during clear days over the course of one year. We generate more realistic estimates for future total power generation at sites in West Africa. Furthermore, we serve economic feasibility studies for PVPP and PTPP, which are important for investment decisions in the solar energy sector. Second, we estimate the variability of daily solar power due to aerosols year round under predominantly clear-sky conditions as well as during a major dust outbreak. This is necessary for the planning of reliable solar power systems including adequately sized energy storage and therewith essential for estimating related costs for power security. Furthermore, it enables us to identify the threat of aerosol-induced blackouts and to evaluate the need for emergency power supply.

This study is the first systematic investigation of aerosol impacts on different solar power technologies (namely PV and PT) for West Africa using a unique set of ground-based meteorological measurements. Furthermore, the impact of aerosols on solar power during a major dust outbreak is quantified.

The data and model chain (SolPaRT) used to quantify the aerosol impact on a PVPP and a PTPP are described in Section 2. In Section 3 SolPaRT is evaluated using measured GHI, and a sensitivity analysis for the impact of different parameters is performed. Section 4 presents and discusses the statistical analysis of daily reductions of solar power due to aerosols in West Africa in 2006. Projected solar power during a major dust outbreak in March 2006 is shown in Section 5 with a regional perspective. Furthermore, the effect of soiling on PV power is analyzed at one location during this dust outbreak. Conclusions and outlook are provided in Section 6.

Additional information about data and further results can be found in the electronic supplementary material.

2 Data and methodology

To quantify the impact of atmospheric aerosols on PV and PT power we use SolPaRT, a model chain that calculates both atmospheric RT and solar power using input data from six locations distributed over West Africa. These locations cover three climate zones according to the Köppen and Geiger climate classification (Peel et al., 2007); hot desert climate (BWh), hot semi-arid climate (BSh) and tropical wet climate (Aw).

2.1 Data

Neher et al. (2017) used the detailed observations from the Atmospheric Radiation Program (ARM) Mobile Facility (AMF) (Ackerman and Stokes, 2003) in Niamey, Niger to assess the aerosol impact on PV power in 2006. Here we expand this study to five additional locations in West Africa (Agoufou, Mali; Banizoumbou, Niger; Dakar, Senegal; Djougou, Benin and Maine-Sorou (called Maine in the following), Niger) using measured AOD with corresponding information on the Ångström exponent and precipitable water vapor (PWV) from AERONET (Aerosol RObotic NETwork, version 3, level 2) (Holben et al., 2001; Holben et al., 1998). Additional meteorological input parameters for SolPaRT are collected from the African Monsoon Multidisciplinary Analysis (AMMA) data base (AMMA, 2018) and surface synoptic observations (SYNOP) (see Table 1). Aerosol optical properties, PWV and albedo are used for the RT calculations. Temperature and wind speed at the surface are needed as additional input for PV power calculations. For the PT power calculations temperature, wind speed and direction, relative humidity (named PT-humidity in the following) and pressure are used. All calculations are performed with a temporal resolution of one hour. More information about the measuring equipment is given in the electronic supplementary material.

AOD observations are used to include aerosols in the RT calculations. The AOD is available at 500 nm for Niamey and at 440 nm for all other locations. The Ångström exponent is used to scale the AOD over different wavelengths. Apart from AOD, the single scattering albedo (SSA) and asymmetry parameter (g) have a significant impact on RT-calculations, too. These two parameters are taken from the desert aerosol type of the Optical Properties of Aerosols and Clouds (OPAC) library by Hess et al. (1998). For Banizoumbou a constant pressure value is used, which has been calculated from station height as no direct measurements are available. An overview on the hourly raw data is given in the electronic supplementary material for AOD, Ångström exponent, PWV, temperature, wind speed and PT-humidity as the most important contributors for the calculation to the simulated solar power (see Section 3.2). Surface albedo is assumed to be 0.28 in Agoufou, Banizoumbou, Maine and Niamey (a typical value for savanna), 0.2 in Djougou (a typical value for mixed vegetation) and 0.09 in Dakar (a typical value for coastal regions) (Rockwood and Cox, 1976).

To exclude the impact of clouds in our calculations, we only consider days with a large abundance of AOD measurements, as this can only be observed under clear-sky conditions. The considered days (‘clear days’) are...
Table 1: Data implemented in SolPaRT with indicating the data base for each available parameter at every location.

| Parameter          | Agoufou  | Banizoumbou | Dakar   | Djougou | Maine   | Niamey |
|--------------------|----------|-------------|---------|---------|---------|--------|
| AOD                | AERONET  | AERONET     | AERONET | AERONET | AERONET | ARM    |
| Ångström exponent  | AERONET  | AERONET     | AERONET | AERONET | AERONET | ARM    |
| Precipitable water | AERONET  | AERONET     | AERONET | AERONET | AERONET | ARM    |
| Temperature        | AMMA     | AMMA        | SYNOP   | AMMA    | SYNOP   | ARM    |
| Wind speed         | AMMA     | AMMA        | SYNOP   | AMMA    | SYNOP   | ARM    |
| Wind direction     | AMMA     | AMMA        | SYNOP   | AMMA    | SYNOP   | ARM    |
| PT-humidity        | AMMA     | –           | SYNOP   | AMMA    | SYNOP   | ARM    |
| Pressure           | AMMA     | AMMA        | –       | AMMA    | –       | ARM    |
| GHI                | AMMA     | AMMA        | –       | AMMA    | –       | ARM    |

Table 2: Information about the six analyzed stations, including latitude, longitude, height, climate classification, land use conditions and number of clear days.

| Location      | Agoufou | Banizoumbou | Dakar   | Djougou | Maine   | Niamey |
|---------------|---------|-------------|---------|---------|---------|--------|
| Country       | Mali    | Niger       | Senegal | Benin   | Niger   | Niger  |
| Latitude      | 15.3 N  | 13.5 N      | 14.4 N  | 9.8 N   | 13.2 N  | 13.5 N |
| Longitude     | 1.5 NW  | 2.7 E       | 17 W    | 1.6 E   | 12 E    | 2.2 E  |
| Height (m)    | 305     | 250         | 0       | 400     | 350     | 205    |
| Climate class | BWh     | BSh         | BSh     | Aw      | BSh     | BSh    |
| Land use      | desert  | desert      | coastal | savanna | desert  | desert |
|               | rural   | rural       | urban   | agriculture | village | airport |
| No. of clear days | 132    | 168         | 161     | 94      | 71      | 78     |

The much lower number of clear days in Niamey compared to Banizoumbou (the stations are only 60 km apart) occurs due to different measuring techniques for AOD. In Banizoumbou the classical AERONET sun photometer measures spectral DNI. In this procedure the cloud-screening process only considers clouds interfering with the sun disk. In contrast, in Niamey, the multifilter shadowband radiometer (MFRSR) measures GHI and DHI at six wavelengths. The cloud-screening process of the MFRSR takes clouds from the whole sky dome into account, which increases the number of time steps being rejected (Russell et al., 2004). Furthermore, misalignment artifacts of the instrument are also screened out as clouds for the MFRSR (Alexandrov et al., 2007). Therefore, less clear days are detected in Niamey compared to Banizoumbou.

2.2 Model description

Based on the input data described above, SolPaRT is used to analyze the impact of atmospheric aerosols on a PVPP and a PTPP (see Figure 1 for a schematic overview).

For the estimation of direct horizontal irradiance (DIR) (the horizontal projection of DNI) and DHI we use libRadtran (Emde et al., 2016; Mayer and Kylling, 2005). Similar to the procedure in Neher et al. (2017) two scenarios, an aerosol-loaded (the measured AOD
and Ångström exponent are included in RT calculations) and an aerosol-free (aerosols are excluded from RT calculations), are simulated. The difference between these scenarios is integrated over each day representing the total daily reduction of power due to atmospheric aerosols.

LibRadtran numerically solves the RT equation by using the DISORT (DIScrete Ordinates Radiative Transfer solver) algorithm to calculate the irradiance (Stamnes et al., 1988). In comparison to many clear-sky models (a comparison is given in Badescu et al., 2013), libRadtran allows an altitude-resolved atmospheric profile. Therewith, we are able to include all relevant atmospheric parameters from the ground-based dataset as well as aerosol composition into the model chain. Furthermore, we are able to include spectral information, which is planned for a next version of the model. In this study, the standard tropical atmosphere from Anderson et al. (1986) is used as a baseline to define the atmospheric state. While temperature and trace gases do not show a significant sensitivity for the irradiance calculation, water vapor is highly relevant. Therefore, local measurements of PWV (see electronic supplementary material) are used to scale the climatological moisture profile. Furthermore, we use a typical desert aerosol composition defined by the OPAC library (Hess et al., 1998). The locally measured AOD with its corresponding Ångström exponent is scaled to all atmospheric layers. For the molecular absorption in the atmosphere a correlated-k method developed by Kato et al. (1999) is applied to reduce the computing time.

The calculated irradiances with and without aerosol are then used as input for a PVPP and PTPP model. For the PVPP we consider crystalline silicon modules. Power calculations are undertaken with a two-diode model (Ishaque et al., 2011a; Ishaque et al., 2011b). The PTPP is based on Andasol I (Kistner et al., 2004) in Spain but without storage. Calculations of the power output are performed by using the green energy system analysis tool (Greenius) (Quaschning et al., 2001a; Quaschning et al., 2001b). The composition of the PVPP and PTPP are given in Table 3.

Calculations for the efficiency of PV modules, use GHI and ambient temperature as inputs. Modeling PV power is often simplified by determining only one point (the maximum power point (MPP)) of the current-voltage curve. However, to get a better estimate of PV power by the non-linear current-voltage curve, additional knowledge is required about module and inverter characteristics. Therefore, we calculate the power of a PVPP by using the two-diode algorithm (Ishaque et al., 2011a). The power plant is connected to the grid with a single inverter (King et al., 2007). With this model arrangement both the direct current (PVDC) and the alternating current (PVAC) power calculation can be undertaken. All modules are orientated towards the south with a tilt angle of 14°, which is roughly equal to latitude. A model comparison was undertaken with a single module, tilted at 14° and measurements of the PVDC showing a relative bias of −0.2% between model output and PV power measurements on clear days in Neher et al. (2017).

The effective irradiance used by the PVPP is calculated by transforming DIR and DHI to the tilted plane and considering reflection losses on the modules’ surfaces. DIR can be analytically transformed to the tilted plane using an Eulerian transformation. DHI is transformed to the tilted plane by using the model designed by Perez et al. (1990). Neher et al. (2017) showed, that this model performs similar to the detailed libRadtran calculations with radiances analytically transformed to the tilted plan in desert regimes. Reflection losses are considered for three different components: the irradiance coming from the direction of the sun, from the direction of the horizon and the isotropic part of DHI using the incidence angle modifier described in De Soto et al. (2006).

The efficiency of a PV module varies with cell temperature (e.g. Parretta et al., 1998). Thus, ambient temperature and wind speed are used to determine the cell temperature. While different approaches are available from the literature (a review can be found in Skoplaki and Palyvos (2009)), we apply the approach by King et al. (2004) here and assume an open-rack mounting, as it is mostly used in PV applications.

To estimate the parabolic trough power (PTP) and heat absorbed by the collector (parabolic trough

| Table 3: Information about the PV and PTP. |
|-----------------------------------------|
| **PVPP** | **PTPP** |
| **Solar irradiance (W/m²)** | GHI | DNI |
| **Output (W)** | PVDC, PVAC | PTH, PTP |
| **Total AC capacity** | 30 kW | 50 MW |
| **Total collector area** | 214 m² | 510.120 m² |
| **Land area** | 825 m² | 2.000.000 m² |
| **Module** | SW235poly | Solar collectors |
| **No of strings** | 16 | Eurotrough |
| **No of modules per string** | 9 | No solar collectors assemblies |
| **Tilting angle** | 14° | No solar collectors per assembly |
| **Orientation** | South | 12 |
| **Inverter** | Xantrax 30 kW | Heat collector element |
| **Turbine** | | Schott (PTR70) |
| **Power block** | | Steam Rankine |
| **Steam Rankine** | | |
| **Evaporation** | | |
| **Efficiency** | | |
| **Output (W)** | | |
| **PVPP** | | |
| **PTPP** | | |
| **Total collector area** | 214 m² | 510.120 m² |
| **Land area** | 825 m² | 2.000.000 m² |
| **Module** | SW235poly | Solar collectors |
| **No of strings** | 16 | Eurotrough |
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| **Inverter** | Xantrax 30 kW | Heat collector element |
| **Turbine** | | Schott (PTR70) |
| **Power block** | | Steam Rankine |
| **Steam Rankine** | | |
| **Efficiency** | | |
| **Output (W)** | | |
| **PVPP** | | |
| **PTPP** | | |
heat – PTH) of a PTPP, the simulation tool greenius is applied (Quaschning et al., 2001a). greenius allocates detailed technical as well as economic analysis of multiple technologies. This tool provides an interface for specific meteorological input for a certain location. The Andasol I power plant serves as a typical reference plant for PT systems (Quaschning, 2011). Therefore, a similar power plant but without storage is assumed for the PTPP (see Table 3), which allows to directly assess the impact of aerosols. If storage was included, the power reduction due to aerosols could be dampened depending on the storage size. With a maximum power output of 50 MW the PTPP is larger than the PVPP. However, PV is a modular technology, which can be easily scaled up or down. Building up the same PVPP several times would give the same numbers for power reductions due to aerosols as only one of the PVPP.

In summary, SolPaRT includes the effect of temperature, wind speed, PT-humidity, pressure, direct and diffuse irradiance on both solar power technologies. Furthermore, the impact of PWV, albedo, aerosols and a standard tropical atmosphere are considered when calculating solar irradiances. In addition, the technical specifications of the module and the inverter are used for PV calculations and the PTPP characteristics for PT calculations (Table 3). However, other factors can have an impact on PVAC and PTP, which are not included in SolPaRT, e.g., spectral variations of the solar irradiance at the surface and soiling. As soiling is believed to be the most important aspect a rough estimation is given in Section 5.2.

3 Assessment of simulations

As a first step we assess the RT simulations using the observed GHI for comparison and calculate typical statistical parameters. In a second step we evaluate the sensitivity of SolPaRT concerning the impact of different meteorological input parameters.

3.1 Validation of modeled global irradiance

The RT calculations are validated with observed GHI at four stations (Agoufou, Banizoumbou, Djougou and Niamey) where pyranometer measurements are available (see Table 1). For this purpose, data from all clear days are taken into account at hourly resolution. Here the coincidence is rather high and minor deviations are expected due to the different viewing perspectives of both instruments, i.e. hemispheric measurement of pyranometer, tilted beam towards the sun by sun photometer (for AOD). The number of data points (N) and all fitting parameters are given in Figure 2. The highest variation of hourly GHI occurs due to the varying solar zenith angle. However, further factors of influence, such as AOD and PWV, are active as well.

A relative bias of 1.9 %, 5.8 %, −3.5 % and 0.4 % is found for GHI in Agoufou, Banizoumbou, Djougou and Niamey, respectively. The explained variance (R²) is always higher than 0.95 and root mean square errors (RMSE) range from 37 W/m² to 65 W/m². Generally there is a good agreement between measurements and simulations. This supports our assumption of a desert aerosol composition for RT calculation. However, for a few situations with high AOD the simulation underestimates the GHI. In libRadtran the AOD is scaled to the different height layers according to the typical desert profile. This leads to uncertainties especially for high AOD. The deviations in N between the two nearby locations Banizoumbou and Niamey originates from the measuring techniques (see Section 2.2). The lower RMSE of 47 W/m² in Niamey compared to 60 W/m² in Banizoumbou reflects the stronger constraint to rule out cloudy situations in Niamey. In summary, the RT calculations are accurate enough to use them for the further modeling steps.

3.2 Sensitivity study for meteorological input parameters

The major driver for the available irradiance is the solar zenith angle, which first needs to be harmonized before the sensitivity of different environmental parameters like albedo or aerosol composition can be investigated. To consider the varying solar zenith angles over the course of the year and all seasons we select 14 representative days, at all six stations separately, for the sensitivity study. First, we determine the minimum zenith angle of each day and sort the days in ascending order. The highest and lowest minimum daily zenith angles are then used as boundaries to define equidistant steps of zenith angles. The days with the minimum zenith angle lying closest to these equidistant steps are then selected for the study. This procedure is separately applied for the first half (January to June) and the second half (July to December) of the year 2006 as zenith angles in spring
and autumn are similar, but other atmospheric parameters may vary. Therefore, both seasons should represent the same amount of days for the sensitivity study. Finally, for each half year seven representative days in equidistant intervals are simulated. The chosen days and the related zenith angles are depicted in the electronic supplementary material.

The variabilities of daily PVAC and PTP due to the meteorological input parameters (aerosol composition, albedo, AOD, PT-humidity, PWV, temperature and wind speed) are assessed for the six stations in West Africa in 2006. For this purpose, the simulation with SolPaRT (on the 14 representative days) is repeated for values at the upper and lower limit of the climatological distribution of a single input parameter while keeping the other parameters at constant reference. For the lower (upper) value the 5 % (95 %) percentile of the measured values in 2006 (for each location separately) is used. As no measurements are available for surface albedo, the highest and lowest assumed values over all sites are taken.

To compare the maximum difference in aerosol composition, two contrasting aerosol profiles, urban (polluted) and antarctic (clean), are used, as they show major differences for the optical properties SSA and \( g \) (SSA = 1 and \( g = 0.784 \) for antarctic (clean) and SSA = 0.817 and \( g = 0.689 \) for urban are assumed by Hess et al., 1998). A lower SSA indicates the presence of more absorbing aerosols, e.g. soot, which would lead to less diffuse irradiance than a higher SSA. A higher \( g \) states a larger fraction of irradiance being scattered into the forward direction, which would increase the circumsolar irradiance (e.g. Boucher, 2015). In this calculation the AOD is assumed as its constant reference. The constant reference values for AOD, aerosol composition and PWV are taken from defaults of the libRadtran library (typical desert profile for AOD and aerosol composition and standard tropical atmospheric profile for PWV). For PT-humidity, temperature and wind speed measured values are used as references. Furthermore, the mean albedo between the different locations is used as the reference albedo (constant for all time steps). All input parameters are listed in the electronic supplementary material.

The model sensitivity is defined as the relative difference between the model output from the two simulations using the upper and the lower value of each meteorological input parameter. The model sensitivity is calculated for PVAC and PTP. The variability can be attributed to the different locations and varying zenith angles. The results identify aerosols as the main influencing factor on both solar technologies (see Figure 3).

Thereby, the AOD has a key role, with a sensitivity of 51 % for PVAC and 100 % for PTP (meaning that no power is generated at high AOD). An additional sensitivity of 11.2 % is found concerning the aerosol composition for PVAC. However, the median sensitivity for aerosol composition on PTP lies below 0.1 %. DNI is mostly influenced by the AOD, whereas DHI is influenced by AOD, SSA and \( g \). As the aerosol composition represents the changes in SSA and \( g \) there is hardly no impact on DNI and therewith on PTP. Furthermore, PWV shows a model sensitivity of 12.4 % for PVAC and 6.5 % for PTP. Median values of model sensitivity of all other parameters are below 10 %. As pressure shows no sensitivity at all, it is not considered in Figure 3.

4 Daily reduction of solar power potential in 2006

To address the first goal of this study (quantification of the general impact of aerosols over the course of one year) daily reductions of power production due to the presence of aerosols are calculated for each clear day at every location. For the PVPP we calculate PVDC and PVAC. For the PTP we calculate PTH and PTP. To investigate whether the loss of solar power production directly scales with the loss of solar irradiance in the atmosphere or if there are non-linear effects, related to the power conversion process within the solar power plant, we also derive the daily reductions of GHI and DNI for comparison.

4.1 Statistical analysis

The daily reductions of GHI, PVAC, DNI and PTP due to aerosols for all clear days are calculated for the six investigated locations and are presented in Figure 4. In comparison to PVAC with median aerosol-induced daily reductions of 13 % to 22 %, PTP median daily reductions due to aerosols are larger with 22 % to 37 % depending on the location (see Figure 4 and Table 4). Median daily reductions of GHI are less profound, ranging from 9.4 % to 14 %. Median daily reductions of DNI
range from 42 % to 53 %. The median, 5 %, 25 %, 75 % and 95 % percentiles for daily reductions of PVAC and PTP as well as for GHI and DNI are summarized in Table 4.

By assuming the desert aerosol type by Hess et al. (1998) being a typical background aerosol in this region, the median daily reduction would be 12 % and 20 % for PVAC and PTP, respectively, averaged over the 14 representative days (used in Section 3.2) and all stations. However, even if these reductions are subtracted from the values in Table 4, the average additional daily reduction by including the measured AOD and atmospheric parameters would lie between 1 % and 10 % for PVAC and between 2 % and 17 % for PTP. Furthermore, the variability by using only one typical background aerosol is much lower, as the variability is mainly driven by AOD variability.

Our results show a similar magnitude for the impact of aerosols on PV power as the study by Li et al. (2017) who found 20 % to 25 % reduction driven by air pollu-

Table 4: Median (Md), 5 %, 25 %, 75 % and 95 % quantiles of daily reduction in % for PVAC, PTP, GHI and DNI for the six different locations in 2006.

| Location    | PVAC | 5% | 25% | 75% | 95% | PTP | 5% | 25% | 75% | 95% |
|-------------|------|----|-----|-----|-----|-----|----|-----|-----|-----|
| Agoufou     | 13   | 5.1| 9.2 | 22  | 41  | 22  | 6.3| 15  | 41  | 89  |
| Banizoumbou | 16   | 5.7| 11  | 23  | 42  | 26  | 7.9| 19  | 40  | 85  |
| Dakar       | 15   | 6.3| 10  | 21  | 35  | 24  | 7.6| 16  | 33  | 66  |
| Djougou     | 22   | 9.7| 15  | 31  | 55  | 37  | 15 | 24  | 60  | 85  |
| Maine       | 15   | 6.4| 11  | 21  | 38  | 24  | 9.2| 18  | 34  | 82  |
| Niamey      | 17   | 5.4| 11  | 23  | 50  | 28  | 9.1| 19  | 43  | 96  |

| Location    | GHI  | 5% | 25% | 75% | 95% | DNI | 5% | 25% | 75% | 95% |
|-------------|------|----|-----|-----|-----|-----|----|-----|-----|-----|
| Agoufou     | 9.4  | 3.5| 6.5 | 16  | 26  | 42  | 17 | 32  | 61  | 75  |
| Banizoumbou | 11   | 4  | 7.4 | 15  | 29  | 46  | 20 | 35  | 58  | 80  |
| Dakar       | 11   | 4  | 7   | 15  | 23  | 42  | 19 | 32  | 54  | 71  |
| Djougou     | 14   | 6.4| 10  | 20  | 36  | 53  | 29 | 41  | 65  | 87  |
| Maine       | 9.5  | 4.5| 7.1 | 14  | 26  | 42  | 21 | 33  | 56  | 75  |
| Niamey      | 11   | 3.8| 7.2 | 14  | 34  | 42  | 18 | 32  | 56  | 86  |
tion in China during 2003 to 2014. Previous studies have used GHI as the primary contributor to derive relative PVAC reductions (Kosmopoulos et al., 2017; Calinoiu et al., 2013), thus not including the effects inside the PV plant. However, our results indicate that the PVAC reduction can be up to 8 percentage points higher than GHI reduction depending on the location. These reductions occur mainly due to reflectance, temperature and inverter losses. The daily reductions for PTP differ from the reductions of DNI by 14 % to 20 %. Thus, to calculate the reductions in PVAC and PTP a more profound approach than only using GHI and DNI is needed, as the relative dependence is not always linear and involves several parameters. The correlation between the daily reduction of solar radiation and power output is shown graphically (see Figure 7) and discussed in section 4.3.

The spatial variability of daily reductions of PVAC and PTP is represented by the distribution of the six locations in West Africa (see Figure 4 and Table 4). Daily reductions vary by up to 9 percentage points for PVAC and up to 15 percentage points for PTP between the locations. On the one hand, the number and seasonal distribution of clear days vary for each location due to the different climate zones. On the other hand, AOD varies at the different locations.

Djougou shows the highest median daily reduction in both, PVAC and PTP, 22 % and 37 % respectively, however there are fewer extreme reductions at this location compared to the others. Djougou is situated in a tropical wet climate (Peel et al., 2007) and south of the Sahel. Therefore the conditions are more humid (higher PWV during the dry season, see input data in the electronic supplementary material) with more frequent rainfall and a longer wet season due to the WAM. Furthermore the effect of dust outbreaks is smaller at this location as the distance to the dust source is larger than for the other locations. Agoufou shows the lowest median daily reduction of 13 % and 22 % for PVAC and PTP, respectively. This station lies in a hot desert climate (Peel et al., 2007) whereas all other locations lie in a hot semi-arid climate. Thus, Agoufou is influenced by less rain than the other stations and thereby a lower humidity and PWV.

4.2 Variability of power output

To investigate the power reductions inside the plants we compare different parameters within the plants. The PVDC before the inverter in a photovoltaic power plant and the PTH of a parabolic trough power plant are the first calculated power characteristics of the two technologies and show the most direct variability due to meteorological parameters. However, the power delivered by the plant (PVAC and PTP) might differ due to technical specifications. The relative difference (in %) between the aerosol-induced daily reduction in PVDC ($\Delta$PVDC, in %) and in PVAC ($\Delta$PVAC, in %) is calculated as

$$\Delta PV = (\Delta PVAC - \Delta PVDC)/\Delta PVAC. \quad (4.1)$$

The relative difference (in %) between the aerosol-induced daily reduction in PTH ($\Delta$PTH, in %) and in PTP ($\Delta$PTP, in %) is calculated as

$$\Delta PT = (\Delta PTP - \Delta PTH)/\Delta PTP. \quad (4.2)$$

These differences are calculated separately for each station (see Figure 5).

In general, the transformation to AC power in a PV plant shows an additional power reduction (positive $\Delta PV$), whereas the power block process dampens the impact of aerosols in a PTPP (negative $\Delta PT$). Median differences between daily reductions due to aerosols of PVDC and PVAC range from 1.25 % to 1.5 %, whereas median differences between daily reductions of PTH and PTP range from –23 % to –49 %.

The additional reduction of PVAC compared to PVDC (positive $\Delta PV$) occurs due to the additional losses in the inverter, because the inverter efficiency increases with PVDC (Luoma et al., 2012). However, the additional reductions due to the inverter are comparably low with a maximum of 1.5 %. The PVPP is only slightly over-dimensioned (around 4 %). Therewith, it cannot compensate the reductions due to aerosols during high insolation. An even more significantly over-dimensioned power plant would not stay in the maximum current and voltage range of the inverter.

On the one hand, lower reductions of PTP compared to PTH (negative $\Delta PT$) are based on the fact that
the PTPP has a maximum electricity generation limit of 50 MW. On the other hand, reduction due to the power conversion in the steam process can arise at very low heat levels (positive $\Delta$PT). To start the power block, a minimum PTH is needed. When the PTH drops below this limit no PTP can be generated at all.

4.3 Impact of aerosol optical depth on power generation

The daily mean AOD is analyzed as a function of daily reductions in GHI and DNI (see Figure 6). Daily GHI reductions due to aerosols scale nearly linear with the AOD at all stations (slopes are between 22 % and 25 %). Prasad et al. (2007) investigate the relation between the reduction of solar irradiance at the surface (termed radiative forcing) and AOD in desert regions in India (their Figure 6b). For an AOD = 1.5 they find a daily mean radiative forcing of around $-80 \text{ W/m}^2$ during dust outbreak periods. For an average daily irradiance at our six locations ranging from 250 $\text{ W/m}^2$ to 270 $\text{ W/m}^2$, this would correspond to a reduction of about 30 %. For GHI we find a similar reduction of around 35 % for AOD = 1.5. Under the presence of smoke, Stone et al. (2008) showed, that an AOD of 0.5 at 500 nm would produce a daily radiative forcing of about $-40 \text{ W/m}^2$. Compared to the daily mean GHI at the locations in this study, this would be around 13 % daily reduction in GHI. Again comparing this value to the relation in Figure 6a, this result fits very well with the around 12 % of daily reductions in GHI at 0.5 AOD. Even when assuming another aerosol source, the AOD seems to be a good indicator for reductions in irradiances (compare to the results in section 3.2).

The aerosol transmittance $T_{\text{AOD}}$ follows an exponential function $T_{\text{AOD}} \sim 1 - \exp(-\text{AOD})$. Thus, the daily DNI reductions can be expressed as

$$T_0 - T_{\text{AOD}} \sim 1 - \exp(-\text{AOD}).$$

The $R^2$ for this correlation ranges from 0.97 to 0.99. However, the shape is not exactly the same.

The relation between daily power reductions and daily reductions in solar irradiances is given in Figure 7, with the AOD indicated as colors. For the PV technology reductions in PV AC and GHI show a linear correlation at all locations (Figure 7a), with a slope around 1.5 and a $R^2$ between 0.98 and 0.99. Even if there are other impacts on PV power production (e.g. module temperature), the GHI seems to be a robust indicator to analyze power reductions due to aerosols. There is no linear relation for DNI and PTP reduction. At lower AOD (marked with colors) the relation seems linear. Here the internal power plant dimension reduces the impact of aerosols, as the power plant has a maximum electricity generation limit. With rising AOD the slope of the relation increases. Here, the minimum heat to start the power block in the PTPP might not have been reached during all time steps (compare to findings in section 4.2).

In general, PTP is reduced about twice as much as PVAC (the relation of AOD and power reductions is visualized in the electronic supplementary material). For a daily mean AOD of around 1.5 no power can be generated by the PTPP anymore and daily reductions of about 50 % for PVAC are reached.
5 Regional impact of a major dust outbreak on solar power production

In the Sahara, large-scale dust outbreaks occur frequently (Taylor et al., 2017). Aerosol loads are high during such extreme events and likely show considerable reductions in solar power. During one fourth of the clear days in 2006 (averaged over all locations) daily reductions of PVAC and PTP exceed 20 % and 35 %, respectively (see Figure 8). These reductions due to the presence of aerosols could potentially lead to blackouts and network instabilities in a solar-based power system. Extreme daily reductions of up to 100 % for PTP and of up to 79 % for PVAC would need high storage capacities or other power resources to overcome this lack in power generation. To address the second goal of this study (quantifying the variability of the aerosol impact on solar power), we choose one major well-documented dust outbreak that occurred between March 6 and 17, 2006 (Tulet et al., 2008; Slingo et al., 2006) to investigate its impact on solar power.

5.1 Regional development of the dust outbreak

The dust outbreak was induced in the Atlas Mountains of northern Algeria on March 5, 2006 (Tulet et al., 2008; Slingo et al., 2006). It reached the central region of the Sahel around Agoufou, Banizoubou and Niamey by March 7, 2006 and coastal regions around Dakar by March 8, 2006 (see Figure 9). More easterly regions of the Sahel around Maine might have been affected between March 8 and 9, 2006 (no AOD is available at this location during those days). The zone south of Sahel around Djougou came under the influence of the storm on March 8 or 9, 2006. The highest AOD of more than 4 was reached at Niamey (see input data in electronic supplementary material).

The highest daily reduction in PVAC of 79 % is modeled for Niamey on March 8, 2006, for Dakar and Banizoubou on March 9, 2006 (no data was available for Agoufou on this day) and for Djougou on March 11, 2006. The decrease of PVAC at the start of the dust period is fastest in the central Sahel (Agoufou, Banizoum-
To overcome these power reductions several days of storage capacities would be needed. Most common storage applications for solar power plants are battery storage for PV systems (Hoppmann et al., 2014) and thermal energy storage for CSP plants (Gallo et al., 2016). Thermal energy storage is currently cheaper than battery storage. Energy costs lie between 120 and 2500 $/kWh for battery storage and between 0.1 and 100 $/kWh for thermal storage (Gallo et al., 2016). Typically, the thermal storage systems of a CSP plant are dimensioned to overcome night times or times with low DNI during one day. The Andasol I power plant, used in this study without storage, has a thermal storage capacity of 982 MWh<sub>e</sub>, which represents 7.5 hours peak load (Kistner et al., 2004). Battery storage for PV plants is mainly used in small-scale systems or for mini-grid stabilization with capacities of several kW (IRENA, 2017). Thus, CSP plants have the advantage compared to PVPP, that they are already used in combination with storage systems at high capacities. However, for a completely solar based power system larger storage capacities to overcome desert dust induced power reductions need to be developed.

### 5.2 Impact of soiling on PV power at Banizoumbou

Up to now, all our results considered atmospheric impacts on solar power due to aerosols. However, soiling causes an additional impact of aerosols on solar panels. Reviews are provided e.g. by Costa et al. (2018); Costa et al. (2016); Sayyah et al. (2014); Sarver et al. (2013) and showed that the impact of soiling can significantly reduce or even completely terminate power generation with solar power plants. Thereby, soiling reduces the transmission of solar irradiances for PV and causes reflection losses for CSP plants (Sarver et al., 2013). The impact on PV and CSP mainly varies due to the location, the front layer material, the tilting angle and weather. Monthly losses range from 3% to 90% for PV and from 14% to 78% for CSP depending on the before mentioned impacts. With SolPaRT the impact of aerosols within the atmosphere can be analyzed, but the inclusion of soiling would require more information, e.g., on deposition rates and cleaning cycle. Here we exemplary estimate the effect of soiling on a PV panel during the dust outbreak at Banizoumbou.

Mass concentrations \( m \) of particles were measured at Banizoumbou during the whole time of the dust outbreak (AMMA, 2018). A constant falling velocity \( v_p \) in the range between 2 and 10 cm/s is assumed, which is typical for a desert region according to Ganor and Foner (2001). For tilting angles of 15° Elminir et al. (2006) found about 20% lower dust concentration densities on PV panels compared to a zero tilt. Therefore, we use a factor of 80% to calculate the dust concentration density \( \rho_{\text{panel}} \) on the panel

\[
\rho_{\text{panel}} = v_p \cdot m \cdot 0.8. \tag{5.1}
\]

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1Thereby the effect of wind speed is not included into the algorithm, as its impact lies between −3 and 1.5% on the cleanness for wind speeds up to 5 m/s (Guo et al., 2015).
Transmission losses $\Delta T$ of PVPP depend on the dust concentration density. A linear relation

$$\Delta T = 4 \cdot \rho_{\text{panel}} - 4 \quad (5.2)$$

for $1 \text{ g/m}^2 < \rho_{\text{panel}} < 20 \text{ g/m}^2$, can be derived from Figure 6 in Elminir et al. (2006). For $\rho_{\text{panel}} > 20 \text{ g/m}^2$ we assume 20% and for $\rho_{\text{panel}} < 1 \text{ g/m}^2$ we assume 0% transmission losses.

As we do not know the exact falling velocity the transmission losses are calculated for several constant falling velocities for Banizoumbou (Figure 10). Without cleaning transmission losses of solar irradiance would be between 22% and 96% depending on the falling velocity. The daily mean transmission loss is 1.9%, 4.8%, 6%, 7.4% and 8% for falling velocities of 2, 4, 6, 8 and 10 cm/s, respectively. This implies an additional loss of solar power by the same percentage.

There are only a few studies analyzing power reductions due to soiling on a daily basis (e.g. Jamil et al., 2016; Sayyah et al., 2014). They found daily losses of up to 6% in Thar Desert in India (Sayyah et al., 2014) and up to 20% in Malaysia (Jamil et al., 2016).

6 Conclusion

In West Africa the occurrence of aerosol particles significantly modulates the availability of solar power. To quantify these effects we use high temporal resolution meteorological data and aerosol properties from six locations, distributed over different climate zones in West Africa. With this unique data set we analyzed the impact of aerosols on photovoltaic and parabolic trough power plants with the energy meteorological model chain SolPaRT for all clear days in 2006. The combination of both solar power and meteorological models is necessary for solar power predictions to be as realistic as possible. As expected, for cloud-free situations the simulation shows highest sensitivity to AOD compared to other atmospheric parameters. The presence of aerosols is responsible for daily reductions in photovoltaic and parabolic trough power plants of up to 79% and 100%, respectively.

Local median daily reductions due to aerosols in 2006 are determined to be 13% to 22% for photovoltaic power (PVAC) and 22% to 37% for parabolic trough power (PTP) depending on the location. For both technologies daily reduction of solar power production is strongly correlated with AOD (see Figure 6). When AOD is around 1.5 a 100% loss of PTP and a 50% loss for PVAC is found on a daily scale.

A parabolic trough power plant can have a compensating effect on the aerosol impact. Due to economic reasons the power block of the power plant is usually underdimensioned to reach a high capacity utilization. This leads to a higher aerosol-induced reduction of absorbed heat than the reduction of PTP. For PVAC no compensating or significantly enhancing effect was found.

Dust outbreaks can have a strong influence on both PVAC and PTP. We analyzed one specific event in March 2006 and estimate that concentrating systems would not produce any electricity for several days in a row during such an event. Photovoltaic modules would reduce their power generation to a minimum of 21% during one day. Furthermore, soiling would cause an additional reduction for both technologies. For photovoltaic modules and depending on the assumed fall velocity, this effect can be as large as 96% shading after the analyzed dust outbreak. For both technologies the installation of a storage system to overcome such periods of large power losses, which can also arise during cloudy times, would be reasonable. For the dust outbreak in March 2006, the storage system should have been sized such that it can provide power for a minimum of four days to compensate PTP and up to 79% of needed PVAC during at least one day for the compensation. However, more events need to be studied to derive more general conclusions on storage needs.

PTP is more susceptible to the impact of aerosols than PVAC. However, combinations of PTP with large scale thermal storage systems are already used. Furthermore, they can be combined with secondary combustion by fossil fuels to compensate times with low incoming solar irradiance. Battery storage systems for the combination with PVPP are still smaller and more expensive than thermal storage systems (IRENA, 2017). With SolPaRT, a modeling tool has been developed which includes the major atmospheric effects on GHI and DNI and takes into account the technical parameters and their environmental dependencies for modules, inverters or power plant characteristics to assess PVAC or PTP. However, additional impacts could be caused by the variable composition of aerosols influencing their extinction efficiency or the spectral variability of solar irradiance. These impacts should be subject to further research as well as the impact of clouds.

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List of abbreviations and symbols

| Symbol | Description |
|--------|-------------|
| \Delta PT | Relative difference (in %) between \Delta PTH and \Delta PTP |
| \Delta PV | Relative difference (in %) between \Delta PVDC and \Delta PVAC |
| \Delta PTH | Daily reduction in PTH |
| \Delta PTP | Daily reduction in PTP |
| \Delta PVAC | Daily reduction in PVAC |
| \Delta PVDC | Daily reduction in PVDC |
| \Delta T | Transmission loss |
| AERONET | AErosol RObotic NETwork |
| AMF | ARM mobile facility |
| AMMA | African Monsoon Multidisciplinary Analysis |
| AOD | Aerosol optical depth |
| ARM | Atmospheric Radiation Program |
| Aw | Tropical wet climate |
| BSh | Hot semi-arid climate |
| BWh | Hot desert climate |
| CSP | Concentrating solar power |
| DHI | Diffuse horizontal irradiance |
| DIR | Direct horizontal irradiance |
| DISORT | DIScrete Ordinates Radiative Transfer solver |
| DNI | Direct normal irradiance |
| \rho_{panel} | Dust concentration density on the panel |
| v_p | Falling velocity |

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