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Rethinking solar resource assessments in the context of global dimming and brightening

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Abstract

Solar resource assessments use solar radiation data from past observations to estimate the average annual solar radiation over the expected lifetime for a solar energy system. However, solar radiation at the Earth's surface is not stable over time but undergoes significant long-term variations often referred to as "global dimming and brightening". This study analyzes the effect of these long-term trends on solar resource assessments. Based on long-term measurement records in Germany, it is found that the additional uncertainty of solar resource assessments caused by long-term trends in solar radiation is about 3% on the horizontal plane and even higher for tilted or tracked planes. These additional uncertainties are not included in most uncertainty calculations for solar resource assessments up to now. Furthermore, for the measurement stations analyzed, the current irradiance level is about 5% above the long-term average of the years 1951–2010. Since the direction of future trends in solar radiation is not known, different possibilities to estimate the future solar resource are compared. In view of long-term trends that could extend beyond the period of past observations and beyond the projected lifetime of a solar energy application, a paradigm shift is proposed: instead of using the longest possible period to calculate an average value, only the 10 most recent years should be used as the estimator for future solar irradiance.

Keywords: Solar radiation; Irradiance; Solar resource assessment; Global dimming and brightening

1. Introduction

To obtain financing for large solar energy applications an assessment of the solar resource at the location of the system must be carried out. This assessment is typically based on the assumption that the long-term average annual solar radiation from the past is not significantly different from the "true" climatological value and can therefore be used as an estimator for the availability of solar resources in the future (see e.g. Gueymard and Wilcox, 2011; Vignola et al., 2012). Discrepancies resulting from this assumption are often not considered or considered to be negligible compared to other modeling uncertainties (e.g. Thevenard and Pelland, 2013).

On the other hand, there is evidence that solar radiation incident on the Earth's surface is not stable over time but is subject to long-term trends spanning multiple decades. Numerous studies reported a general decrease in surface solar radiation at many observation sites from the beginning of widespread measurements in the 1950s up to the 1980s (e.g. Ohmura and Lang, 1989; Liepert et al., 1994; Stanhill and Cohen, 2001; Gilgen et al., 1998; Wild,

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2009a, and references therein), a phenomenon often referred to as "global dimming". More recent studies using updated records found a trend reversal and partial recovery in surface solar radiation at many of the sites since the mid-1980s, a phenomenon referred to as "brightening" (Wild et al., 2005). Increasing and decreasing air pollution and associated aerosol loads, as well as their effects on clouds, are considered as major contributors to the dimming and brightening, respectively. The transition from dimming to brightening is in line with a trend reversal in air pollution and aerosol burdens in the atmosphere during the 1980s, particularly in the industrialized regions, which can be attributed to more effective air pollution regulations and the breakdown of the economy in Eastern European countries. Changes in solar irradiance at the top of atmosphere as well as changes in stratospheric aerosol related to volcanic eruptions are considered less important for the explanation of the observed decadal changes of surface solar radiation. For a more detailed discussion of the causes of dimming and brightening the reader is referred to Wild (2009a,b, 2012).

In this work we will analyze long-term trends for 8 measurement stations in Germany and quantify the effects of these trends on solar resource assessments. We will analyze (i) the differences between consecutive multi-year averages, (ii) the deviations of individual years from multi-year averages, and (iii) changes in irradiance distributions over time. Furthermore, solar radiation in tilted and tracked planes will be modeled from the measurements in the horizontal plane. Trends on these values will be compared to the trends in horizontal planes.

All trends in this paper are reported as absolute values and also as percentage per decade with a 90% confidence interval. For consistency in comparing trends over periods with different lengths, the percentages are calculated in relation to the average values of the entire time series.

2. Available data and data filtering

The German Meteorological Service (Deutscher Wetterdienst, DWD) measures global and diffuse solar radiation at about 30 observation stations across Germany. For some of these stations data for more than 50 years is available, exceeding more than 70 years for the observation station Potsdam. Thermopile pyranometers were used for these measurements since the beginning. The pyranometers measuring diffuse solar radiation are shaded by a shadow band. Because a shadow band covers more than the solid angle of the sun, the diffuse radiation measurements are corrected using a standard procedure (WMO, 2012). The analysis presented herein uses data from eight DWD stations, for which more than 40 years of global horizontal irradiance (GHI) is available. Table 1 lists those stations along with their World Meteorological Organization (WMO) station ID, geographical coordinates and the starting year and month of the measurements.

The irradiance data is stored in hourly time resolution. GHI data is available for this study from 1951 (or from the beginning of the measurement, see Table 1) to 2010, while diffuse horizontal irradiance (DIF) is available for 1991–2010. All data are quality checked by the DWD and erroneous measurements are removed from the time series. Note however, that in a multi-decadal measurement there may be breaks or irregularities in the data. For a discussion of the measurement uncertainties the reader is referred to Section 7.

As there are some gaps in the data due to downtimes of the measurement equipment or erroneous data, a suitable method must be used to calculate annual averages from the hourly data (Roesch et al., 2011). For the analysis of long-term trends in GHI and their influence on solar resource assessments in Sections 3 and 4 annual averages of GHI are calculated as follows: (i) daily totals are calculated if all hourly values for the day are available, (ii) the monthly sum is calculated from the mean daily totals if more than 50 % of the daily totals in the month are available, and (iii) annual means are calculated if all monthly values for the year exist. As data filling technics may introduce additional uncertainties and may have influences on the trends calculated, we did not apply any further data filling methods (beside the implicit data filling used to calculate the averages).

In Section 5 trends for the components of GHI from 1991 to 2010 are analyzed. For this analysis GHI and DIF are obtained from the measurements, while direct horizontal irradiance (DHI) is calculated from the former components. To exclude measurement errors, additional filtering methods are applied, which are based on the methods given in Younes et al. (2005) and Journée and Bertrand (2011). For the quality envelope test (see Journée and

Table 1
Measurement stations under consideration.

Measurement station	WMO station ID	Latitude	Longitude	Altitude (m)	Begin of measurement
Braunschweig	10,348	52°18′N	10°27′E	83	07/1962
Fichtelberg	10,578	50°26′N	12°57′E	1219	05/1958
Hamburg	10,147	53°38′N	10°00′E	14	07/1949
Hohenpeissenberg	10,962	47°48′N	11°01′E	990	01/1953
Potsdam	10,379	52°22′N	13°05′E	107	01/1937
Trier	10,609	49°45′N	06°40′E	278	01/1964
Weihenstephan	10,863	48°24′N	11°42′E	472	01/1961
Wuerzburg	10,655	49°46′N	09°58′E	275	05/1957

Bertrand, 2011, section 2.4) a simplified procedure is applied: the clearness index

$$K_t = GHI/E \quad (1)$$

is calculated, where E is the extraterrestrial irradiance on a horizontal surface. The diffuse fraction

$$K = DIF/GHI \quad (2)$$

is than modeled from the measurements using the model by Erbs et al. (1982). To built the quality envelope, the modeled line is shifted ±0.2 points in x (K_t) and y (K) direction, while the physical limits

$$0.0 \leqslant K, K_t \leqslant 1.0 \quad (3)$$

are preserved. All values outside this envelope are removed from the data. By applying this method, measurements with unphysical correlations, e.g. a high clearness index, but a diffuse fraction near 1.0 should be removed.

In Section 6 irradiance trends in tilted and tracked planes will be analyzed. The irradiance values are calculated from the filtered time series used in Section 5.

The inclusion of DIF data in Sections 5 and 6 leads to a smaller usable data set. Some GHI values are discarded because the corresponding DIF value is missing, and in addition some DIF/GHI pairs are discarded because they are deemed physically impossible. As a result, some annual values are missing that were present in Section 3. For the analysis in these sections only locations with at least 15 valid annual values (out of 20) are used, which are Braunschweig, Hamburg, Potsdam, Trier and Wuerzburg.

3. Long-term trends in global horizontal irradiance

The first step of the analysis is to quantify the trends in the data and to identify the approximate point at which the trend reversal from the dimming to the brightening period occurs. In preparation, for each site, the annual anomalies (the percentage deviation from the all-time average) are calculated. Then, for each year, the mean anomalies over all sites are determined.

The resulting time series of mean anomalies is partitioned into all possible combinations of two subsets with a minimum time span for a subset of 10 years, starting with 1951–1960 and 1961–2010 and ending with 1951–2000 and 2001–2010. A linear regression is performed on each combination and subset to determine its slope. The point at which the trend reversal occurs was defined as the point where the absolute difference between the two slopes is at its maximum.

Using this approach, the time span for the dimming period is determined to extend from the beginning of the data set (1951) to 1983, while the brightening phase reaches from 1984 to the end of the data set (2010). The separation into these time periods corresponds quite well with the dimming and brightening periods reported in previous publications (Wild et al., 2005; Wild, 2009a; Lohmann et al., 2006). The sum of squared residuals when using these two trends is reduced by about 25% compared to the sum of squared residuals of a single trend line for the full data set.

The time series of all locations are now partitioned into these dimming and brightening periods and for each one the trends are calculated. Fig. 1 shows the annual anomalies in GHI for all stations under consideration as well as the trend line and a 10-year moving average for the mean anomalies over all locations. The trend magnitudes are listed in Table 2.

Note that from 1951 to 1963 not all stations were operating (see Table 1), so for those years the mean anomaly time series is composed of measurements from fewer stations. This introduces some uncertainties for the detection of the overall trend. However, starting in the year where data from all stations is available (the year 1964) would significantly reduce the time span of data. The calculated trend using the mean anomalies from 1964 onwards is (-1.5 ± 2.7) %/decade, so compared to trend for the whole time period, there is only a marginal difference.

The magnitude and signs of all trends are in line with expectations from the literature (negative for the dimming period and positive for the brightening period) with one exception: Braunschweig has a positive trend during the dimming phase. We presume this is attributable to local influences.

The confidence intervals for the site-specific trends are quite large in comparison to the magnitudes of the trends, which may call into question their significance. This is principally due to the large year-to-year variations, which could be reduced by a suitable filter such as a moving average. When using the 10-year moving average for the mean

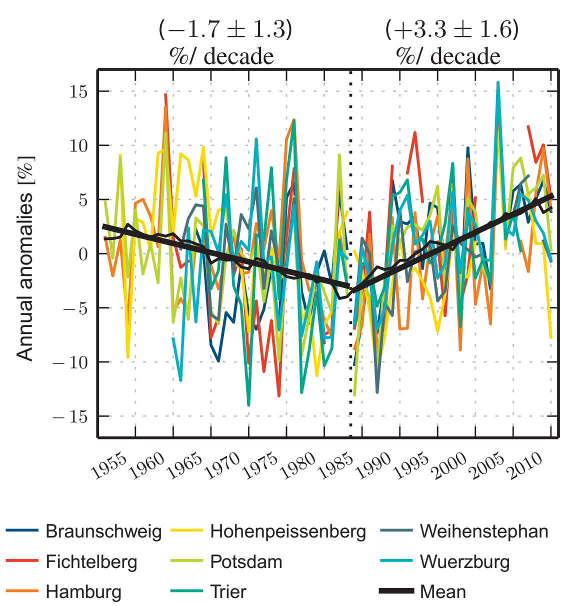

Fig. 1. Annual anomalies of GHI from the long-term average for each site. The colored thin lines connect annual anomalies for individual locations. In black the 10-year moving average (thinner line) and the trend (thicker line) for the mean anomalies of all individual time series are shown. The trend line parameters are shown at the top of the diagram. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Long-term trends in GHI for the locations considered in this study and the mean anomalies. For the dimming period 1951–1983 the trends are negative (with the exception of Braunschweig). In the brightening period 1984–2010 all trends are positive.

Station	1951–1983		1984–2010	
	W/(m^{2}decade)	%/Decade	W/(m^{2}decade)	%/Decade
Braunschweig	3.2 ± 3.2	2.8 ± 2.8	4.3 ± 2.4	3.8 ± 2.1
Fichtelberg	−3.7 ± 4.6	−3.3 ± 4.2	4.5 ± 3.2	4.0 ± 2.9
Hamburg	−0.6 ± 1.7	−0.5 ± 1.6	4.5 ± 2.6	4.1 ± 2.4
Hohenpeissenberg	−4.3 ± 2.5	−3.1 ± 1.8	3.6 ± 2.7	2.6 ± 1.9
Potsdam	−1.8 ± 1.8	−1.6 ± 1.5	4.7 ± 2.2	4.1 ± 1.9
Trier	−4.1 ± 6.0	−3.3 ± 4.9	2.7 ± 2.9	2.2 ± 2.4
Weihenstephan	−3.3 ± 3.1	−2.4 ± 2.3	4.9 ± 2.7	3.7 ± 2.0
Wuerzburg	−0.4 ± 3.4	−0.3 ± 2.7	3.2 ± 2.2	2.6 ± 1.7
Mean Anomalies	−2.1 ± 1.6	−1.7 ± 1.3	4.0 ± 2.0	3.3 ± 1.6

anomalies (shown in Table 1) to calculate the trend, the trend is similar, but the confidence interval is much smaller: (-1.8 ± 0.2) %/decade for the dimming phase and (3.0 ± 0.2) %/decade for the brightening phase. A more complex model for the dimming and brightening phenomenon (rather than piecewise linear) could further improve the fit and provide improved confidence intervals, however, to the knowledge of the authors no physically meaningful model for this phenomenon has been published.

The exceptionally sunny year 2003 shows the biggest positive annual mean anomaly with 14.2% more horizontal irradiance than the long-term average. Excluding 2003 from the trend analysis leads to a trend of (2.8 ± 1.3) %/decade for the brightening period, which is only slightly less positive than the trend that includes 2003. The biggest negative annual mean anomaly is −9.1% in the year 1987.

4. Influence of GHI trends on solar resource assessments

For solar resource assessments the critical factor is that the mean annual irradiance for a defined time period in the future (the prediction period) is accurately estimated. To achieve this, typically historically observed (or satellite derived) irradiance data of a certain time period (the reference period) is used to calculate a “long-term” average irradiance, which is then used as an estimator for the prediction period.

To assess the accuracy of this approach we analyze three typical cases where either a 10-year, a 20-year or a 30-year reference period is used to derive the estimator for the “long-term” average. The 10-year reference period represents the minimum time span for solar resource assessment that is recommended to “average out” the influence of single years with very high or low anomalies (Lohmann et al., 2006). The 30-year reference period represents a maximum, but is a usual time span for solar resource assessments in Germany, as the DWD provides 30-year averages (1981–2010) for arbitrary locations in Germany (computed from a mixture of measurements and satellite data).

In all cases the prediction period is set to 20 years, which is the de facto standard time period for solar resource assessments for PV systems in Germany. This standard has developed in large part because the German feed in tariff is paid for 20 years.

The deviation Δ of the average irradiance in the reference period to the average irradiance in the prediction period is calculated using Eq. (4)

$$\Delta = 1 - \frac{\overline{GHI}_{[Y-n,Y]}}{\overline{GHI}_{[Y+1,Y+20]}} \quad (4)$$

where $\overline{GHI}_{[Start,End]}$ is the average GHI in the interval, Y is the year under consideration (in other words, the year when the hypothetical solar resource assessment is done) and n is the number of years for the reference time series (10, 20 and 30 years). Since some annual values are missing in the dataset, 10% missing annual values were tolerated; if there were more values missing the deviation was not calculated. For the site Fichtelberg, this meant that no deviations at all could be calculated and for Trier and Weihenstephan the 30-year values are not available. The range for the year Y is smaller than the range of the irradiance dataset because the reference period and prediction period must both fit within the data range.

Fig. 2 shows the deviations for all locations and their evolution over time.

As expected Δ is negative in the early years because of the dimming trends, meaning that the actual solar radiation during the 20-year prediction period was less than would have been predicted based on the reference period. This is true for all three reference period choices as the dimming period lasted more than 30 years. The brightening period had the opposite effect in later years: the actual solar radiation there was greater than would have been predicted.

The deviations for individual sites extend to about ±8% for the 10-year reference period, to about ±6% for the 20-year reference period and from −4% to 6% for the 30-year period. This seems to suggest that a longer reference period is preferable. On the other hand, the root mean square deviation (RMSD) of Δ_{Mean} (i.e. the points indicated by the black line in Fig. 2) is only marginally affected: it amounts to 3.3% for the 10-year reference period, 3.1% for the 20-year period and 2.9% for the 30-year period.

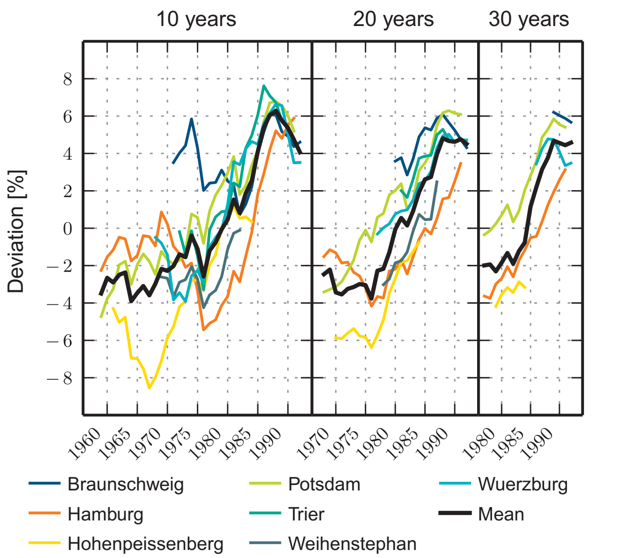

Fig. 2. Deviation between the average irradiance in the prediction period (the subsequent 20 years starting at the year given on the *x*-axis) and the irradiance averaged over the reference period of 10 years (left), 20 years (middle) and 30 years (right) prior to the year given on the *x*-axis. The black line shows the mean deviations for individual years.

It should be noted that these numbers refer to different time periods of different lengths (see the three portions in Fig. 2): while for the 10-year reference period the deviations from the late 1950s to the beginning of the 1990s are calculated, only deviations from the late 1970s are available for the 30-year reference period. Additionally, the period where deviations for all three reference periods are available (late 1970s to the beginning of the 1990s) is a period where a trend reversal occurs (see Fig. 1). To identify an optimal reference period duration that minimizes the deviation would require a longer data set.

Beside the overall deviation in the mean values over the whole period, the range of deviations in individual years is of interest in solar resource assessments. Normally the deviations of individual years are calculated from the average of the full time series (the anomalies). For the individual sites analyzed here, these deviations extend from −14.0% to 15.8%. We additionally calculated the deviation of individual years in the prediction period from the average of the reference period. This method seems to be a more realistic measure for deviations of individual years in a solar resource assessment, as it includes dimming/brightening influences as well as usual year-to-year variations.

Calculated in this manner, the deviations of individual years are in a range of −16.6% to 21.8% for the 10-year reference period, −14.1% to 19.2% for the 20-year reference period and −12.5% to 18.6% for the 30-year reference period. On average over all years and locations the year with the minimum (maximum) irradiance in the prediction period is −8.6% below (10.5% above) the average of the reference period for the 10-year reference period, −8.3% below (11.4% above) for the 20-year reference period and −7.6% below (11.7% above) for the 30-year reference period. Nevertheless, the same limitations as before apply, when these results are compared to the range of the deviations from the all time average and against each other: they refer to different time periods of different lengths.

In summary, by using the RMSD of the mean deviations between reference and prediction period as an indicator for the standard uncertainty of GHI predictions resulting from long-term trends in solar radiation, it can be seen that a longer reference period barely reduces the uncertainty: in all three cases it is near 3%. To the knowledge of the authors this factor is not included in most uncertainty calculations for solar resource assessments. GHI for individual years in the prediction period may vary from the estimated average of GHI in a range of about −15% to 20%.

5. Trends for direct and diffuse irradiance in the horizontal plane

The annual variability and long-term trends in GHI play an important role in the planning of solar energy systems because system output is strongly correlated with GHI. However, solar energy systems are usually designed to take advantage of the stronger direct radiation component, thus the trends in system output are not necessarily identical to the GHI trends. This is obvious for technologies like concentrated solar power (CSP) or concentrated photovoltaics (CPV) as they are tracking the sun and can use only direct irradiance for energy conversion. Yet, this also applies for non-concentrating photovoltaics or solar thermal systems, which are tilted or are tracking the sun to capture a larger portion of the direct irradiance.

In this section we examine long-term trends of diffuse and direct irradiance in the horizontal plane. While GHI and DIF are available as measured values, DHI is calculated as the difference between them. In the following section we then use these measurements to determine the trends in irradiance received on tilted and tracking planes of a solar energy system.

As described in Section 2 the data availability and the data filtering is different for the time series used in this section. A maximum of 20 years of data is available for a smaller number of sites and additional gaps exist where diffuse measurements are unavailable. We therefore recalculated the brightening trends in GHI for this shorter period to use them as the basis for comparison in this section only. To calculate the trends, the data is aggregated into annual values as described in Section 2. The annual anomalies and the trends are shown in Fig. 3, the trend values are given in Table 3.

Table 3 shows, that using only the last 20 years of the brightening period produces smaller GHI trend values compared to the trends for the full brightening period (Table 2), but all trends are still positive.

Of greatest importance in this table are the trends for DIF and DHI: while the trends for DIF are all negative,

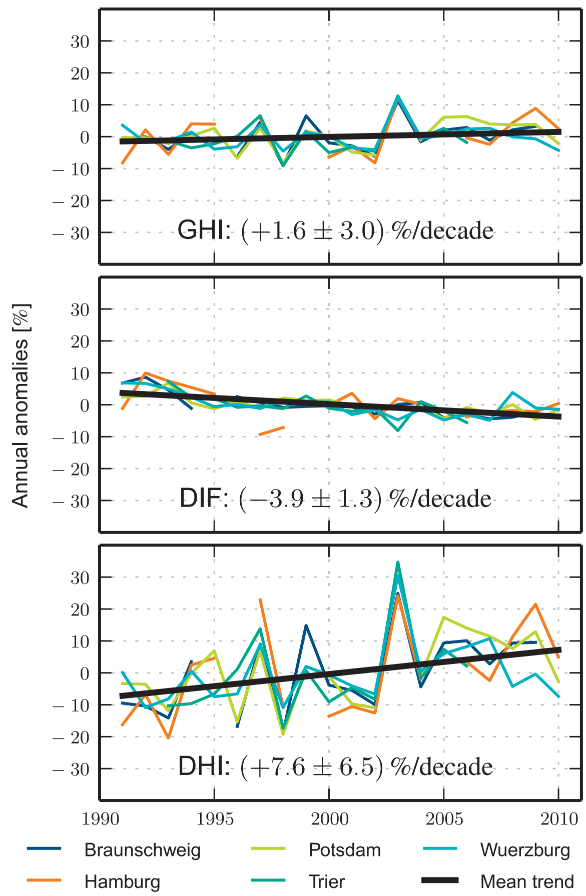

Fig. 3. Annual anomalies for irradiance on the horizontal plane: global (top), diffuse (middle) and direct irradiance (bottom) in the time period from 1991 to 2010. The number on the bottom of each plot shows the trend for the mean anomalies.

all trends for DHI are positive and much higher than the trends for GHI. This is in line with expectations, as decreases in air pollution and aerosol concentration which are a driving force for global brightening will reduce scattering and absorption in the atmosphere, thereby simultaneously increasing the direct and decreasing the diffuse irradiance. A reduction in the duration of cloud cover is likely another reason and has a similar opposite effect on direct and diffuse irradiance (see e.g. Gueymard, 2012; Lohmann et al., 2006; Norris and Wild, 2007, for a more detailed discussion on these effects).

Interannual deviations are also the biggest for DHI, reaching from −15.8% to 28.2% for the mean anomalies (−8.2% to 12.1% for GHI, −4.0% to 6.7% for DIF).

In this section we have shown that the positive trend for GHI in the brightening period coincides with an increase in DHI and a decrease of DIF. This significant shift from diffuse to direct irradiance in the horizontal plane results in a mean trend for the diffuse fraction of (−2.9 ± 1.7) %-points/decade.

6. Trends for tilted or tracked planes

To determine the trends for tilted or tracked planes, the following values are calculated from hourly data in the period 1991–2010:

- global irradiance in a tilted plane (GTI) with a tilt angle of 30° and orientation to south
- global normal irradiance (GNI)
- direct normal irradiance (DNI)

For the calculation of the diffuse radiation on tilted or tracked planes the transposition model of Perez et al. (1990) is used. The absolute accuracy of this model see e.g. Gueymard, 2009, for an evaluation is not of primary importance for our purpose, since we are “only” looking for trends in the results. In fact, we performed the same calculations using the model by Klucher (1979) and obtained nearly identical trends.

Fig. 4 shows the data and the trends for tilted or tracked planes. The numbers for individual locations and the mean anomalies are given in Table 4.

All trends on tracked and tilted planes are higher than the trends calculated for the horizontal plane (see Table 3). GTI shows a 0.5%-points/decade higher trend than GHI for the locations analyzed. This increase is logical, since a tilted plane facing the sun receives more direct irradiance and less diffuse. So the increase in direct irradiance has a stronger influence on the GTI trend. For GNI the fraction of direct irradiance is higher yet compared to the tilted plane. The trend is 1.9%-points/decade higher than the GHI trend and more than doubled. DNI shows a slightly higher trend compared to DHI (+0.9%-points/decade). However, this trend is about five times higher than the trend for GHI.

Table 3
Trends for GHI, DIF and DHI for the period 1991–2010. Trends for GHI and DHI are positive, while for DIF the trends for all locations are negative.

Station	GHI		DIF		DHI	
	W/(m^{2}decade)	%/Decade	W/(m^{2}decade)	%/Decade	W/(m^{2}decade)	%/Decade
Braunschweig	2.8 ± 4.3	2.4 ± 3.7	−3.4 ± 1.0	−5.3 ± 1.6	6.3 ± 4.3	11.6 ± 7.9
Hamburg	3.4 ± 4.9	3.0 ± 4.3	−1.9 ± 2.0	−3.2 ± 3.3	5.3 ± 4.7	10.0 ± 9.0
Potsdam	.9 ± 3.3	.4 ± 2.8	−1.9 ± 0.8	−3.1 ± 1.3	4.8 ± 3.6	8.4 ± 6.3
Trier	1.6 ± 5.9	1.3 ± 4.8	−2.9 ± 1.8	−4.5 ± 2.8	4.5 ± 6.4	7.5 ± 10.6
Wuerzburg	0.4 ± 3.5	0.3 ± 2.7	−2.6 ± 1.2	−3.8 ± 1.9	3.0 ± 4.0	4.8 ± 6.4
Mean Anomalies	1.9 ± 3.6	1.6 ± 3.0	−2.5 ± 0.8	−3.9 ± 1.3	4.4 ± 3.7	7.6 ± 6.5
w/o 2003	1.3 ± 2.8	1.1 ± 2.4	−2.4 ± 0.8	−3.8 ± 1.3	3.8 ± 2.9	6.6 ± 5.1

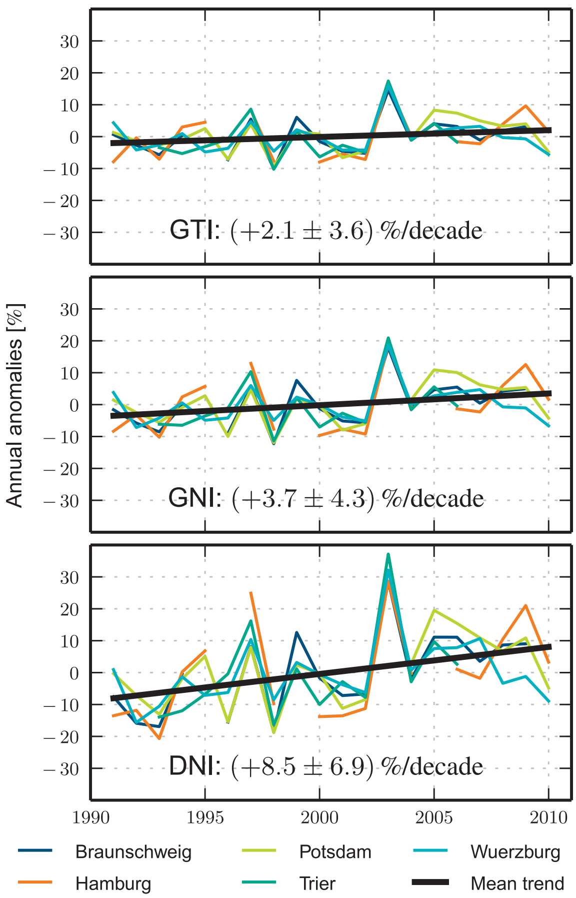

Fig. 4. Anomalies for irradiance on tilted or tracked planes: global tilted (30° South, top), global normal (middle) and direct normal irradiance (bottom). The number on the bottom of each plot shows the trend for the mean anomalies.

These higher trends will lead to overall higher deviations between reference and prediction periods and therefore will further increase the uncertainties of the solar resource in tilted or tracked planes. For GHI the uncertainty due to the trends estimated in Section 3 is about 3%. This is approximately double the magnitude of the trend for the period 1991–2010 derived in Section 5. Application of this factor to the tilted and tracked planes, would lead to an uncertainty of about 4–5% for GTI, about 6–7% for GNI and up to 15% for DNI.

The higher trends also increase interannual deviations compared to the horizontal plane: the mean anomalies are in a range of −15.3% to 30.3% for DNI, −9.9% to 18.4% for GNI and −8.6% to 15.8% for GTI.

The trends in GTI, GNI and DNI bring us one step closer to understand the effects of trends on the yields of different solar energy technologies. However, the efficiencies of solar thermal collectors, photovoltaic modules, inverters and many other system components are not linear with solar irradiance. Therefore the trends in the distribution of the irradiance by magnitude must also be examined. To compare the irradiance distribution of different years, the empirical cumulative distribution function is useful (Espinar et al., 2009). We use the cumulative energy distribution here, as this method allows to directly read the fraction of the energy that is received below or above a certain irradiance level from the figure. For every year in the time series we computed the incoming energy in each bin of 10 W/m^2 and calculated the fraction of the energy in this bin on the whole incoming energy in the respective year. These fractions are then cumulated and plotted against the irradiance. Fig. 5 shows the development of the energy distribution over time for the tilted and tracked planes in Potsdam. Again the direct irradiance shows the biggest trends: in the first years often less than 10% of DNI arises at irradiance levels above 800 W/m^2, while for recent years 20% arises above this level. The same shift can be seen for GTI and GNI, although to a lesser extent. This trend to higher irradiance levels will have consequences e.g. on modeling of the behavior of PV modules (which is further influenced by the observed changes in the diffuse fraction) or on inverter dimensioning and simulation. A full assessment of these effects is beyond the scope of this paper and would require irradiance measurements of a higher time resolution than the hourly data used here (Burger and Rüther, 2006).

7. Discussion

There are some inherent uncertainties and difficulties when analyzing the long-term development of irradiance and determining its consequences for solar resource assessments:

- While there are a few approaches (Reda, 2011; Strobel et al., 2009), there is no generally accepted method available to estimate site-dependent uncertainties for solar

Table 4
Trends for tilted (GTI) and tracked (GNI, DNI) planes for the period 1991–2010.

Station	GTI		GNI		DNI	
	W/(m^{2}decade)	%/Decade	W/(m^{2}decade)	%/Decade	W/(m^{2}decade)	%/Decade
Braunschweig	4.6 ± 5.8	3.3 ± 4.2	10.9 ± 8.9	6.1 ± 5.0	13.7 ± 8.0	13.5 ± 7.9
Hamburg	4.5 ± 6.4	3.4 ± 4.9	8.0 ± 10.5	4.6 ± 6.1	9.9 ± 9.6	9.9 ± 9.6
Potsdam	3.4 ± 4.6	2.5 ± 3.3	7.7 ± 7.7	4.2 ± 4.1	9.3 ± 7.1	8.6 ± 6.5
Trier	3.4 ± 8.6	2.4 ± 6.0	6.6 ± 13.1	3.6 ± 7.0	9.1 ± 12.5	8.4 ± 11.5
Wuerzburg	1.2 ± 5.1	0.8 ± 3.4	3.2 ± 7.9	1.7 ± 4.1	6.1 ± 7.7	5.4 ± 6.8
Mean Anomalies	3.0 ± 5.1	2.1 ± 3.6	6.8 ± 7.9	3.7 ± 4.3	9.0 ± 7.4	8.5 ± 6.9
w/o 2003	2.1 ± 3.8	1.5 ± 2.7	5.5 ± 6.1	3.0 ± 3.3	7.8 ± 5.7	7.5 ± 5.4

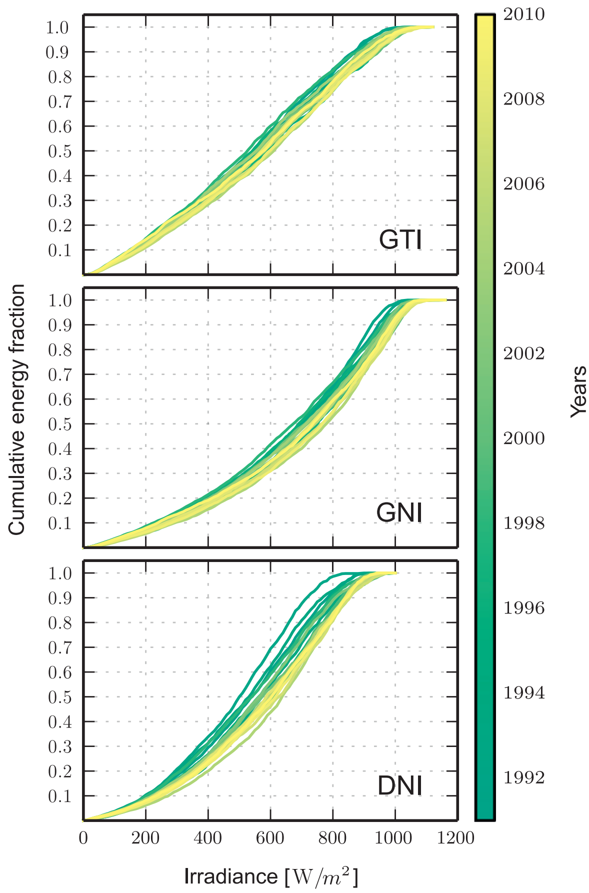

Fig. 5. Cumulative energy distribution on tilted and tracked planes for Potsdam. The distribution is calculated for every year of available data. The years are color coded to highlight the changes over time.

radiation measurements over a certain period of time, for example a year. The focus of this study has been on long-term trends, and as such the uncertainties of individual measurements, or of aggregated values such as hourly or annual totals, have not been carried forward. To keep uncertainties as low as possible data with the highest possible accuracy should be used: the Baseline Surface Radiation Network (BSRN, Ohmura et al., 1998) measures all three components of irradiance directly (GHI, DIF, DNI) at the highest standard possible today, while only measurements of GHI and DIF are available for this study. However, BSRN data is available for only a few stations around the globe (and only for one station in Germany). Furthermore BSRN measurements started at the beginning of the 1990s, so long-term trends cannot yet be detected.

- When computing trends from long-term measurements additional uncertainties are introduced by data filling methods or the method used to compute averages (Roesch et al., 2011) as well as changes in instrument quality, calibration techniques and general measurement principles (e.g. pyranometer ventilation, direct measurement of GHI with a pyranometer versus indirect measurement using DNI and DIF, see e.g. Gueymard and Myers, 2009 for details). These changes can themselves introduce spurious trends that are difficult or impossible to distinguish from the true trends in the phenomenon that is being measured.
- The irradiance values on tilted or tracked planes used in this work are modeled, not measured. While for direct irradiance only simple calculations are necessary, which are not expected to introduce shifts, for the diffuse irradiance a more complicated model is used. The possibility that this model skews the results cannot be excluded, but a check with a different model was performed, which confirmed the results. However, long-term measurements in tilted or tracked planes would be desirable. The inclusion of such measurements within the BSRN network would enable such analyses at a high quality level in the future.
- Our analysis is based on ground measurement data, but for most solar resource assessments today satellite derived data is used. There are some publications that analyze whether long-term trends in satellite data are similar to those found in ground measurements, but these focus mainly on GHI and DNI (Pinker et al., 2005; Lohmann et al., 2006; Posselt et al., 2012; Lohmann et al., 2007). For solar energy applications in general, further analysis of satellite data should be carried out to evaluate the trends in diffuse and direct radiation on various types of tracked and tilted surfaces. Such analysis will also need to carefully consider the additional uncertainties that are inherent in the satellite methods.

Despite the uncertainties, there are facts that increase our level of confidence that the long-term trends we discuss here are real: the trends we derived are consistent with the numbers published in the literature based on different measurement instruments, different aggregation methods and different locations. Furthermore, changes in surface solar radiation are not only evident from direct measurements, but also from measurements of related quantities like diurnal temperature range or sunshine duration (Wild, 2009a, 2012). An increased irradiance and increased system yields can also be observed for photovoltaic systems at various locations in Germany: in recent years measured plane-of-array irradiance and system yields are generally higher than predictions based on long-term average irradiances (Müller et al., 2009).

If there are trends, the follow-up question is: how will the trends develop in the future? Projections of future trends in GHI have to rely on global climate models (GCM’s). Such projections made using current generation of GCM’s are still afflicted with considerable uncertainty, as they critically depend on hypotheses about the future developments of anthropogenic aerosol emissions and the projection of changes in cloudiness. Studies also show that current GCMs are not able to adequately reproduce the variations in GHI observed over the past decades (Wild, 2009b; Wild and Schmucki, 2011; Ruckstuhl and Norris,

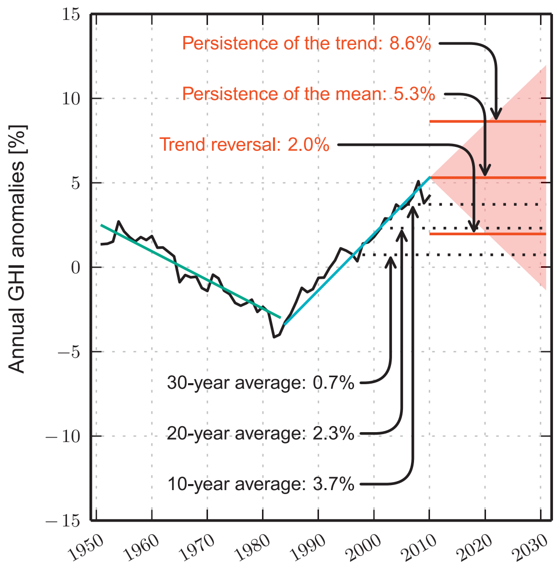

Fig. 6. Different possibilities to estimate future solar resources. The moving average of the mean GHI anomalies (black) and the trend lines (green for the dimming period and blue for the brightening period) are shown together with the possible irradiance in the future. Future irradiance is indicated by the red plane, the mean values for the three scenarios are given as red lines. The trend of the mean anomalies used to derive scenarios 1 and 3 is 3.3% (see Section 3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2009). As a conclusion it can be stated, that the development of the trends in the future is unknown.

To assess the implications for solar resource assessments, three different scenarios will be analyzed:

1. Persistence of the trend: the brightening trend from the recent past continues
2. Persistence of the mean: the irradiance in the future stays at the current level. As an indicator for the current mean irradiance the endpoint of the brightening trend line is used.
3. Trend reversal: the brightening trend from the past is completely reversed immediately.

While the first scenario expresses the expectation for an upper bound, the third scenario expresses the expectation for the lower bound of the future solar resource. The further analysis is based on the assumptions that nothing is known on the future development of the solar resource (a future increase is no more likely than a future decrease) and that the current irradiance level is above the all time average (which can be concluded from the results derived in the previous sections). Note that the lack of knowledge of the development of future solar resource could also be described using probability theory and a uniform distribution. Furthermore, the expectations for an upper and lower bound could be widened. However, as long as the assumptions for the scenario analysis hold, the general conclusions should be the same.

Fig. 6 shows these scenarios for the mean anomalies together with different options for a hypothetical solar resource assessment in the year 2011. The numbers for all locations are given in Table 5 (for the trends used to derive scenarios 1 and 3 see Table 3).

From Fig. 6 it becomes evident, that the 30-year reference period underestimates future irradiance even in the case of the trend reversal scenario by −1.3%. The 20-year average is closer to the trend reversal scenario (0.3%), however, for the two other scenarios (and all possible values between them) the 10-year average is the best estimator. In fact, the 10-year average is the best estimator for all trends above about −2.3%, which covers most of the possible trends in the future. The 30-year average is the best estimator, only if the trend is below −3.9%, which would require an immediate reversal to a strong dimming. In between these two trend values the 20-year average would perform best. Note that the 10-year average still underestimates a wide range of possible future irradiance values. Only if the trend is below about −1.5 % it will overestimate future irradiance. For this reason it can still be seen as a conservative estimator. From Table. 5 it can be seen, that these conclusions still hold for the individual locations. Note that these conclusions should also be true (but with different signs) if there would have been a dimming trend in the last years. Only in the case of a trend reversal or in

Table 5
Deviations of average GHI in different reference periods and the three scenarios of the future development of GHI against the all time average (1951–2010). Fichtelberg is not included due to the lack of data in recent years.

Station	Reference periods			Scenarios		
	30 years (1981–2010) %	20 years (1991–2010) %	10 years (2001–2010) %	Persistence of the trend %	Persistence of the mean %	Trend reversal %
Braunschweig	1.8	3.4	4.5	10.6	6.8	3.0
Hamburg	−0.6	1.2	2.8	9.1	5.1	1.0
Hohenpeissenberg	−1.2	−0.3	2.4	4.8	2.2	−0.4
Potsdam	1.0	3.0	3.6	10.5	6.5	2.4
Trier	0.8	2.2	3.2	6.4	4.3	2.1
Weihenstephan	−0.0	1.6	4.6	9.0	5.3	1.6
Wuerzburg	0.9	2.6	3.4	7.2	4.7	2.1
Mean Anomalies	0.7	2.3	3.7	8.6	5.3	2.0

the presence of short-term trends (shorter than the reference period) a longer reference period could produce a better estimator than a shorter period.

By looking at Fig. 6, one could come to the conclusion, that the endpoint of the regression line (the "Persistence of the mean") could itself be a good estimator. However, using the endpoint of a linear regression to calculate an estimator for future solar irradiance may introduce additional uncertainties. It is also not sufficient to have a single annual average value to project forward; resource assessments are technology-specific and require irradiance values in a high time resolution to calculate accurate yield prognoses. Scaling a time series from the past, or concatenating fragments in order to generate a hypothetical meteorological year with the correct annual average carries the risk of skewing the energy distribution of the time series (see Section 6).

An alternative approach would be to use the full irradiance time series of the 10 most recent years as the input for further simulations. In practice this could be done by using high quality satellite data (see e.g. Ineichen, 2013), which are available for most parts of the world nowadays.

8. Conclusions

In Germany the period 1951–2010 is clearly divided into a period of dimming, where the annual average global horizontal irradiance decreased, and a period of brightening, where the GHI increased. The turning point lies in the early 1980s. For the stations analyzed the calculated trend for the dimming period is (-1.7 ± 1.3) %/decade, and the trend for the brightening period is (3.3 ± 1.6) %/decade. The observed brightening trend is composed of an increase in the amount of direct radiation, and a decrease in diffuse radiation of smaller magnitude, as seen in data from 1991 to 2010. As the fraction of direct irradiance increases, the trends are amplified for tilted or tracked planes.

These trends make it difficult to establish a representative or "true" long-term average value that could be used to predict future solar energy availability. In fact, historical data from Germany show that using the average global horizontal irradiance from the past to predict the average of the subsequent 20 years the dimming and brightening trends create an additional uncertainty of about 3%. This trend-related uncertainty is estimated to 4–5% for global irradiance in a 30° tilted, south facing plane, about 6–7% for global normal irradiance and to 15% for direct normal irradiance. These values represent significant additional uncertainties for solar resource assessments.

In the presence of long-term trends, the question for solar resource assessments is no longer, what is the "true" climatological value, but what is the best predictor for the next 20 years. A suitable estimator should be a recent time period, that is long enough to filter the influence of single years with high anomalies, but which is short enough, to minimize the influence of past trends. We propose to use the solar irradiance data of the 10 most recent years as a good compromise to fulfill these conditions.

When we apply this methodology to current solar resource assessments in Germany today, we project about 3% higher global horizontal irradiance values and up to 5% higher irradiance in tilted planes compared to a 30-year average. For tracked planes or direct normal irradiance the differences are even higher. While we recognize the importance of avoiding overly optimistic solar resource assessments, we believe that this new approach will provide more appropriate predictions in general.

While we have focused on Germany, the conclusions should also apply in other parts of the world where substantial long-term variations have been observed.

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