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Solar Spectral Characterization of Three Different Locations at Alpine Latitudes Using Average Photon Energy

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Abstract

The characteristic of the solar spectrum is one of the most important factors to be taken into account when evaluating the solar resource of a certain area, for photovoltaic applications. In fact, the spectral distribution of irradiance, coupled with the spectral responsivity of photovoltaic modules, is responsible for the effective performance of a photovoltaic system in real outdoor conditions. This paper investigates the variability of solar spectrum at three different locations at Alpine latitudes: Vienna (Austria), Kanzelhöhe (Austria) and Lugano (Switzerland). The Average Photon Energy (APE) index is used to quantify the spectral distribution. It is derived from outdoor measurements and computed for the range 350-900 nm. The diurnal and seasonal variability of APE is assessed under real conditions of cloudiness as well as under clear sky conditions. The results are interpreted considering the atmospheric properties of the investigated sites, and an example of assessment of how much the spectral variability influences the performance in generated current of photovoltaic modules is shown.

Keywords: solar spectrum, spectral effect, average photon energy, photovoltaic, spectral responsivity, spectral simulation

1. Introduction

Several studies (Gottschalg et al., 2005; Minemoto et al., 2009) have investigated the role of spectral variability on the performance of different photovoltaic (PV) technologies. Results demonstrate that the selection of the optimal PV material should also depend upon the spectral peculiarity of the installation site. The purpose of this work is to characterize and compare three locations at Alpine latitudes: Kanzelhöhe, Vienna and Lugano, with different altitudes and climatic conditions from the point of view of the solar spectrum variability. This is a first step towards an exhaustive comparison of the performance of different PV technologies with respect to the spectral distribution of the incoming irradiance at those sites.

In the last years an increasing number of sites in the world have been equipped with spectroradiometers thanks to decreasing costs and increasing accuracy of these instruments. To the authors' knowledge many studies exist that investigate the spectrum at specific locations (Cornaro and Andreotti, 2012; Gottschalg et al., 2003), but very few compare measurements at different sites, especially in Europe. Furthermore, a comparison of results from different studies is difficult, since a) different indexes (Average Photon Energy, Average Wavelength, Useful Fraction, Spectral Mismatch Correction, etc.) are used, b) the investigated spectra span

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different wavelength ranges, or c) refer to different tilt angles of the plane of sensor installation.

2. Experimental setup

The three locations under investigation are equipped with spectroradiometers acquiring spectra with a frequency of one minute. The information concerning the sites and instrumentation is reported in Table 1.

Tab. 1: Characteristics of the investigated sites and related spectroradiometers

Location	Kanzelhöhe	Vienna	Lugano
Coordinates	46.678 N 13.902 E	48.269 N 16.427 E	46.026 N 8.961 E
Altitude (m a.s.l.)	1526	170	214
Spectroradiometer owner	University of Natural Resources and Life Sciences (BoKu)	Austrian Institute of Technology (AIT)	University of Applied Sciences and Arts of Southern Switzerland (SUPSI)
Spectroradiometer model	EKO MS-710	Ocean Optics HR2000A	EKO MS-710, MS-712
Wavelength (nm)	300-1100	300-1100	300-1700
Tilt	0°	0°	45°
Azimuth	-	-	173°
Number of months of available data	27	35	14

The database available from each site cover different time periods, ranging on the whole from July 2010 to December 2013, for a total of 76 months of spectral data.

In addition to spectral information, diffuse and global horizontal broadband irradiance is measured next to or in proximity of the spectroradiometers.

3. Methodology

3.1. Average photon energy

The APE is used in this study as the index to uniquely quantify the spectrum characteristics (Minemoto et al., 2009), i.e. the extent to which the spectral distribution is spread towards lower rather than higher wavelengths. According to Gottschalg et al. (2005), APE is defined as the average energy of the photons within the spectrum, as in the following equation:

$$APE = \frac{\int E(\lambda)d\lambda}{q\int \Phi(\lambda)d\lambda}$$

(eq. 1)

where q is the electronic charge, E the spectral irradiance and Φ the photon spectral flux density. High values of APE stand for a spectral distribution shifted towards lower wavelengths (blue shift), while low values of APE stand for a spectral distribution shifted towards higher wavelengths (red shift).

In this study, APE for the three sites is calculated in the range 350-900 nm in order to make the spectral information comparable between sites and to filter out possible noise in proximity of the spectroradiometer measurement window limits. Furthermore, data of diffuse and global horizontal irradiance are available for the calculation of the diffuse fraction (ratio of diffuse and global irradiance) in order to classify cloudiness in a specific time span.

3.2. Spectral simulation

In order to compare spectra measured on different planes and azimuth (0° tilt for Kanzelhöhe and Vienna, 45°

tilt and 173° azimuth for Lugano), a simulation of the spectra is needed. A simple translation of the measured spectral information from the horizontal to the tilted plane is in fact not possible in this case, since no spectral data of the direct or diffuse component are available.

The simulation of global, direct and diffuse spectral irradiance at a specific location and time is performed using the *uvspec* model, implemented within the library l*ibRadtran* (Mayer and Kylling, 2005). More specifically, the discrete ordinates radiative transfer (DISORT) code (Stamnes et. al, 1988) has been selected as radiative transfer solver. The most influencing atmospheric properties, such as aerosol optical thickness at different wavelengths, ozone column and precipitable water, are retrieved from aeronet network (NASA, 2014), when available. If this is not the case, data of atmospheric composition are retrieved from the MACC (Monitoring Atmospheric Composition and Climate, 2014) project. Transposition models (Padovan and Del Col, 2010) are then applied to translate the simulated spectral information of Kanzelhöhe and Vienna to the tilted plane as in Lugano. The sky model applied in this study assumes an isotropic distribution of diffuse irradiance (Liu and Jordan, 1963).

3.3. Photovoltaic performance assessment

In order to assess the influence of the solar spectrum on the performance of a generic PV device, the short circuit current (I_{sc}) is calculated using the following equation (Gottschalg et al., 2005):

$$I_{sc} = A \int SR(\lambda) G(\lambda) d\lambda \qquad \text{(eq. 2)}$$

where *A* is the device area, *SR* is the spectral responsivity of the photovoltaic technology and *G* is the spectral irradiance.

4. Results and discussion

4.1. Spectral simulation and data verification

One winter and one summer clear sky days have been selected for each investigated location in order to perform a simulation of the solar spectrum with a frequency of one hour. The APE index has been therefore derived for each time step, and compared to the corresponding measured value. Figure 1 reports the simulated and measured values of APE for Kanzelhöhe (horizontal plane), Vienna (horizontal plane), and Lugano (45° tilted plane).

Information from aeronet network, which is considered the most reliable source since it derives from ground measurements, was available only in Kanzelhöhe for the winter day. In the case of Kanzelhöhe summer day, Lugano summer day and Vienna, atmospheric properties were derived from MACC project. Finally, neither aeronet nor MACC data were available for the winter day in Lugano.

It is evident that in the case of Kanzelhöhe the simulated values show a good agreement with the measurements, as well as in the case of the summer day in Lugano. As for Vienna, the strong discrepancies between simulated and measured values is due to a possible underestimation of the irradiances at VIS red and NIR wavelengths, occurring in the measurement process. Figure 2 shows a comparison of measured and simulated spectrum at 12 GMT of the considered summer day. Also AM 1.5 standard spectrum is added as reference. It is evident that the spectral irradiance distribution at higher wavelengths (from around 750 nm) does not assume the characteristic shape, which is also visible in the AM1.5 standard spectrum. Another discrepancy seems to occur in the range 450-500 nm. This problem, which occurs in all spectra related to the two selected days, might be caused by a damping in the signal transmission through the optical fibre, and will be further investigated.

Also the simulated values of APE for the winter day in Lugano, based on default values of atmospheric properties, does not agree with the daily profile of measured APE. This fact confirms once more the validity of the spectral simulation methodology used in the other cases and the need for reliable sources of data describing the atmosphere composition.

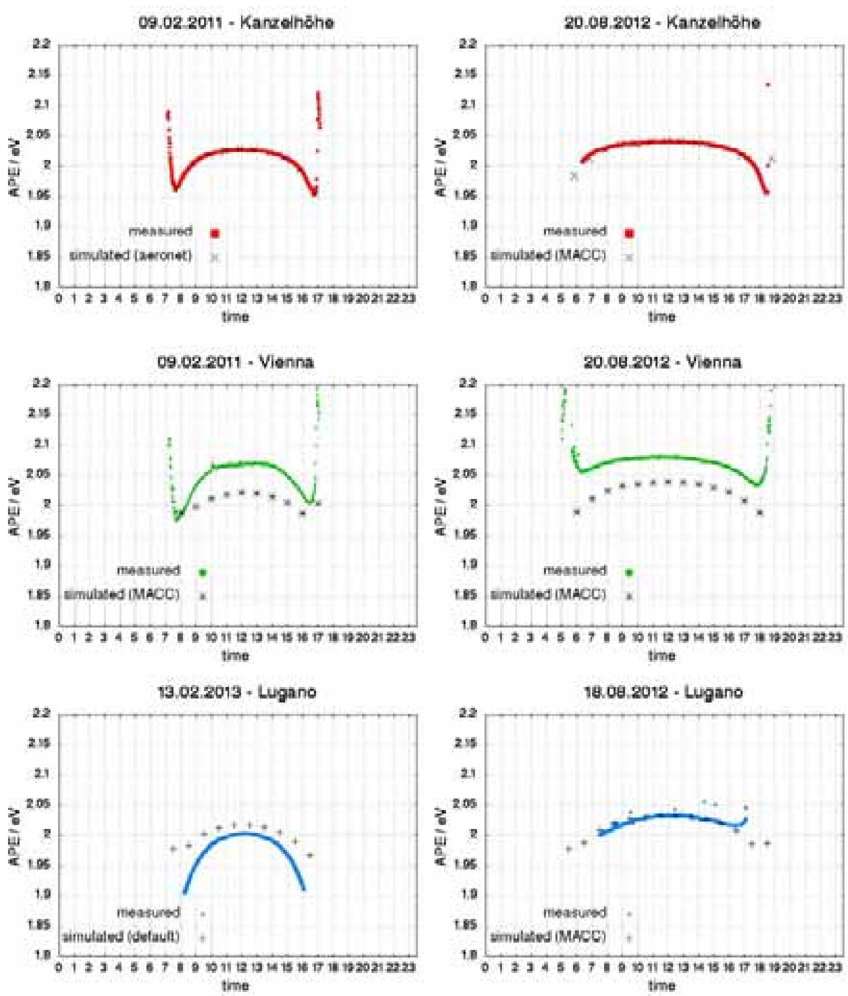

Fig. 1: Simulated and measured APE during a winter (left) and summer (right) clear sky day in the three investigated locations.

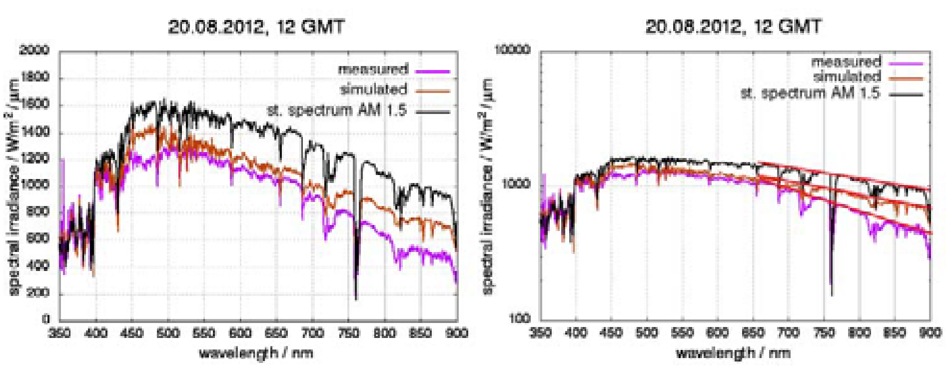

Fig. 2: Comparison of simulated and measured spectrum for a summer clear sky day in Vienna, in normal (left) and logarithmic (right) scale. AM 1.5 standard spectrum is also reported.

4.2. Daily APE profiles on the horizontal plane

As seen, the measurements of solar spectrum in Vienna seem to be affected by a systematic lowering of the spectral irradiance at VIS red and NIR wavelengths. On the other hand, the same methodology to simulate the solar spectrum in Vienna fits well the experimental measurements of Kanzelhöhe and, when reliable values of atmospheric properties are available, Lugano. It is therefore reasonable to focus only on the simulated values of APE in order to carry out a comparison between the locations of Vienna and Kanzelhöhe, on the horizontal plane.

Figure 3 reports the daily profiles of APE, of the relative difference in APE between the investigated sites, of the Aerosol Optical Depth (AOD) at 550 nm, of precipitable water, and of solar zenith angle. It is evident that in general the APE is lower in winter than in summer in both locations, i.e. the spectrum is more red-shifted. This is confirmed by several studies which analyze measured spectra at Northern sphere latitudes (Cornaro and Andreotti, 2013; Gottschalg et al., 2003; Schweiger et al., 2012; Ishii et al., 2013), and seems to be related to higher levels of precipitable water occurring during summer at those latitudes (Ortiz de Galisteo et al., 2013), as corroborated by the daily profiles measured at the two investigated locations.

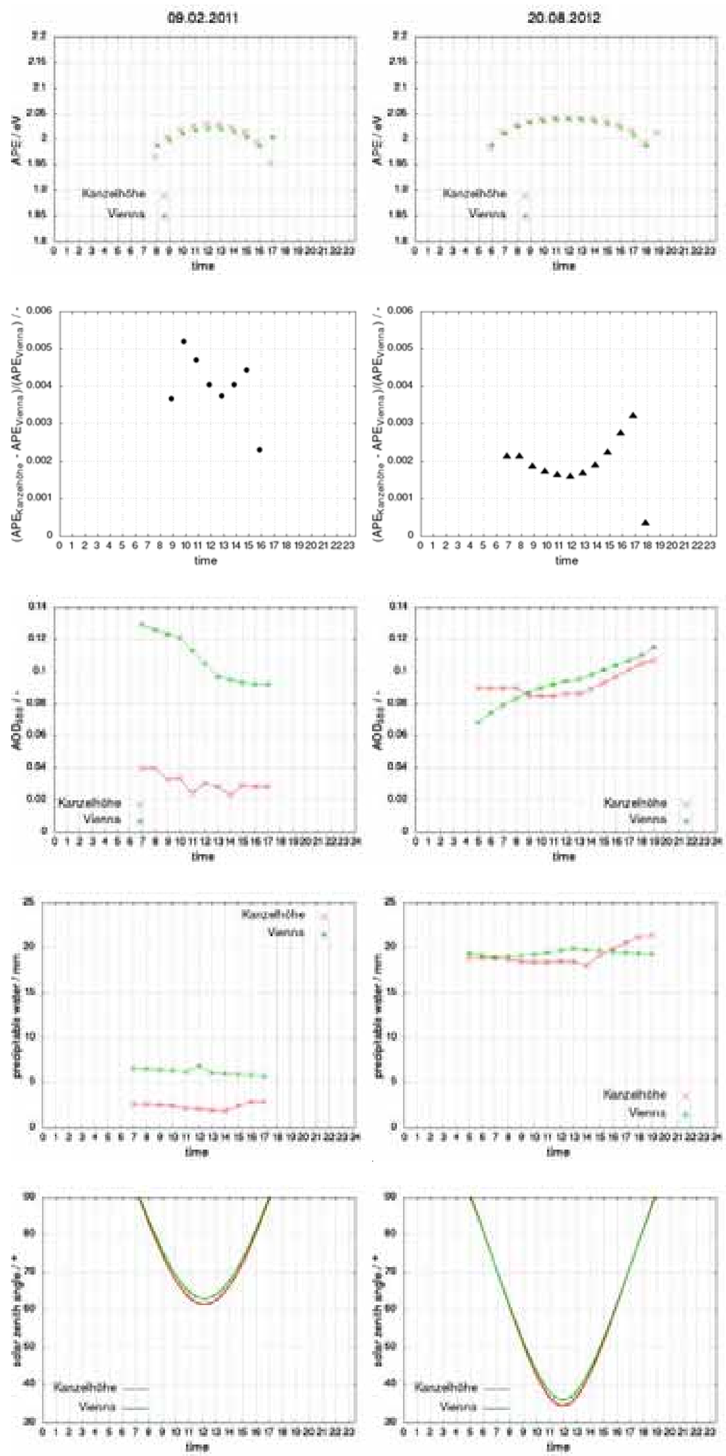

Fig. 3: From top to bottom. Simulated daily profiles of APE, relative difference of APE with respect to Vienna, aerosol optical depth, precipitable water and solar zenith angle for a winter (left) and summer (right) clear sky day.

In both seasons the solar spectrum in Kanzelhöhe results more blue shifted than in Vienna. This divergence is more evident in winter (0.45% difference in APE on average) than in summer (0.2% in APE on average). Focusing on the winter day, and looking at the related AOD, it is possible to explain this fact with a considerable difference in aerosol levels between the two locations registered on that day. In fact, as Behrendt et al. (2013) report, increasing values of AOD result in a gradual shift towards red wavelengths of the solar spectrum, i.e. lower values of APE.

Finally, the variability of APE differences between Kanzelhöhe and Vienna, which assumes a symmetric-like profile with a minimum value around noon, can be explained by the difference in the values of solar zenith angle (i.e. of irradiance incidence angle on the considered plane, in the horizontal case), which is minimum at noon.

It is therefore clear that an exhaustive analysis of spectral variability must take into account not only the geometric differences in the solar position, but also a complete characterization of the variability of aerosol and water vapor content of the atmosphere.

4.3. Daily APE profiles on the tilted plane

It is interesting to assess the characteristic of solar spectrum on a tilted plane, since photovoltaic modules are very often mounted on inclined surfaces to optimize the energy production. Figure 4 shows the daily profile of APE on a 45° tilt plane for the investigated winter and summer clear sky days. A comparison is possible in this case with the APE derived from solar spectrum measurements in Lugano.

The spread between Kanzelhöhe and Vienna APE detected for the horizontal plane case is still evident here, still more pronounced in winter than in summer. With respect to the horizontal case, the profile looks more pronounced, i.e. there is a higher variability during the day. In particular, Lugano shows a good agreement with the APE profiles of Kanzelhöhe.

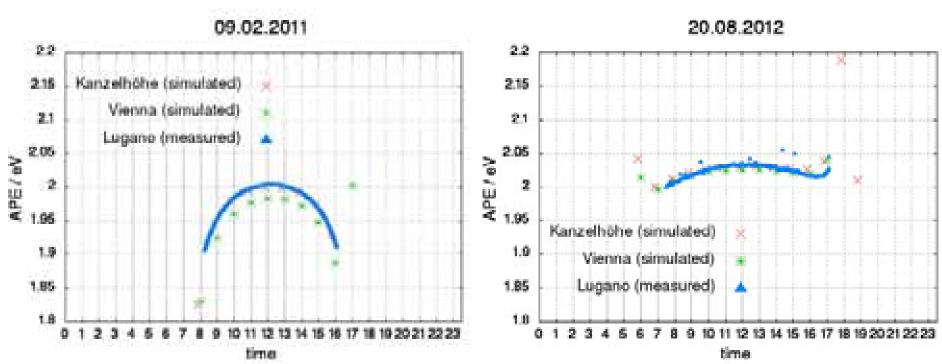

Fig. 4: Simulated daily profiles of APE in Vienna and Kanzelhöhe, for a winter (left) and summer (right) clear sky day, on the tilted (45° plane), and comparison with values measured in Lugano.

4.4. Seasonal variability of APE

The seasonal variability of APE index can be assessed by calculating daily or monthly values of APE as an average weighted on the broadband irradiance, i.e. on the integral value of the spectral irradiance. Figure 5 shows the variability of daily values of APE in a 42-months range, from July 2010 to December 2013, as well as a zoom from July 2012 only of points calculated during clear sky days. The values of APE in Vienna are likely to be affected by damping of the signal transmission and should not therefore been taken into consideration, as already discussed in section 4.1. Another problem affects the APE values of Vienna between July 2011 to March 2012, when they suddenly drop for more than 10% to a stable value around 1.85 eV. This malfunctioning is actually due to a damage occurred to the quartz dome, which broke leaving the sensor at open air and to the aging of the diffuser material.

Focusing on Kanzelhöhe and Lugano, it is possible to see a certain degree of seasonal variability. In general, APE is lower in winter than in summer, thus confirming the results of the analysis of daily profiles. In particular, this seasonal variability seems more pronounced with tilted angles as in Lugano (4% of relative difference in APE with respect to the summer values), rather than on the horizontal plane (1.2% for

Kanzelhöhe). This is a noteworthy fact, since it infers that PV plants installed on tilted planes are more prone to performance variability due to spectral effects than the horizontal case.

Finally, the values of APE on the tilted plane tend to diverge more from those on the horizontal plane when close to winter.

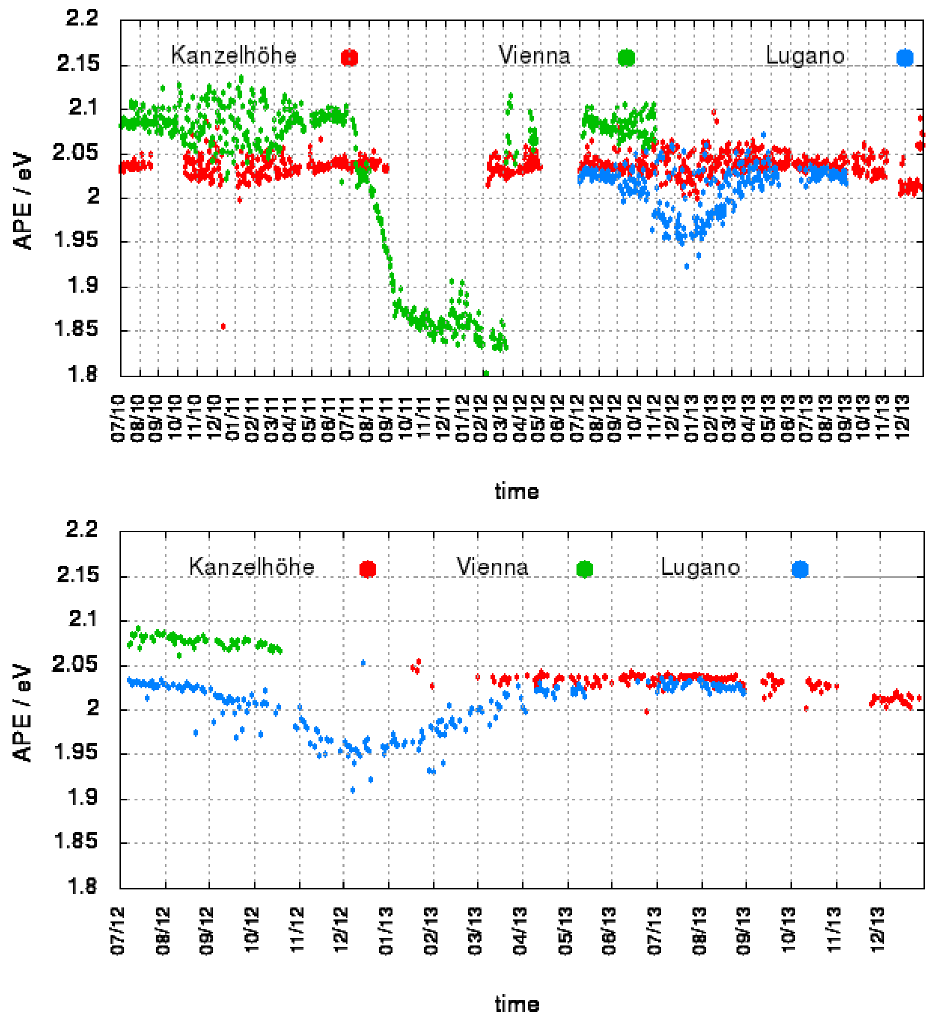

Fig. 5: Seasonal profiles of daily average APE for the three sites under investigation: a) real conditions of cloudiness, b) clear sky conditions (from July 2012)

4.5. Spectral effect on module performance

In order to evaluate to which extent the difference of solar spectrum in different locations affects the performance of a PV device, the same winter and summer clear sky days have been taken into consideration. A generic polycrystalline-silicon module, whose spectral responsivity is known, has been considered to calculate the short circuit current using equation 2. Figure 6 shows the relative difference in I_{sc} between the same module as it was installed in Vienna and in Kanzelhöhe. The simulated spectra have been previously normalized in order to make spectra with different broadband irradiance comparable.

The more red-shifted spectra (lower APE) seen in Vienna for both days result in a higher performance of the considered PV device in this location, in terms of I_{sc}. This is due to the increasing responsivity of polycrystalline silicon modules when moving from the VIS to the near-IR region. For example, around noon in a winter day the module installed in Vienna produces 0.6% more current than in Kanzelhöhe, while in summer almost 0.3% more. It has to be pointed out that a higher performance in terms of I_{sc} does not necessarily mean a higher performance in terms of energy production, since the module voltage is strongly dependent on the ambient temperature.

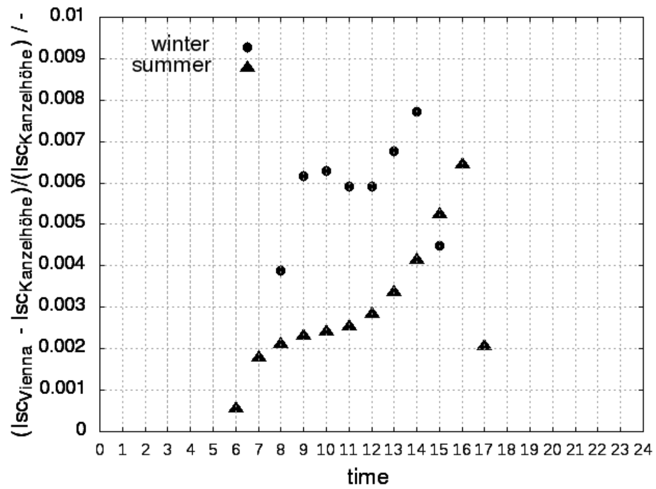

Fig. 6: Relative difference of I_{sc} of a polycrystalline silicon module installed in Vienna and Kanzelhöhe, for a winter and summer clear sky day.

5. Conclusions

Spectral irradiance measurements from three different sites and two different tilt angles have been collected for more than three years to assess the variability of solar spectrum at those locations. The study has been carried out using the APE index computed in the range 350-900 nm.

The analysis of data confirms a seasonal oscillation of solar spectrum towards more blue-rich contents in summer, and more red-rich contents in winter. This seasonal oscillation is more evident on tilted planes (4% in APE registered in Lugano on a 45° tilted plane). The relative difference of solar spectra between horizontal and tilted surfaces presents a minimum during summer and a maximum during winter.

The spectral characterization of a location strongly depends on its atmospheric characteristics, and especially on aerosol and precipitable water content. Furthermore also ground albedo, which depends on azimuth and tilt angle of the plane, and the azimuthal ground view factor of the location play an important role, especially for tilted planes. A deeper study of the variability of those factors in the considered locations is therefore worthy.

Results show that depending upon the photovoltaic technology and its responsivity to solar irradiance, the effect of the sole solar spectrum on its performance in generated current between different locations is not negligible (up to 0.8% between the locations of Vienna and Kanzelhöhe for a generic winter clear sky day and for a polycrystalline silicon PV device). This confirms once more the importance that the selection of the optimal PV material should also take into consideration the spectral peculiarity of the installation site. A more extensive study on the overall effect of spectral variability on the investigated sites will be object of a future study involving more photovoltaic technologies.

Simulations of solar spectrum carried out with DISORT radiative transfer equation solver and atmospheric input parameters from aeronet network or MACC project demonstrates the usefulness of this methodology in reconstructing solar spectral information, when measurements are missing, or in validating available on-site measurements to detect possible malfunctioning issues. The use of default or low temporal resolution (order of month) input values for atmospheric properties should be avoided.

6. Acknowledgements

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