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The quest for the optimum angular-tilt of terrestrial solar panels or their angle-resolved annual insolation

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ABSTRACT

Although solar energy is the fastest growing power technology, terrestrial solar panels typically fall behind their performance ratings established under standardised test-conditions. In particular, the angular-tilt of a panel can greatly affect its overall performance. Many studies thus aim to find the optimum tilt that maximises the annual insolation level. However, no widespread consensus has so far been found, partly because of different model assumptions applied. Here, a technique is proposed to use actual, historical solar spectra for the rigorous assessment of a panel's tilt at a specific site. By combining multiple, free-accessible satellite-retrieved data products, the total all-sky insolation levels are tracked with a minutely changing global (hemispherical) solar spectrum over many years. While time-resolved annual insolation profiles can considerably vary among each other, the solar angle-resolved profile turns out to be robust to climatic conditions and is even site-independent for latitude-tilted panels. These findings can potentially unlock innovative yield optimisation methods.

Keywords: Photovoltaics; Solar spectrum; Insolation; Clouds; Solar panel; Panel orientation

1. INTRODUCTION

While many plants naturally follow the motion of the Sun to maximise photosynthesis (heliotropism), most terrestrial solar energy systems do not. Hoyt Hottel already noticed in 1941 that “artificial flat-plate converters of solar energy are too cheap to warrant being mounted to follow the sun but may profitably be tilted permanently towards the Equator” [1]. Today, tracking systems are still seen as expensive and in need of maintenance, but they also require energy for their operation, are prone to heavy snow layers or storm damage and often not applicable for small scale systems – as they can be too heavy for rooftop applications, for example.

The question then arises for which angular-tilt the annual **in**coming **sol**ar radi**ation** (insolation) is maximised for a planar surface. Though a simple sounding problem, it is a complicated exercise [2], because one needs to consider Earth’s rotation, obliquity, orbital eccentricity and revolution around the Sun in addition to the site’s geographical altitude, latitude and longitude.

As the optimum angular-tilt has been widely studied in the literature, Yadav and Chandel recently reviewed various calculation methods, algorithms and optimisation techniques [3]. The authors compare the results of analytical, numerical and experimental methods in order to assess the suitability of a technique for a particular location. They conclude that the optimum tilt is very site-specific due to environmental factors and must be accurately determined by considering long-term observational datasets. In fact, Jacobson and Jadav estimated two very different optimum tilts for almost the same geographical latitude: 34° for London in the UK and 45° for Calgary in Canada [4]. Today, a data-driven approach is thus emerging as a standard practice. For example, Siraki and Pillay [5] considered monthly average daily insolation levels for five different latitudes (spaced 10° apart); Darhmaoui and Lahjouji

[6] averaged the daily global solar radiation over 4-years of datasets for 35 sites in the Mediterranean region; Rakovec et al. [7] interpolated the hourly measurements of 10-year long data sets for four distinct locations in Slovenia; Li and Lam [8] used the 10-minute averages of *half-secondly* irradiance measurements over the entire year 2004 for the City University of Hong Kong.

Some authors also have started to use the “typical meteorological year” (TMY) as a type of hourly solar resource data, in which the entirety of original multi-year solar radiation and meteorological data sets is condensed into one year's worth of the most usual conditions. However, albeit TMY data collections may enable to estimate the optimum angular-tilt for all major cities worldwide [4] and facilitate (online) PV performance estimations [9], they ultimately are auxiliary datasets and cannot reflect the nonlinear dynamics of a globally changing climate [10, 11, 12]. For example, the combination of recurring temperature extremes, higher atmospheric pollution levels, intensified water crisis and disastrous river dynamics [13] could affect solar power systems directly or indirectly by variations in the solar spectrum and zonal albedo.

In the end, the actual solar spectrum remains the key parameter to know, because all other parameters are directly or indirectly depending on it. While the sunshine received by a terrestrial solar panel is continuously changing due to Earth’s rotation and revolution, it does also depend on the chemical composition and meteorological condition of the atmosphere – both being subject to fluctuations on a minutely time scale.

As datasets for the global solar spectrum are hardly available at this resolution, Bright et al. proposed to generate a synthetic time series stochastically from mean hourly weather observation data [14]. Although the model produces realistic irradiance profiles, it is of a nonspatial nature and not intended to match real-world observational data. For example, the individual simulations at nearby locations would not correlate.

On the other hand, now more than 700 satellites are recording data for Earth observation purposes [15]. The National Aeronautics and Space Administration (NASA), as well as the European Space Agency (ESA), offer wide ranging resources down to 1 min time stamps. Why not combine such valuable information to model the global solar spectrum at a specific location?

Peters et al. recently initiated a few studies based on this approach [16, 17], but neglected most of the dynamic processes by considering only daily average values of a single-year and used scale-to-match procedures, indirectly derived parameters as well as the standardised extra-terrestrial spectrum (ASTM E490). The authors worked with the **S**imple **M**odel of the **A**tmospheric **R**adiative **T**ransfer of **S**unshine *(SMARTS)* by C. Gueymard [18, 19], as the open-source program conveniently allows to include satellite retrieved data sets. However, if the time resolution of the modelled spectra is only dictated by the embedded data series, minutely changing atmospheric and meteorological conditions can always be included.

Here, by combining datasets from multiple, free-accessible satellite-product services, section 2 shows how the incident solar spectrum can be tracked on a tilted plane for every minute over many years. This allows to accurately analyse in section 3 not only the insolation level as a function of the angular-tilt, but also its solar angle dependency. While time-resolved annual insolation profiles can considerably vary among each other, the **an**gle-**r**esolved **an**nual **i**nsolation **p**rofile *(ANRANIP),* as defined in Fig. 1, turns out to be robust to climatic changes and becomes even site-independent for latitude-tilted panels. These findings could potentially unlock innovative yield optimisation methods, as explained in section 4.

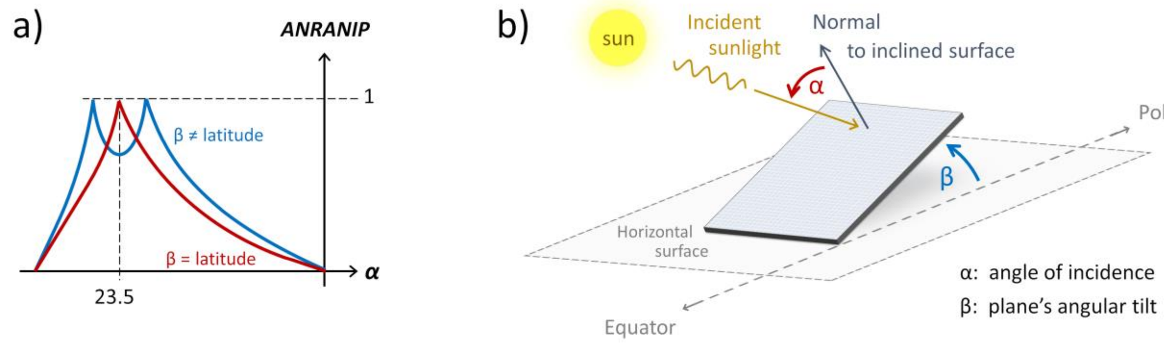

Fig. 1. The **an**gle **r**esolved **an**nual **in**solation **p**rofile *(ANRANIP).*

The *ANRANIP* shows **(a)** how the incident solar energy is dispersed over the angles of incidence α for an inclined surface; α is defined as positive if measured from the surface normal to Sun's position **(b)**. The *ANRANIP* depends on the plane's angular tilt β, measured from Earth's ground, and is normalised to its global peak value.

2. METHODS

The spectra are calibrated to the actual measured extra-terrestrial irradiance TOA at the top of Earth's atmosphere. Since the so calculated clear-sky global spectrum $CSGTI$ on a tilted plane differs from the total all-sky irradiance GTI, e.g. due to clouds, it must be multiplied with the clear-sky index σ,

$$GTI = \sigma \cdot CSGTI \qquad \text{with } \sigma = \frac{GHI}{CSGHI}\,. \tag{1}$$

The clear-sky index σ is defined as the ratio of the measured global horizontal irradiance GHI and the computed clear-sky global irradiance $CSGHI$ on a horizontal plane. Since σ is independent of tilt and orientation, i.e. independent on solar geometry [20], the transposition from a horizontal (β = 0°) to tilted surface (β > 0°) can be performed by setting $\frac{GTI}{CSGTI} = \frac{GHI}{CSGHI}$, which yields Eq. 1. Finally, records for TOA, GHI and $CSGHI$ are freely available from the **C**opernicus **A**tmosphere **M**onitoring **S**ervice (CAMS) [21], thus σ and hence GTI are readily calculated from SMARTS output data, see Tab. 1. CAMS is the European Union's contribution to the **G**lobal **E**arth **O**bservation **S**ystem of **S**ystems (GEOSS); it is delivering geospatial information from -66° to 66° in both latitudes and longitudes since February 2004 – with a 0.5° spatial and up to one-minute temporal resolution.

input to SMARTS	output from SMARTS
location (latitude, longitude, altitude), date and time (UTC)	angle of incidence α
angular-tilt β of solar panel (facing toward Equator)	clear-sky global irradiance for a tilted plane (*CSGTI)*
temperature, relative humidity, surface pressure **[22]**	clear-sky global solar spectrum for a tilted plane
total precipitable water column **[23]**	
CO_2 concentration **[24, 25]**, total-column abundance of ozone **[26]**	
ground albedo of a light soil (non-Lambertian reflectance)	
aerosol type and tropospheric pollution level **[27]**	
extra-terrestrial irradiance on top of Earth's atmosphere **[21]**	

Tab. 1. A list of the required data (left) for the relevant output parameters from SMARTS (right).

For a tilted plane, the all-sky solar spectrum *GTI* is derived with a 1 nm spectral and 1 min temporal resolution from the modelled clear-sky spectrum *CSGTI* via the clear-sky index σ [21]. All referenced quantities are based on freely accessible data sets gathered from satellites. As the time step is 24h for [23, 26], 12h for [24, 25] and 3h for [27], the data were first interpolated to the one-minute resolution of the series [21, 22]. Measurements of the total optical depth and partial optical depths of the major atmospheric species – dust, sea salt, black carbon and organic matter – were used to select the correct aerosol type and its tropospheric pollution level via the established McClear model from Lefèvre et al. [28].

3. RESULTS

In this paper, the cities Trondheim (Norway), Paris (France), Cairo (Egypt) and Nairobi (Kenya) are chosen as a representative set for the distinctive climatic characteristics on Earth. Yet, before analysing their insolation levels, it is instructive to compare their modelled spectra with the AM 1.5G standard solar spectrum from NREL [29], since it is widely used in the literature and for the benchmarking of solar cells. For this comparison, the average of all non-zero spectra of a 14-year long time series was taken to highlight the overall effects and the differences to the spectral standard, see Fig. 2.

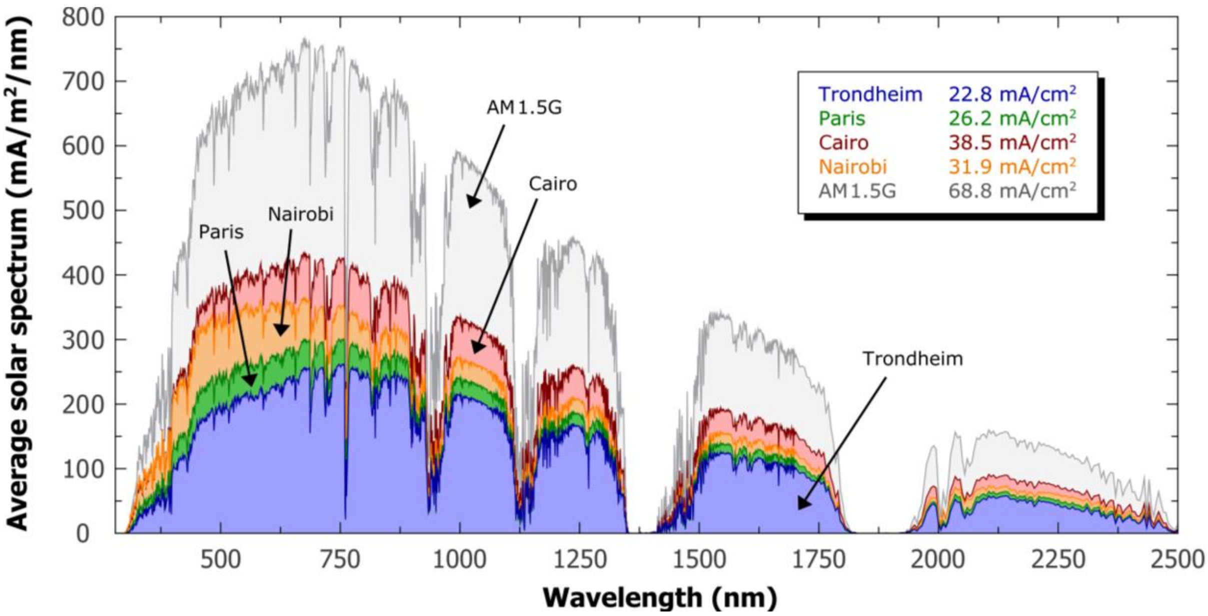

Fig. 2. A comparison of long-time averaged solar spectra at distinct climatic locations. For each city, the 14-year time series of non-zero historical solar spectra at one-minute intervals was averaged and expressed as electrical current density. The global standard AM 1.5G spectrum from NREL [29] is shown for comparison, highlighting the differences to a typical solar spectrum received by a latitude-tilted surface in the outdoors. The inset quotes the total currents after integrating from 280 to 4000 nm wavelength. Since a time-series of solar spectra cannot be adequately represented in a single graph, the average spectrum was chosen as the most appropriate quantity of comparison.

Whereas the spectrum of Nairobi qualitatively experiences the greatest energy loss in the near infra-red, the spectra of Trondheim and Paris suffer the most in the visible range; the spectrum of Cairo instead resembles most the AM 1.5G standard, because it apparently differs from it just by a scaling factor of 0.6.

While the direct comparison to the average spectra might first not seem fair, it does highlight the great degree of idealisations set out for the AM 1.5G standard. For example, it was defined for normal incident sunlight (of a clear sky), but which is the least likely condition for a fix-tilted panel, according to Fig. 3.

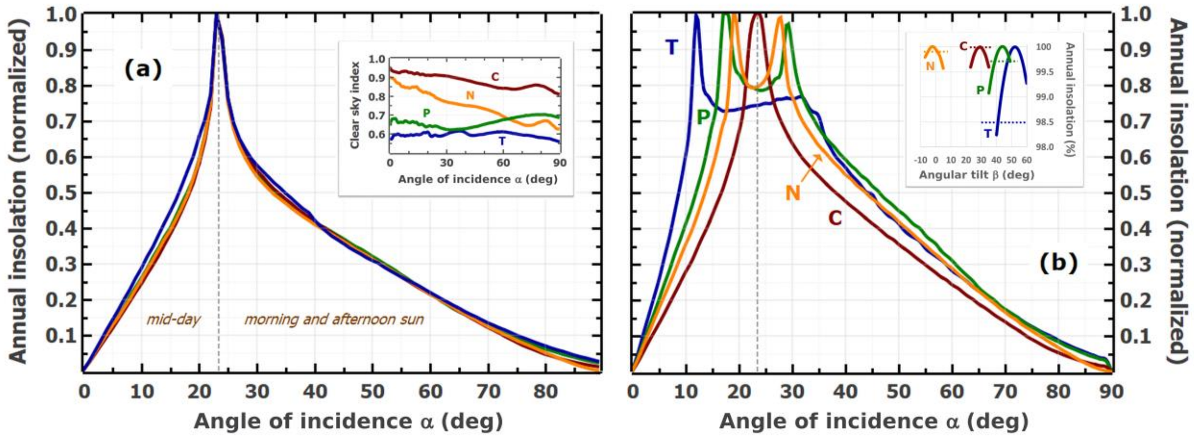

Fig. 3. A comparison of the normalised angle-resolved annual insolation levels for the investigated cities Trondheim (T), Paris (P), Cairo (C) and Nairobi (N).

All latitude-tilted panels **(a)** exhibit the same angle-resolved annual insolation profile *(ANRANIP)* from year-to-year, despite being subject to different environments (see inset). In contrast, if panels are tilted to maximise annual yield **(b)**, the *ANRANIP* becomes site-dependent and exhibits two maxima. The inset shows that major differences to the optimum case appear at high-latitude locations (up to 1.5% in absolute), with the dotted lines corresponding to the insolation levels of latitude-tilted planes. Here, the all-sky *GTI* as a function of α is found via SMARTS from a minutely time series of reconstructed, historical global solar spectra from 2004 to 2018, see Eq. 1 and Tab. 1. All *GTI* values with the same angle of incidence α (rounded to the nearest integer) are added together irrespective of their timestamps, before the resulting graph is normalised to its peak value.

Please note, Fig. 3 does *not* suggest that a panel's optimum angular tilt is β = 23.45°. Instead, it points out that the area of a panel receives most energy from Sun at an angle-of-incidence α = 23.45°, if and only if it is mounted at latitude-tilt, regardless of atmospheric changes, the climatic conditions or its geographical location. In fact, since latitude-tilted surfaces are parallel to a horizontal plane at the Equator, they experience the same apparent motion of the Sun: sunlight is received under an angle of α = 23.45° twice a day and once at solstice, whereas the normal incidence (α = 0°) only occurs at the equinoxes (at solar noon). By analysing the most frequent condition of photovoltaic module technologies, Bora et al. [30] indicate that the *ANRANIP* of a latitude-tilted surface indeed peaks at α = 23.45°, i.e. at Earth's obliquity.

For angular-tilts β smaller than the latitude angle, the insolation is received at lower (higher) angles of incidence in the summer (winter) periods. In effect, the two days with the minimum angle of incidence move from the equinoxes toward the summer solstice. If they merge, the smallest angle of incidence would only occur once a year. In addition, as the incident angles on the solstices differ from 23.45° and from each other (at solar noon), the *ANRANIP* of a non-latitude-tilted surface has two maxima, evenly spread around 23.45°. The spread is given by the difference between the latitude and selected tilt. Finally, for tilts even smaller than the difference between the latitude and polar circle (66.55°), no insolation will be received at all on certain winter days.

4. DISCUSSION

The quest for the optimum angular-tilt of a terrestrial solar panel might not solely be resolved by maximising its annual insolation level, because it may not necessarily lead to the maximum output of a solar energy system [31] – regardless of the solar resource data used.

Firstly, the (local) foreground albedo seen by a tilted surface changes over time [32], which is a key factor in ice- and snowscapes, yet many authors still assume a *constant* foreground albedo of 0.20 (typical grassland), often equal to the zonal albedo used for the backscattering calculations. The so derived optimised tilts will likely be incorrect [7, 32], because the local and zonal albedo have a spectral and unequal dependency as the ground surface is rarely uniform over large areas. Secondly, modules can get immersed in fog (smog) or partly covered by ice, snow, hardened dust, sand, dirt, pollen, leaves or bird droppings; they can become prone to fungi and mildew [33] and be permanently damaged by hail [34], frost [35] or even a shadow if monolithically integrated [36, 37, 38, 39]. Solar panels also undergo daily heat and cold cycles, as they inevitably age. Consequently, many environmental factors have a major impact on the useful energy output of a solar energy system over its operational lifetime.

Their effects tend to lessen with higher angular-tilts, as the greater the tilt, the more debris can drop down or be washed away by rain, but also the cooler the panel's temperature [40], which leads to increases in the energy yield. From this perspective, the latitude-tilt would be a better choice, because it is often found to be greater than the optimum tilt according to Fig. 4, with a reduction in annual insolation of ca. 1.5% at most according to Tab. 2. However, the land costs, any space and mounting constraints or compliances with building regulations might also influence a panel's tilt.

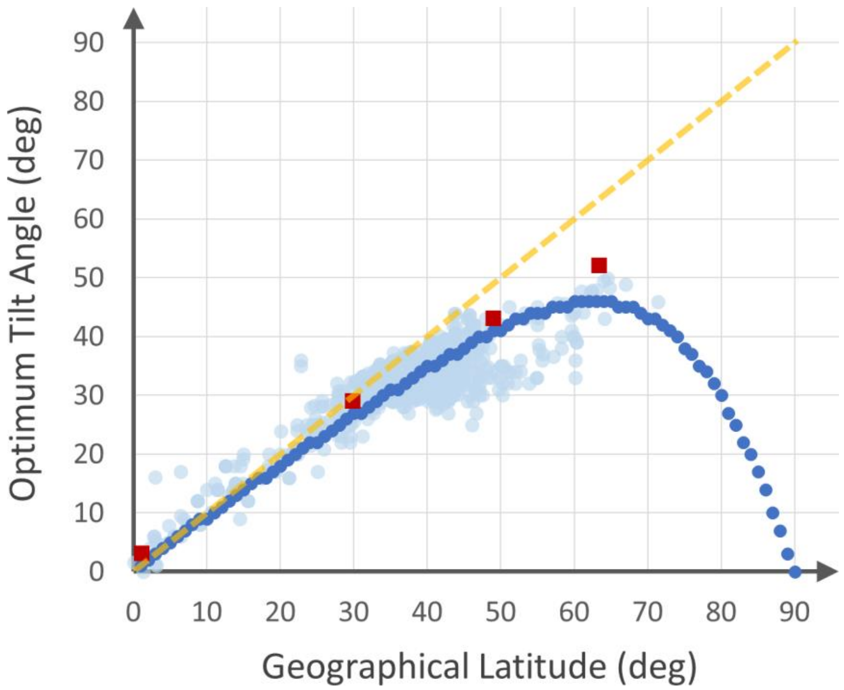

Fig. 4. The optimum angular-tilt that maximises the annual insolation on a flat plane.

It is a function of the geographical latitude among other factors, implied by the large spread of literature data (light coloured symbols) [31, 8, 7, 5, 6, 41, 42, 43, 4]. The dark coloured (round) symbols refer to the optimum-tilted plane if environmental factors were negligible. The square dots stand for the here investigated cities Trondheim (63.4°), Paris (49.0°), Cairo (29.9°) and Nairobi (-1.2°), whose optimum angular-tilts are based on a minutely time series of reconstructed, historical global solar spectra between February 2004 and February 2018.

City	Country	Latitude	Longitude	Altitude	ASPD	Annual Insolation Level	
						@Latitude	@Optimum
Trondheim	Norway	63°26′	10°28′	263 m	9:40 h	1143	1161 (52°)
Paris	France	48°58′	2°38′	92 m	10:44 h	1485	1490 (43°)
Cairo	Egypt	29°56′	31°40′	284 m	11:20 h	2342	2342 (29°)
Nairobi	Kenya	-1°11′	36°55′	1796 m	11:39 h	2043	2045 (3°)

Tab. 2. A comparison of sunshine duration and insolation levels for four distinct climatic locations. The annual insolation level is given in kWh/m^2 for a surface at latitude tilt (left column) and at optimum angular-tilt (right column). The optimum tilt (quoted in brackets) is derived from non-zero historical, global (hemispherical) solar spectra at 1 min intervals between 2004 and 2018. *ASPD* refers to the **A**verage **S**unshine **P**er **D**ay with the average taken over the same period (2004-2018). For Nairobi, the optimum tilt is found slightly higher than the latitude angle and with the panel facing away from the Equator – in agreement with Jacobson and Jadhav [4]. The annual insolation, as a time and spectrally integrated quantity, is not significantly affected by seasonal weather fluctuations (see Supplementary Fig. S1).

If environmental factors and installation restraints prevent a clear definition or application of the optimum angular-tilt, the annual insolation level might instead be best exploited by the inverse approach: for a given angular-tilt, the panel's reflection properties are optimised to its *ANRANIP*, as it mostly depends on astronomical factors.

Weather effects can be seen as a source of superimposed noise, which is effectively averaged out. Accordingly, the insolation received at a certain angle of incidence is more robust to climatic influences, whereas a time-resolved insolation profile can considerably vary from year to year. For example, while a latitude-tilted panel at Nairobi received almost 40% less insolation in June 2008 with reference to its monthly average (see Supplementary Fig. S2), the angle-resolved insolation only exhibits a 6% deviation at most (see Supplementary Fig. S3 and S4). The perspective of how yield can be maximised thus may change, when the panel's

ANRANIP is considered in the analysis. In fact, independent of the geographical location, all latitude-tilted panels have the same *ANRANIP* with the greatest deviations only occurring near the peak position, i.e. at an angle of incidence of 23.45°.

In summary, variations in the solar spectrum may play a crucial role in the future asset of solar energy technologies, such as the emerging perovskite-on-silicon tandem cell or other novel multi-junction approaches. For this purpose, a rigorous modelling technique is proposed for retrieving actual solar spectra at one-minute intervals, using free-accessibly satellite product services, such as the SoDa-pro platform. Here, the four cities Trondheim (Norway), Paris (France), Cairo (Egypt) and Nairobi (Kenya) were chosen as a representative set for four different climatic zones on Earth. By tracking the incident global solar spectra from 2004 to 2018, their spectral, temporal and solar-angle resolved insolation profiles are accurately analysed as a function of the panel's angular-tilt. Only small differences in the total insolation levels could thereby be found between optimum and latitude tilted panels (with ca. 1.5% at most). However, since the angle-resolved annual insolation is far less sensitive to weather dynamics than a time-resolved profile, a panel's energy yield can always be increased for any given angular-tilt by adapting its anti-reflection properties to its *ANRANIP*. This practice reduces not only unnecessary reflection losses but also the risk of visual distress to pilots (e.g. flash blindness or veiling) near airports or high rises. In addition, the panel's yield optimisation would become decoupled from the considerations of mounting practicalities or building regulations. Since the *ANRANIP* allows to quantify how much solar energy falls from where onto a façade, wall or glass window over a calendar year, it could be applied as a simple but effective architectural design tool for passive solar buildings.

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6. ADDITIONAL INFORMATION

Competing interests: The author declares no competing financial and non-financial interests in relation to the work described.

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