

Article

Control of the Solar Radiation Reception Rate (SRRR) Using a Novel Poly-Tilted Segmented Panel (PTSP) in the Region of Makkah, Saudi Arabia

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Abstract: This work deals with controlling the solar radiation reception rate (SRRR) (ratio of the incident solar radiation on tilted panel to the global incident solar radiation). Controlling the SRRR will permit the amount of the received solar energy on solar panels to be adjusted. This SRRR control is very useful for several technological applications such as solar thermal and photovoltaic technologies in extremely sunny regions around the world, such as the case of Makkah, Saudi Arabia. Thus, the sustainability of the cities and villages, located in such regions, is promoted. A novel design proposing a poly-tilted segmented panel (PTSP) is proposed as an original techno-logical solution enabling the control of the SRRR. Design technical details are clearly explained. The proposed design presents a cheap, simple and effective alternative to conventional sun tracking systems. The SRRR on the proposed PTSP is mathematically modeled. The influence of the combinations “number of segment/tilt angles” on the SRRR is assessed for the most significant days in the year: equinox, summer solstice and winter solstice. A specific “document-aided design”, showing the SRRR level reached by each specific combination “num-ber of segment/tilt angles”, is provided. Based on these documents, the adequate combination “number of segment/tilt angles” is easily determined by knowing the desired SRRR level. The SRRR level is determined based on the global incident solar radiation and the desired level of the incident so-lar radiation on the tilted panel. Results are properly presented, discussed and interpreted for each segment/tilt angles combination.

Keywords: solar radiation; solar panel; energy control; tilt angle; segmentation; equinox; solstice; sustainability



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1. Introduction

Solar radiation [1–4] can be considered as the most interesting renewable energy in terms of availability and distribution [5–7]. It is obvious that solar radiation received on a considered location, around the world, varies considerably during the year [8–12]. This variation considerably affects the amount of daily or even hourly solar radiation received by thermal absorbers or photovoltaic panels as a fixed inclined surface facing the south [13–17].

The literature of the last three years presents some interesting works dealing with the enhancement of solar radiation reception by an inclined surface equipped with a sun tracker (variable inclinations). M. Das and E.K. Akpinar [18] experimentally investigated the influence of solar tracking on solar drying performance. Results showed that the average thermal and the drying efficiencies are enhanced by 42% and 50%, respectively,

when using a solar tracking system. A. Fazlizan et al. [19] experimentally investigated the maximum solar radiation detection of a photovoltaic (PV) panel in a tropical climate. The PV panel is equipped with a particular two-axis solar tracker, controlled by a smart algorithm called maximum light detection. Results showed that the uses of this particular solar tracker would permit to the PV panel to enhance the energy generation in all sky conditions: 49% in gloomy, 46% in intermittent and 35% sunny. R. ElGamal et al. [20] experimentally studied the effect of solar tracking system integration on the performance of an apple slice solar dryer. Results showed that the thermal efficiency of the dryer was enhanced by 45% when using solar tracking, and it reached an improvement of 87.1% at the highest flow rate of around 44 m³/h. In addition, the solar tracking and the high flow rate permits improve the drying rate to reach an effective moisture diffusivity around 5.43×10^{-10} m²/s. C. Jamroen et al. [21] experimentally investigated the effect of the use of UV sensor, instead of light-dependent resistors (LDR)-based dual-axis solar tracking system on PV energy generation. Results showed that energy generation is increased by 19.97% and 11% compared to fixed PV panel and LDR-based solar tracking system, respectively. W. Batayneh et al. [22] theoretically (using isotropic and anisotropic model's simulation) and experimentally investigated the effect of the use of single and dual axis tracking system on the performance of PV cells. Results show that, under a typical meteorological year, the use of a dual-axis tracker enhances the power generation by 8.5% and 37% compared to a dual-axis tracker and fixed PV cell, respectively.

The aim of this work is to propose a novel design called the poly-tilted segmented panel (PTSP) as a technological solution that permits control of the solar radiation reception rate (SRRR) (ratio of the incident solar radiation on tilted panel to the global incident solar radiation). The contribution of our research can be explicitly and concisely stated as:

“Our novel design presents a static, cheap, simple and efficient alternative to conventional sun tracking systems. The proposed novel design is also supported by specific ‘document-aided design’ (figures or bar plots as Supplementary Materials) permitting easy assessment and control of the SRRR level reached by each specific combination ‘number of segment/tilt angles’”. The control of the SRRR is very useful for several technological applications (such as solar thermal and photovoltaic technologies) since it permits the control/adjustment of the amount of the received solar energy on solar panels. This control is necessary to carry out under extremely sunny conditions, such as the case of the city of Makkah (21.3891° N, 39.8579° E), Saudi Arabia, in order to ensure proper functioning of some solar powered technologies (such as solar thermal [23,24] and photovoltaic [25,26]). It is of note that the SRRR control conditions are related to a specific threshold level of solar radiation associated to the standard test condition (STC) in the case of PV panels [27], as well as some technical requirements in the case of solar thermal panels (see Section 2). Additionally, an SRRR control strategy, aiming to determine the adequate PTSP “number of segment/tilt angles” combination, is implemented as it is explained in Section 4.

The SRRR control will promote the sustainability of the cities and villages located in such extremely sunny regions. The promoting of the sustainability in rural regions or green cities is based on several aspects, among them the appropriate and safe use of the solar energy. The control of the amount of solar energy falling on a tilted panel is an aspect reflecting an adequate use of solar energy, especially in extremely sunny regions around the world. Thus, the control of the SRRR in extremely sunny regions promotes the sustainability, in terms of adequate use of solar energy, as follows:

- For PV panels’ technological applications, the SRRR control avoids the malfunctions and improves the equipment safety [27–31].
- For solar thermal panels, the SRRR control avoids additional charges and fees related to additional equipment and their maintenance.
- The proposed PTSP design, in itself, presents an efficient sustainable design (environmentally friendly (not powered electrical energy), simple and cheap) alternative to expensive sun tracking systems which are powered by electrical energy deriving from fossil energy.

The technological configuration of this novel design is based on the segmentation of the solar panel and the allocation of a definite tilt angle to each segment, hence the PTSP design. Varying the combinations “number of segment/tilt angles” permits the quantification (leveling) of the SRRR on the PTSP. This will ensure the SRRR control. As such, this is the gap of knowledge that is necessary to fill.

Section 2 states the problem in terms of parameters influencing the SRRR as well as the proposed novel design called PTSP permitting to control the SRRR. Section 3 presents the mathematical model associated to the SRRR on a PTSP. Numerical results about the influence of the PTSP combinations “number of segment/tilt angles” on the SRRR quantification (leveling) are presented, discussed and interpreted in Section 4. Section 5 lists the main conclusions of this research work.

2. Problem Statement

The solar constant describing the extraterrestrial solar radiation is around 1366.1 W/m^2 [5]. The reception of the solar energy by a panel on the earth depends on several parameters (Figure 1 [32]): the tilt angle between the panel and the horizontal, the declination angle between the equator plane and the line matching the earth and the sun [33], the latitude angle between the equator plane and the line matching the earth center and the considered location of the flat absorber, the hour angle [34], and the azimuth angle between the projection of the line, matching the location of the flat panel and the sun, on the horizontal plane and the south direction [35]. In this context, it should be remembered that the use of renewable energies, such as solar energy, is one of the foundations on which sustainable development is based. Strongly sunny regions around the world benefit from large amounts of solar energy, obviously renewable and free, most of the year. Thus, both conventional and original technological solutions dealing with solar energy would permit the establishment of sustainable development in cities and villages located in such sunny regions. However, there are some regions around the world, such as the region of Makkah (21.3891° N , 39.8579° E), Saudi Arabia, that are so extremely sunny that a control of the amount of solar energy is required in order to ensure the proper functioning of some technologies dealing with solar energy (such as solar thermal and photovoltaic technologies). Conventionally, sun tracking systems installed on solar panels [36] are used in order to improve the control (specially the maximization) of the solar energy amount received on a titled panel. This does not exclude the possibility of regulating such tracking systems in a way that the received solar energy amount does not exceed a certain specific level less than the maximum level of energy that can be reached. The sun tracking systems continually vary the tilt angle of the panel according to zenith angles. This technological solution is very efficient, but obviously involves expensive additional design, manufacturing and maintenance charges. This research work proposes a novel design presenting a cheap, simple and efficient alternative to sun tracking systems. The proposed design is based on the segmentation of the panel and the allocation of a definite tilt angle to each segment.

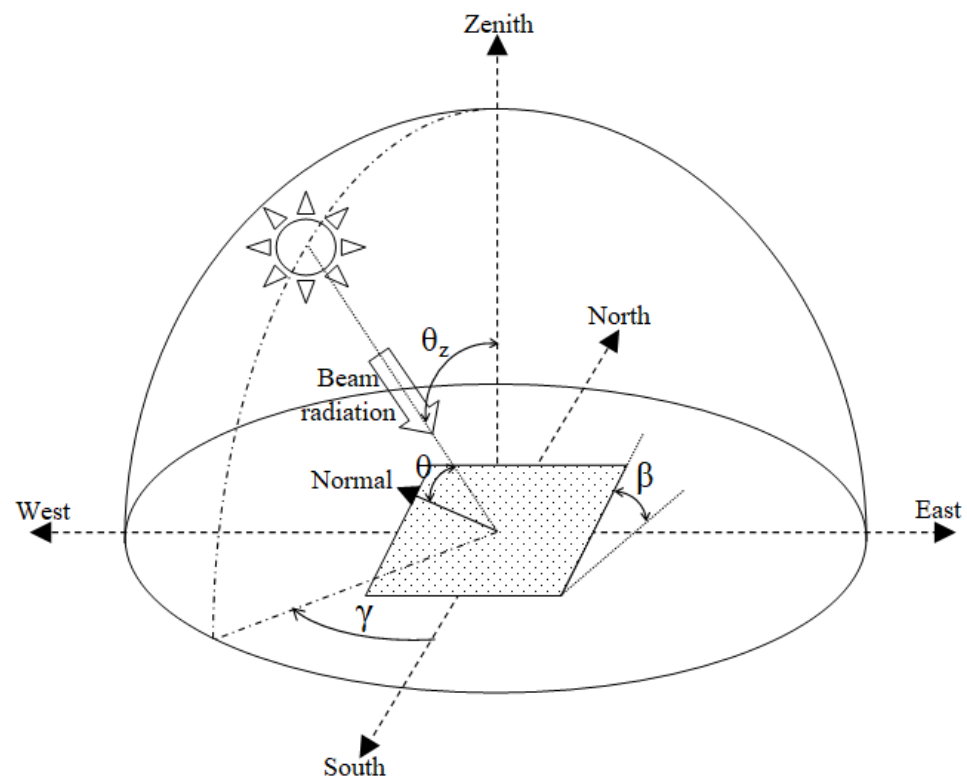


Figure 1. Basic solar angles associated with the tilted panel.

Figure 2 depicts the principle of the proposed novel solution. Since no use of tracking systems is allowed in our proposed design for reasons of cheapness and simplicity, the original idea of this work is to give the possibility of sun tracking during the day using the segmentation of the panel and the allocation of a tilt angle to each panel segment. The considered panel is subdivided into several isometric segments. A specific tilt angle is affected to each segment, hence the PTSP design. Thus, the SRRR, associated directly to the received amount of solar energy and defined as the ratio of the incident solar radiation on tilted panel to the global incident solar radiation, will vary from one tilted segment to another during the hours of the day. The segmentation (number of subdivided segments), as well as the affected tilt angle to each segment, considerably influences the total SRRR associated to the whole PTSP system. Hence, the combination “number of segment/tilt angles” permits precise control of the SRRR, adjusting, therefore, the daily received amount of solar energy. It is of note that the proposed PTSP novel design is not intended to maximize the global SRRR during the day, but rather to regulate the SRRR in order to control the amount of the received solar energy in the panel and limit it to a certain level for technological reasons. In fact, the SRRR control is extremely useful in several technological applications requiring a precise level of solar energy, not necessarily the maximum, such as solar thermal technology, or preventing very high levels of solar energy, such as in the case of photovoltaic (PV) panels. Too high solar irradiance induces some deleterious effects, negatively affecting the performance [27–31] of PV panels. For solar thermal panels, extremely sunny conditions principally produce an outlet fluid temperature inappropriate for some technical requirements or human comfort, which might need some additional equipment to regulate the fluid temperature (additional fees as well as maintenance charges). Thus, the SRRR control would ensure the good performance and safety of solar panels. In addition, it would limit the use of additional regulating equipment widely used for solar thermal panel applications.

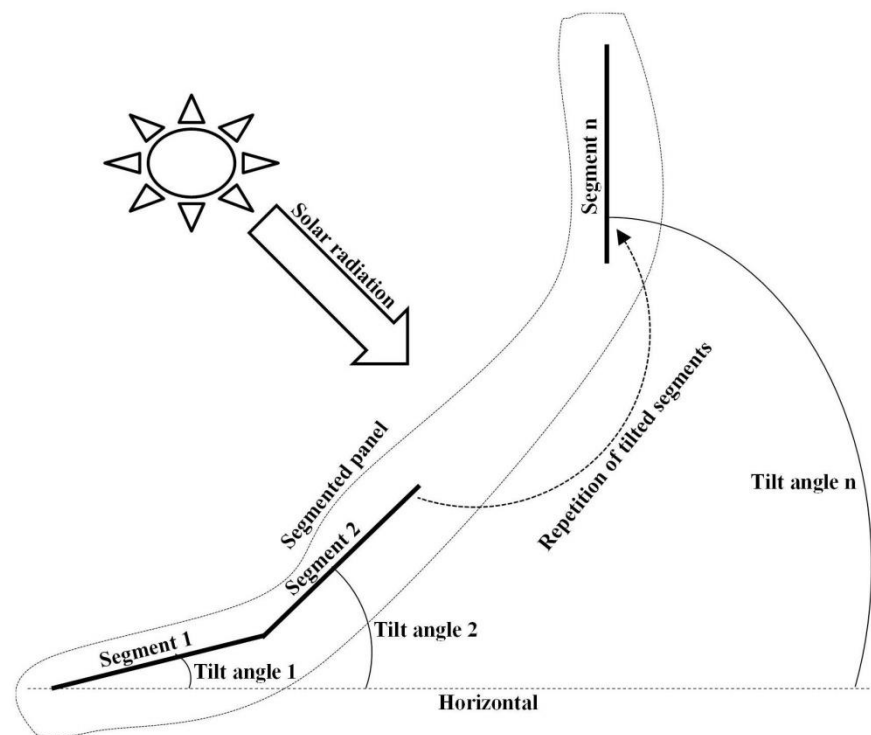


Figure 2. Poly-tilted segmented panel.

To our knowledge, there are no research works proposing our novel design, called PTSP, and investigating its performance. This gap of knowledge is filled in this study.

3. Mathematical Modeling

The SRRR provided by a poly-tilted segmented panel, composed of m segments that can be tilted at an angle equal to an n -divisor of $\frac{\pi}{2}$, carried out during one day from sunrise to sunset, is written as:

$$SRRR(\%) = \frac{I_t}{I_g} \times 100 = \left(\frac{1}{m} \sum_{l=1}^m \left[\frac{1}{(T_{l,s} - T_{l,r})} \int_{T_{l,r}}^{T_{l,s}} \cos(\theta) dT_l \right] \right) \times 100 \quad (1)$$

with:

$\frac{1}{(T_{l,s} - T_{l,r})} \int_{T_{l,r}}^{T_{l,s}} \cos(\theta) dT_l$ presents the average value of $\cos(\theta)$ from sunrise time $T_{l,r}$ to sunset time $T_{l,s}$ for just one tilted segment under all the possible tilt angles, β .

$\frac{1}{m} \sum_{l=1}^m \left[\frac{1}{(T_{l,s} - T_{l,r})} \int_{T_{l,r}}^{T_{l,s}} \cos(\theta) dT_l \right]$ presents the average value of $\cos(\theta)$ from sunrise time $T_{l,r}$ to sunset time $T_{l,s}$ for the whole PTSP (all segments).

The relation between the incidence angle θ and all the other basic solar angles is expressed as [37]:

$$\cos(\theta) = \sin(\delta) \sin(\varphi) \cos(\beta) - \sin(\delta) \cos(\varphi) \sin(\beta) \cos(\gamma) + \cos(\delta) \cos(\varphi) \cos(\beta) \cos(\omega) + \cos(\delta) \sin(\varphi) \sin(\beta) \cos(\gamma) \cos(\omega) + \cos(\delta) \sin(\beta) \sin(\gamma) \sin(\omega) \quad (2)$$

The declination angle δ is expressed as [38]:

$$\delta = 23.45 \times \sin\left(2\pi \times \frac{284 + d}{365}\right) \quad (3)$$

The hour angle ω is expressed as [32]:

$$\omega = \frac{\pi}{12}(T_{so} - 12) \quad (4)$$

The hour angle at the sunrise ω_r and the sunset ω_s is expressed as [32]:

$$\omega_r = \omega_s = \cos^{-1}(-\tan(\varphi) \times \tan(\delta)) \quad (5)$$

The solar time T_{so} is expressed as [39]:

$$T_{so} = T_l + \frac{E}{60} + \frac{L_{sm} - L_{lo}}{15} \quad (6)$$

The equation E of time is given by the following piecewise function [39]:

$$E = \begin{cases} -14.2 \times \sin\left(\frac{\pi(d+7)}{111}\right) & \text{for } 1 \leq d \leq 106 \\ 4 \times \sin\left(\frac{\pi(d-106)}{59}\right) & \text{for } 107 \leq d \leq 166 \\ -6.5 \times \sin\left(\frac{\pi(d-166)}{80}\right) & \text{for } 167 \leq d \leq 246 \\ 16.4 \times \sin\left(\frac{\pi(d-247)}{113}\right) & \text{for } 247 \leq d \leq 365 \end{cases} \quad (7)$$

The azimuth angle γ is expressed as [32]:

$$\gamma = \sin^{-1}\left(\frac{\cos(\delta) \times \sin(\omega)}{\cos\left(\frac{\pi}{2} - \theta_z\right)}\right) \quad (8)$$

The zenith angle θ_z is expressed as [39]:

$$\theta_z = \cos^{-1}(\sin(\varphi) \times \sin(\delta) + \cos(\varphi) \times \cos(\delta) \times \cos(\omega)) \quad (9)$$

The segment/tilt angle combination of the PTSP as a Tuples, depending on the number of segments m and the number of angle division n ($1/n \times \pi/2$), is expressed as [40]:

$$\beta = \text{Tuples}\left(\text{Range}\left(0, \frac{\pi}{2}, \frac{\pi}{n}\right), m\right) \quad (10)$$

4. Results and Discussion

The numerical investigation of performance related to the proposed PTSP design aims to investigate the effects of some combinations “number of segment/tilt angles” on SRRR levels. Only some specific days were investigated (Equinox, summer and solstices, as examples). Of course, any other day of the year could be investigated using the same model. Figures 3–14 could be simply seen as a specific “Document Aided Design” showing the SRRR level reached by a specific combination “number of segment/tilt angles”. Knowing the global incident solar radiation and the maximum allowed level of the incident solar radiation on the tilted panel, the appropriate SRRR level could be determined based on the documents, depicted by Figures 3–14.

$$\left\{ \begin{array}{cccc} \text{SRRR : } 59.0447 \% & , & \text{SRRR : } 65.6831 \% & , & \text{SRRR : } 65.6831 \% & , & \text{SRRR : } 72.3215 \% \\ \{0, 0\} & & \left\{0, \frac{\pi}{2}\right\} & & \left\{\frac{\pi}{2}, 0\right\} & & \left\{\frac{\pi}{2}, \frac{\pi}{2}\right\} \end{array} \right\}$$

Figure 3. Solar Radiation Reception Rate for $m = 2$ and $n = 1$ at the equinox in the region of Makkah, Saudi Arabia.

$$\left\{ \begin{array}{cccc} \text{SRRR : } 53.4472 \% , & \text{SRRR : } 58.1487 \% , & \text{SRRR : } 58.1487 \% , & \text{SRRR : } 62.8503 \% \\ \left\{ \frac{\pi}{2}, \frac{\pi}{2} \right\} & \left\{ 0, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, 0 \right\} & \left\{ 0, 0 \right\} \end{array} \right\}$$

Figure 4. Solar Radiation Reception Rate for $m = 2$ and $n = 1$ at the summer solstice in the region of Makkah, Saudi Arabia.

$$\left\{ \begin{array}{cccc} \text{SRRR : } 45.6128 \% , & \text{SRRR : } 65.6495 \% , & \text{SRRR : } 65.6495 \% , & \text{SRRR : } 85.6862 \% \\ \left\{ 0, 0 \right\} & \left\{ 0, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, 0 \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{2} \right\} \end{array} \right\}$$

Figure 5. Solar Radiation Reception Rate for $m = 2$ and $n = 1$ at the winter solstice in the region of Makkah, Saudi Arabia.

$$\left\{ \begin{array}{cccc} \text{SRRR : } 59.0447 \% , & \text{SRRR : } 65.6831 \% , & \text{SRRR : } 65.6831 \% , & \text{SRRR : } 72.3215 \% , \\ \left\{ 0, 0 \right\} & \left\{ 0, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, 0 \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{2} \right\} \\ \text{SRRR : } 75.9673 \% , & \text{SRRR : } 75.9673 \% , & \text{SRRR : } 82.6057 \% , & \text{SRRR : } 82.6057 \% , & \text{SRRR : } 92.8899 \% \end{array} \right\}$$

$$\left\{ \begin{array}{ccccc} \left\{ 0, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{4}, 0 \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{4} \right\} \end{array} \right\}$$

Figure 6. Solar Radiation Reception Rate for $m = 2$ and $n = 2$ at the equinox in the region of Makkah, Saudi Arabia.

$$\left\{ \begin{array}{cccc} \text{SRRR : } 53.4472 \% , & \text{SRRR : } 58.1487 \% , & \text{SRRR : } 58.1487 \% , & \text{SRRR : } 62.8503 \% , \\ \left\{ \frac{\pi}{2}, \frac{\pi}{2} \right\} & \left\{ 0, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, 0 \right\} & \left\{ 0, 0 \right\} \\ \text{SRRR : } 67.841 \% , & \text{SRRR : } 67.841 \% , & \text{SRRR : } 72.5425 \% , & \text{SRRR : } 72.5425 \% , & \text{SRRR : } 82.2347 \% \end{array} \right\}$$

$$\left\{ \begin{array}{ccccc} \left\{ \frac{\pi}{4}, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{4} \right\} & \left\{ 0, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{4}, 0 \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{4} \right\} \end{array} \right\}$$

Figure 7. Solar Radiation Reception Rate for $m = 2$ and $n = 2$ at the summer solstice in the region of Makkah, Saudi Arabia.

$$\left\{ \begin{array}{cccc} \text{SRRR : } 45.6128 \% , & \text{SRRR : } 65.6495 \% , & \text{SRRR : } 65.6495 \% , & \text{SRRR : } 69.2276 \% , \\ \left\{ 0, 0 \right\} & \left\{ 0, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, 0 \right\} & \left\{ 0, \frac{\pi}{4} \right\} \\ \text{SRRR : } 69.2276 \% , & \text{SRRR : } 85.6862 \% , & \text{SRRR : } 89.2643 \% , & \text{SRRR : } 89.2643 \% , & \text{SRRR : } 92.8424 \% \end{array} \right\}$$

$$\left\{ \begin{array}{ccccc} \left\{ \frac{\pi}{4}, 0 \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{4} \right\} \end{array} \right\}$$

Figure 8. Solar Radiation Reception Rate for $m = 2$ and $n = 2$ at the winter solstice in the region of Makkah, Saudi Arabia.

$$\left\{ \begin{array}{ccccccc} \text{SRRR : } 59.0447 \% , & \text{SRRR : } 63.4703 \% , & \text{SRRR : } 63.4703 \% , & \text{SRRR : } 63.4703 \% , & \text{SRRR : } 67.8959 \% , & \text{SRRR : } 67.8959 \% , & \text{SRRR : } 67.8959 \% , \\ \left\{ 0, 0, 0 \right\} & \left\{ 0, 0, \frac{\pi}{2} \right\} & \left\{ 0, \frac{\pi}{2}, 0 \right\} & \left\{ \frac{\pi}{2}, 0, 0 \right\} & \left\{ 0, \frac{\pi}{2}, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, 0, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{2}, 0 \right\} \\ \text{SRRR : } 70.3264 \% , & \text{SRRR : } 70.3264 \% , & \text{SRRR : } 70.3264 \% , & \text{SRRR : } 72.3215 \% , & \text{SRRR : } 74.752 \% , & \text{SRRR : } 74.752 \% , & \text{SRRR : } 74.752 \% , \\ \left\{ 0, 0, \frac{\pi}{4} \right\} & \left\{ 0, \frac{\pi}{4}, 0 \right\} & \left\{ \frac{\pi}{4}, 0, 0 \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{2}, \frac{\pi}{2} \right\} & \left\{ 0, \frac{\pi}{4}, \frac{\pi}{2} \right\} & \left\{ 0, \frac{\pi}{2}, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{4}, 0, \frac{\pi}{2} \right\} \\ \text{SRRR : } 74.752 \% , & \text{SRRR : } 74.752 \% , & \text{SRRR : } 74.752 \% , & \text{SRRR : } 79.1776 \% , & \text{SRRR : } 79.1776 \% , & \text{SRRR : } 79.1776 \% , & \text{SRRR : } 81.6082 \% , \\ \left\{ \frac{\pi}{4}, \frac{\pi}{2}, 0 \right\} & \left\{ \frac{\pi}{2}, 0, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{4}, 0 \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{2}, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{4}, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{2}, \frac{\pi}{4} \right\} & \left\{ 0, \frac{\pi}{4}, \frac{\pi}{4} \right\} \\ \text{SRRR : } 81.6082 \% , & \text{SRRR : } 81.6082 \% , & \text{SRRR : } 86.0338 \% , & \text{SRRR : } 86.0338 \% , & \text{SRRR : } 86.0338 \% , & \text{SRRR : } 92.8899 \% \end{array} \right\}$$

$$\left\{ \begin{array}{ccccc} \left\{ \frac{\pi}{4}, 0, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{4}, 0 \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{4}, \frac{\pi}{2} \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{2}, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{2}, \frac{\pi}{4}, \frac{\pi}{4} \right\} & \left\{ \frac{\pi}{4}, \frac{\pi}{4}, \frac{\pi}{4} \right\} \end{array} \right\}$$

Figure 9. Solar Radiation Reception Rate for $m = 3$ and $n = 2$ at the equinox in the region of Makkah, Saudi Arabia.

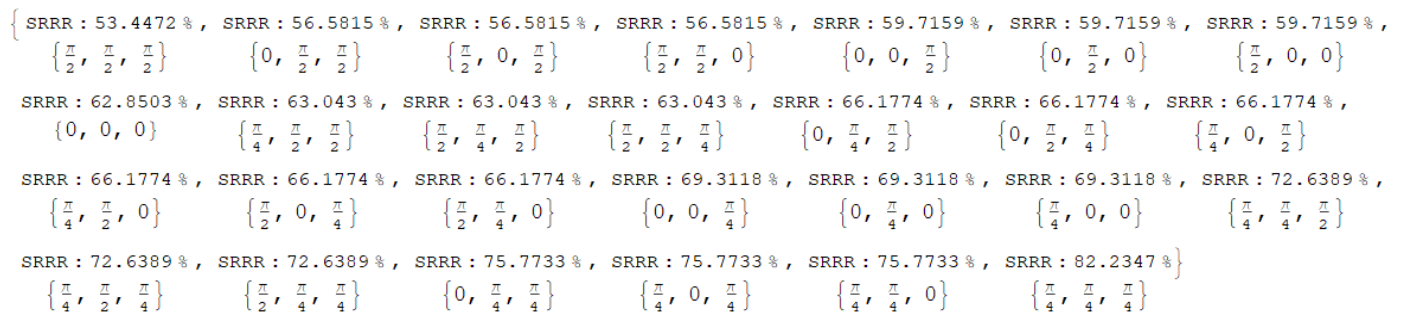


Figure 10. Solar Radiation Reception Rate for $m = 3$ and $n = 2$ at the summer solstice in the region of Makkah, Saudi Arabia.

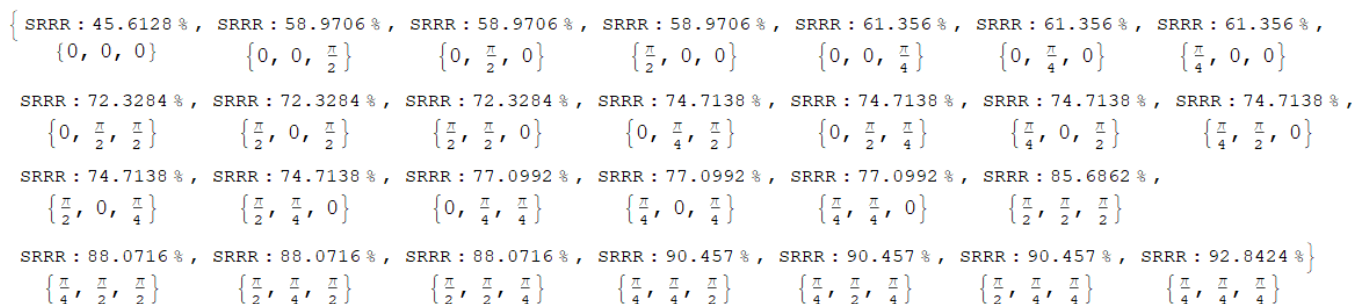


Figure 11. Solar Radiation Reception Rate for $m = 3$ and $n = 2$ at the winter solstice in the region of Makkah, Saudi Arabia.

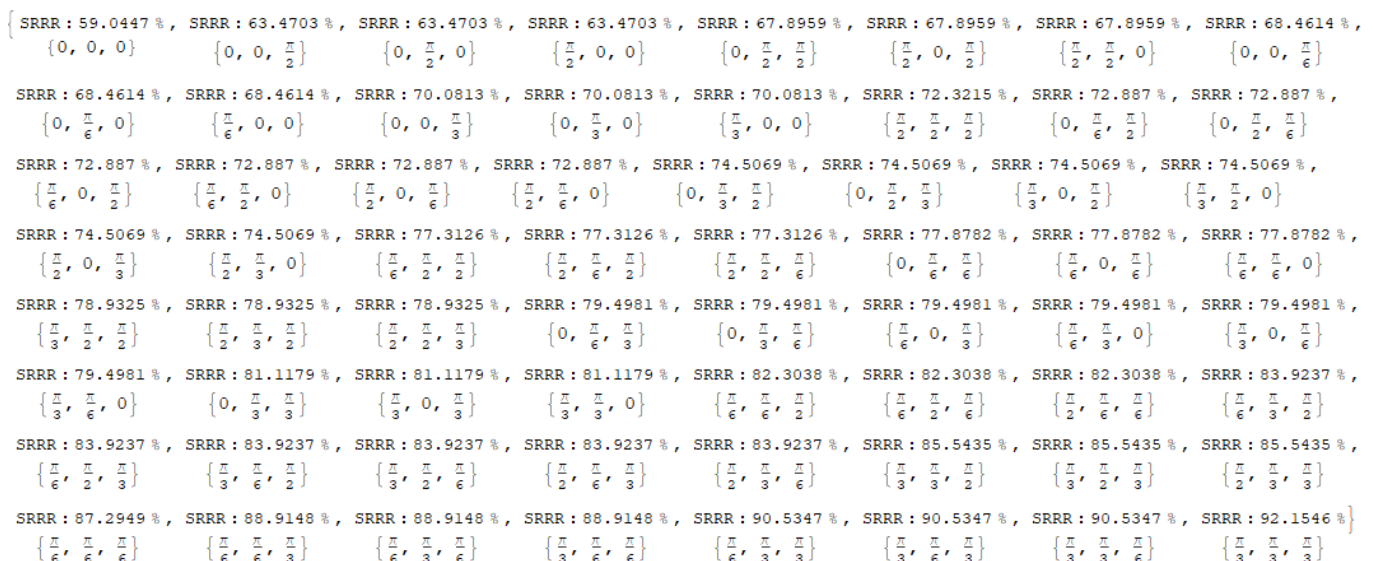


Figure 12. Solar Radiation Reception Rate for $m = 3$ and $n = 3$ at the equinox in the region of Makkah, Saudi Arabia.

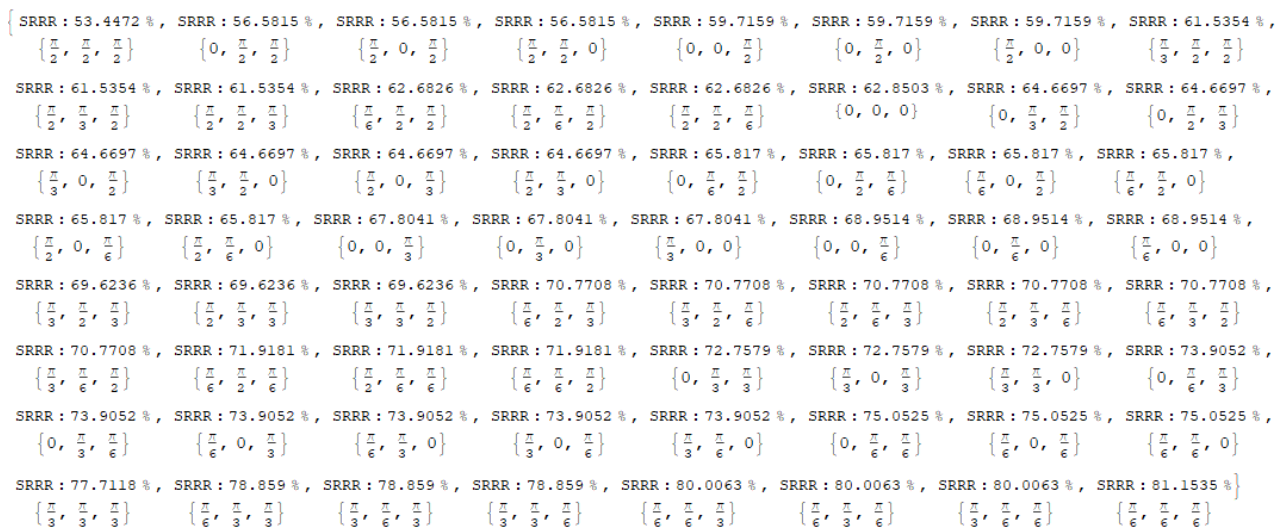


Figure 13. Solar Radiation Reception Rate for $m = 3$ and $n = 3$ at the summer solstice in the region of Makkah, Saudi Arabia.

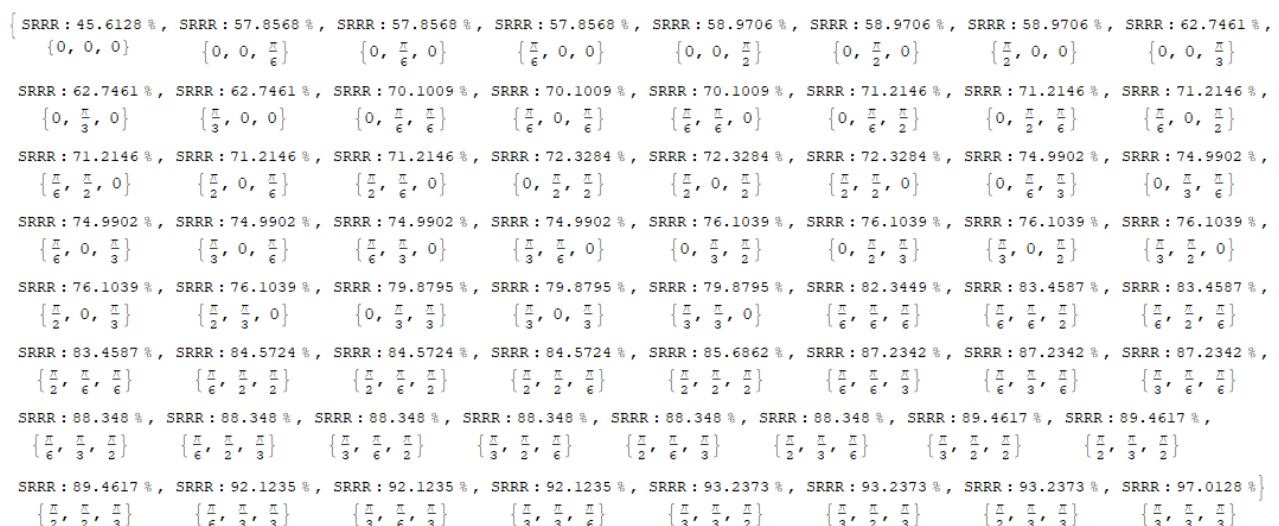


Figure 14. Solar Radiation Reception Rate for $m = 3$ and $n = 3$ at the winter solstice in the region of Makkah, Saudi Arabia.

The SRRR provided by a PTSP, composed of m segments that can be tilted at an angle equal to a n -divider of $\frac{\pi}{2}$, is numerically evaluated, at three significant days of the year—equinox (vernal or autumnal), summer solstice and winter solstice—in the region of Makkah, Saudi Arabia (21.3891° N, 39.8579° E). Each component in Figures 3–14 presents a combination case showing how the segments of the poly-tilted panel are inclined. A label indicating the SRRR level is attached at the top of each combination. For example, in Figure 9, the fifth component from the left presents the combination $\{0, \pi/2, \pi/2\}$ reflecting the case of a poly-tilted panel subdivided into three inclined segments. The first segment is inclined by 0 rd, the second one is inclined by $\pi/2$ rd, and the third one is inclined by $\pi/2$ rd. This combination case gives an SRRR around 67.8959% at the equinox in the region of Makkah, Saudi Arabia (21.3891° N, 39.8579° E). This example is explained in order to show how to simply read the results depicted by Figures 3–14.

Figures 3–5 depict the SRRR in the case of $m = 2$ and $n = 1$. Figure 3 shows the SRRR at the equinox (20 March or 22 September) for a PTSP composed by two segments that can be titled by 0^{rd} or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 59.04% to 72.32% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$, respectively. For a

desired minimum SRRR of 80%, no segment/tilt combination can be recommended. If the SRRR must be limited for technical reasons (for example, a value of SRRR limited to 75%), all segment/tilt combinations are recommended.

Figure 4 shows the SRRR at the summer solstice (21 June) for a PTSP composed by two segments that can be titled by 0^{rd} or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 53.45% to 62.85% for segment/tilt combinations of $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{0^{\text{rd}}, 0^{\text{rd}}\}$, respectively. For a desired minimum SRRR of 80%, no segment/tilt combination can be recommended. If the SRRR must be limited to 66%, all segment/tilt combinations are recommended.

Figure 5 shows the SRRR at the winter solstice (21 December) for a PTSP composed by two segments that can be titled by 0^{rd} or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 45.61% to 85.69% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$, respectively. For a desired minimum SRRR of 80%, only the segment/tilt combination $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ is recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ is recommended.

Figures 6–8 depict the SRRR in the case of $m = 2$ and $n = 2$.

Figure 6 shows the SRRR at the Equinox for a PTSP composed by two segments that can be titled by $0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 59.04% to 92.89% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively. For a desired minimum SRRR of 80%, the segment/tilt combinations $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$ are recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ are recommended.

Figure 7 shows the SRRR at the Summer Solstice for a PTSP composed by two segments that can be titled by $0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The solar SRRR varies from 53.45% to 82.23% for segment/tilt combinations of $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively. For a desired minimum SRRR of 80%, the segment/tilt combination $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$ is recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$, $\{0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{0^{\text{rd}}, 0^{\text{rd}}\}$ are recommended.

Figure 8 shows the SRRR at the winter solstice for a PTSP composed by two segments that can be titled by $0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 45.61% to 92.84% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively. For a desired minimum SRRR of 80%, the segment/tilt combinations $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$, $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$ are recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ are recommended.

Figures 9–11 depict the SRRR in the case of $m = 3$ and $n = 2$.

Figure 9 shows the SRRR at the equinox for a PTSP composed by three segments that can be titled by $0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 59.04% to 92.89% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively. For a desired minimum SRRR of 80%, the segment/tilt combinations $\{0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$ are recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ are recommended.

Figure 10 shows the SRRR at the summer solstice for a PTSP composed by three segments that can be titled by $0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 53.45% to 82.23% for segment/tilt combinations of $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively. For a desired minimum SRRR of 80%, only the segment/tilt combina-

tion $\left\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\right\}$ is recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\left\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ are recommended.

Figure 11 shows the SRRR at the winter solstice for a PTSP composed by three segments that can be titled by $0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 45.61% to 92.84% for segment/tilt combinations of $\left\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\right\}$, respectively. For a desired minimum SRRR of 80%, the segment/tilt combinations $\left\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\right\}$ are recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\left\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ and $\left\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\right\}$ are recommended.

Figures 12–14 depict the SRRR in the case of $m = 3$ and $n = 3$.

Figure 12 shows the SRRR at the equinox for a PTSP composed by three segments that can be titled by $0^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 59.04% to 92.15% for segment/tilt combinations of $\left\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$, respectively. For a desired minimum SRRR of 80%, the segment/tilt combinations $\left\{0^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$ are recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\left\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\right\}$ and $\left\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ are recommended.

Figure 13 shows the SRRR at the summer solstice for a PTSP composed by three segments that can be titled by $0^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 53.45% to 81.15% for segment/tilt combinations of $\left\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}\right\}$, respectively. For a desired minimum SRRR of 80%, the combination $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}\right\}$ are recommended. If the SRRR must be limited to 66%, the segment/tilt combinations $\left\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ and $\left\{0^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ are recommended.

Figure 14 shows that the SRRR at the winter solstice for a PTSP composed by three segments that can be titled by $0^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$ with regard to the horizontal. The SRRR varies from 45.61% to 97.01% for segment/tilt combinations of $\left\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$, respectively. For a desired minimum SRRR of 80%, the segment/tilt combinations $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$, $\left\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ and $\left\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$ are recommended. If the SRRR must be limited to 66%, the segment tilt combinations $\left\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}\right\}$, $\left\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\right\}$ and $\left\{0^{\text{rd}}, 0^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\right\}$ are recommended.

Based on the previous results, it is deduced that the increase in tilt angle division, from one to two divisions, for the same number of panel segmentation (two segments) considerably enhances the maximum SRRR by 20.57% from 72.32% to 92.89% at the equinox, by 19.38% from 62.85% to 82.23% at the summer solstice, and by 7.15% from 85.69% to 92.84% at the winter solstice.

The increase in tilt angle division, from two to three divisions, for the same number of panel segmentation (three segments) slightly reduces the maximum SRRR by 0.74% from 92.89% to 92.15% at the equinox, and by 1.08% from 82.23% to 81.15% at the summer solstice. At the Winter Solstice, an increase by 4.17% from 92.84% to 97.01% is recorded. It is deduced, also, that despite the fact that the increase in the panel segmentation, from two

to three segments (keeping the same number of tilt angle division (two divisions)) does not affect the range of SRRR (at the equinox, summer solstice and winter Solstice), it gives more possibilities for the SRRR levels. The range of SRRR is, then, more quantified. This is very convenient for applications associated to precise levels of SRRR.

5. Conclusions

The main conclusions of this work can be summed up into five points:

1. A PTSP is proposed as a novel technological solution permitting control of the daily received amount of solar radiation directly related to the SRRR. It is necessary to carry out SRRR control under extremely sunny conditions, such as the case of the city of Makkah (21.3891° N, 39.8579° E), Saudi Arabia, in order to ensure proper functioning of some solar powered technologies (such as solar thermal and photovoltaic). Sustainability of cities and villages located in extremely sunny regions is, then, promoted.
2. At the equinox:
 - For two segments and two tilt angle divisions (0^{rd} or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 59.04% to 72.32% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$, respectively.
 - For two segments and three tilt angle divisions ($0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 59.04% to 92.89% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively.
 - For three segments and three tilt angle divisions ($0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 59.04% to 92.89% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively.
 - For three segments and four tilt angle divisions ($0^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 59.04% to 92.15% for a segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\}$, respectively.
3. At the summer solstice:
 - For two segments and two tilt angle divisions (0^{rd} or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 53.45% to 62.85% for segment/tilt combinations of $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{0^{\text{rd}}, 0^{\text{rd}}\}$, respectively.
 - For two segments and three tilt angle divisions ($0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the solar SRRR varies from 53.45% to 82.23% for segment/tilt combinations of $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively.
 - For three segments and three tilt angle divisions ($0^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 53.45% to 82.23% for segment/tilt combinations of $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively.
 - For three segments and four tilt angle divisions ($0^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 53.45% to 81.15% for segment/tilt combinations of $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$ and $\{\frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}, \frac{\pi}{6}^{\text{rd}}\}$, respectively.
4. At the winter solstice:
 - For two segments and two tilt angle divisions (0^{rd} or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 45.61% to 85.69% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{2}^{\text{rd}}, \frac{\pi}{2}^{\text{rd}}\}$, respectively.

- For two segments and three tilt angle divisions (0^{rd} , $\frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 45.61% to 92.84% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively.
 - For three segments and three tilt angle divisions (0^{rd} , $\frac{\pi}{4}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 45.61% to 92.84% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}, \frac{\pi}{4}^{\text{rd}}\}$, respectively.
 - For three segments and four tilt angle divisions (0^{rd} , $\frac{\pi}{6}^{\text{rd}}$, $\frac{\pi}{3}^{\text{rd}}$ or $\frac{\pi}{2}^{\text{rd}}$): the SRRR varies from 45.61% to 97.01% for segment/tilt combinations of $\{0^{\text{rd}}, 0^{\text{rd}}, 0^{\text{rd}}\}$ and $\{\frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}, \frac{\pi}{3}^{\text{rd}}\}$, respectively.
5. When the tilt angle division increases from two to three divisions for three segments, the maximum SRRR is slightly reduced by 0.74% at the equinox and by 1.08% at the summer solstice, while it increases by 4.17% at the winter solstice. When the number of segments increases from two to three segments for two tilt angle divisions, the SRRR range is not affected but it is more quantified, which gives more possibilities to the SRRR control management since further SRRR levels within the SRRR range are specified. This will permit accurate adjustment of the appropriate SRRR.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en15072357/s1>, Clear and significant bar plots, indicating SRRR results, are provided as supplementary materials, published online alongside the manuscript. It is to note that supplementary Figures S10–S12 are subdivided into two parts (a and b) for reasons of clarity. Figure S1. SRRR for $m = 2$ and $n = 1$ at the equinox in the region of Makkah, Saudi Arabia. Figure S2. SRRR for $m = 2$ and $n = 1$ at the summer solstice in the region of Makkah, Saudi Arabia. Figure S3. SRRR for $m = 2$ and $n = 1$ at the winter solstice in the region of Makkah, Saudi Arabia. Figure S4. SRRR for $m = 2$ and $n = 2$ at the equinox in the region of Makkah, Saudi Arabia. Figure S5. SRRR for $m = 2$ and $n = 2$ at the summer solstice in the region of Makkah, Saudi Arabia. Figure S6. SRRR for $m = 2$ and $n = 2$ at the winter solstice in the region of Makkah, Saudi Arabia. Figure S7. SRRR for $m = 3$ and $n = 2$ at the equinox in the region of Makkah, Saudi Arabia. Figure S8. SRRR for $m = 3$ and $n = 2$ at the summer solstice in the region of Makkah, Saudi Arabia. Figure S9. SRRR for $m = 3$ and $n = 2$ at the winter solstice in the region of Makkah, Saudi Arabia. Figure S10. (a) SRRR for $m = 3$ and $n = 3$ at the equinox in the region of Makkah, Saudi Arabia (Part a); (b) SRRR for $m = 3$ and $n = 3$ at the equinox in the region of Makkah, Saudi Arabia (Part b). Figure S11. (a) SRRR for $m = 3$ and $n = 3$ at the summer solstice in the region of Makkah, Saudi Arabia (Part a); (b) SRRR for $m = 3$ and $n = 3$ at the summer solstice in the region of Makkah, Saudi Arabia (Part b). Figure S12. (a) SRRR for $m = 3$ and $n = 3$ at the winter solstice in the region of Makkah, Saudi Arabia (Part a); (b) SRRR for $m = 3$ and $n = 3$ at the winter solstice in the region of Makkah, Saudi Arabia (Part b).

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Nomenclature

d	Day number
E	Equation of time
I	Incident solar radiation (W/m^2)
L	Longitude
m	Number of panel segments
n	Number of tilt angle divisions
$PTSP$	Poly-tilted segmented panel
$SRRR$	Solar radiation reception rate (%)
T	Time (hour)
β	Tilt angle combination (rd°)
γ	Azimuth angle (rd°)
δ	Declination angle (rd°)
θ	Incidence angle
φ	Latitude angle (rd°)
ω	Hour angle (rd°)
g	Global
l	Local time
lo	Local meridian
r	Sun rise
s	Sun set
t	Tilted panel
sm	Standard meridian
so	Solar time
z	Zenith

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