Modelling the Efficiency of Terrestrial Photovoltaic Systems

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1. Abstract

A computer simulation capable of investigating the interrelationship of module packing densities and module inclination angles and their effects on overall energy yield for a given PV system installation area is presented. It is demonstrated that the simulation is a useful tool in the optimization of proposed system designs, the analysis of electrical performance and, moreover, the prediction of the occurrence of degenerative system effects such as hot-spots. In one case, it is shown that increasing the system height to module spacing ratio from 0.18 to 0.24 results in potentially severe shading effects. Results for Seville (Spain) and Loughborough (UK) are compared. The potential pros and cons of tracking systems are demonstrated, in that elevation only tracking results in an annual irradiance harvest reduction of 0.4% in Loughborough and increase of 3.4% in Seville. Varying module inclination angles shows how significant irradiance losses can occur when static PV arrays are not optimally mounted, reducing the inclination from 40 degrees to zero results in an annual irradiance harvest reduction of ~20% in Seville and ~14% in Loughborough.

Keywords: Shading, Simulation, Irradiance Distribution, Tracking, PV Array.

2. Introduction

In PV applications where there is limited available space, such as BIPV, the overall power output may have to be maximised. An appropriate definition of system efficiency here is the energy output for a given area over the course of a period of interest, which is herein considered a full year.

PV systems are often installed in static rows with a fixed spacing between them. Each module has a fixed inclination angle, typically in the range of latitude less ten degrees. Typically row spacing is such that row to row shading may occur, which reduces system performance.

The energy yield of a system can be varied by altering inclination angles and module packing densities. Generally, the

packing density (for similar shading amounts) can be increased with shallower module mounting. However, this incurs the penalty of lower irradiance intercept – steeper angles will require a wider row to row spacing or incur a higher shading penalty. In order to maximise energy collection, one could employ module tracking, although this will normally result in a relatively low module population.

This paper investigates this multidimensional problem. A simulation tool is derived and used to identify system shading and irradiance losses under given sets of conditions.

3. Development of simulation tool

The aim of the tool is to calculate the irradiance on every point of a solar module, allowing for a detailed analysis of the shading issue. This is achieved by separating the input global horizontal data into its diffuse and direct components and creating an appropriate distribution of these across a sky-dome. In order to populate the sky-dome with appropriate irradiance values, the position of the Sun is obtained using the Solar Position Algorithm[1] and a meteorological data set is used to produce a realistic set of time-specific global horizontal irradiances. Meteonorm[2] is used here but the input of other datasets is easily possible. The global irradiance is split into beam and diffuse components using the Erbs, Klein and Duffy method[3]. This data is translated to the sky-dome via a simple geometric transformation, assuming isotropic sky conditions. The irradiance on a given point is then calculated using an inverse ray tracing algorithm.

The inverse ray tracing determines if a particular segment of the sky-dome is visible from a particular vantage point. This is done by determining if any objects obstruct the view to that element or not. The irradiance for the vantage point is then the sum over all visible sky patches. The size of the mesh grid is user-defined, thus pixel size is also user defined.

The simulation operates with the following assumptions: the area surrounding the system can be defined by a uniform hemisphere with no obstructions; all light comes from the sky-dome and is either entirely absorbed by the module or entirely absorbed by the ground, hence light is non-reflective; the distribution of diffuse irradiance is isotropic.

This will not greatly influence the usability of the simulation.

4. Results and discussion

4.1. Validation

In a first step, the results are compared with proven algorithms to gain confidence in the proposed irradiance split. Meteonorm is used as a data source of horizontal information, which is then transformed to one angle of inclination. The results for hemispherical radiation received by a 45 degrees inclined surface from the solid angle of 2πcompared.

The simulation ran in hourly steps for a module orientated due south in Loughborough, UK, for the year 2007. The probability distribution function of the deviations in the output data is shown in Figure 1.

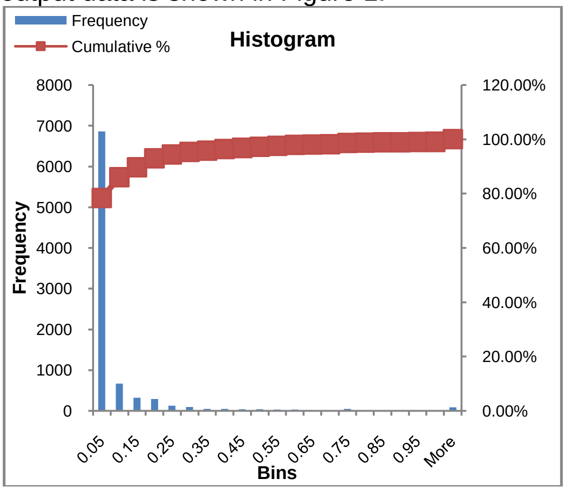


Figure 1. Deviations in the output data of the simulation and a meteorological data set.

Figure 1 shows that over 80% of the values generated by the 2 algorithms were within 5% agreement. Over 85% of the generated values were within 10%. Differences beyond 10% are largely due to a difference in the calculation of Sun position in the two programmes. Large differences are observed for time steps where cosine corrections within the simulation cause significant deviation. It is difficult to say which calculation is more accurate, albeit the SPA[1] used here is one of the of the more accurate algorithms for solar position calculation available today.

4.2. Effects of altering module packing density

To demonstrate the effects of altering module packing density, the simulation ran for a 2-row system in Loughborough, UK at 13:00 on January 1st, 2007. The generated global, beam and diffuse horizontal irradiances were 180W/m^2, 73W/m^2 and 107W/m^2, respectively. The angle of inclination was 45 degrees and the system orientation due south. The module dimensions were 10m by 1.5m by 0.05m and the row spacing adjusted for investigation. The mesh grid containing the points of interest was set to a 200 by 30 point integer grid.

The module density was incremented from 1 module per 7.5m to 5 modules per 7.5m. The irradiance on the southmost module was calculated consistently as 373.702 W/m^2. The minimum, maximum and average irradiance values of the module surface distributions are shown in Figure 2. The results are displayed in terms of system height to module spacing ratios.

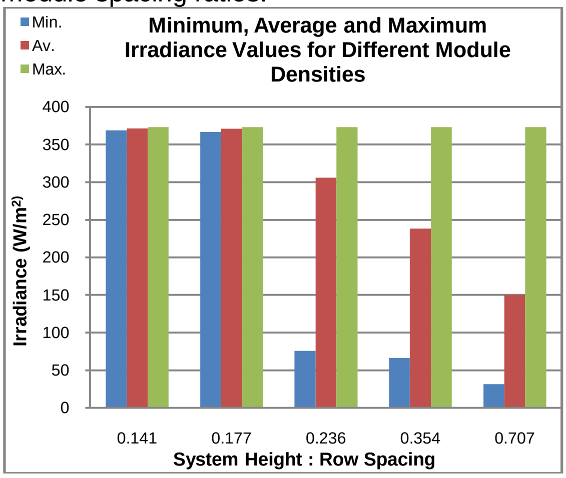


Figure 2. Collected irradiance distributions of the northern modules of systems with various module packing densities.

Figure 2 demonstrates that, under the given conditions, a system height to module spacing ration of 0.236 (module packing density of 1/4.5m) leads to a near 300 W/m^2 (~80%) difference in min and max irradiance values yet just a near 70 W/m^2 (~20%) difference in max and average. A consequential reduction in system performance is expected here, despite the increase in module packing density.

Further investigation into the above case is revealing. The generated irradiance distribution for this module is shown in Figure 3.

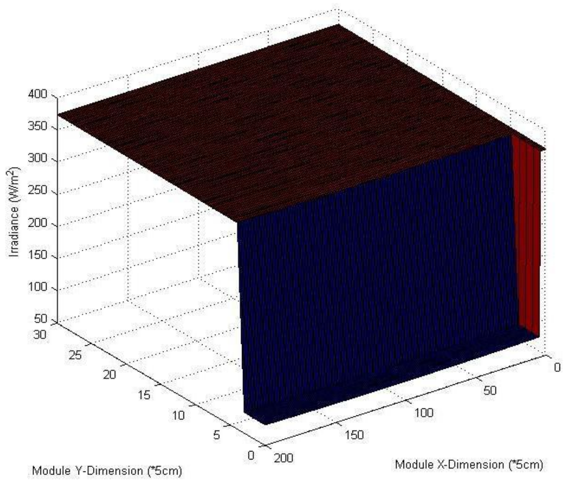


Figure 3. Irradiance distribution for the face of the northmost module (ref Figure 2, 1/4.5).

Here, the bottom of the module collects substantially less irradiance than the rest. Situations of this kind lead to dramatically reduced module and/or system performance. Data of this form can be extracted and used in an analysis of the electrical performance of the system, through, for example, Bishop's equations[4]. These predictions can be used to ascertain suitable minimum row spacing requirements and thus maximum module packing densities.

The results are certainly plausible and as such the method is robust enough for confidence in the simulations carried out in the following sections.

4.3. Effects of inclination angle on irradiance harvest

The simulation ran for a static, south orientated module. The inclination angle of the module was varied from 0 to 90 degrees with increments of 10 degrees. The tracked (elevation) harvest was included for comparison.

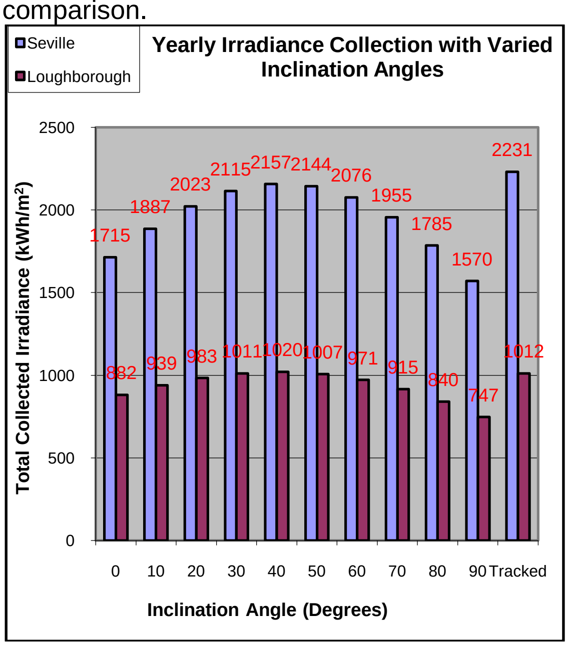


Figure 4. Yearly irradiance collection for static modules of varying inclination angles in Seville and Loughborough

Figure 4 demonstrates that module inclination angle is an important factor in system design. A variation of 40 degrees (from 40 to 0) in the above case results in a harvest reduction of around 442kWh/m^2 (~20%) for Seville and around 138kWh/m^2 (~14%) for Loughborough.

4.4. Effects of elevation tracking on irradiance harvest

The results for Loughborough and Seville are compared. To simplify data analysis, only the southmost modules are considered.

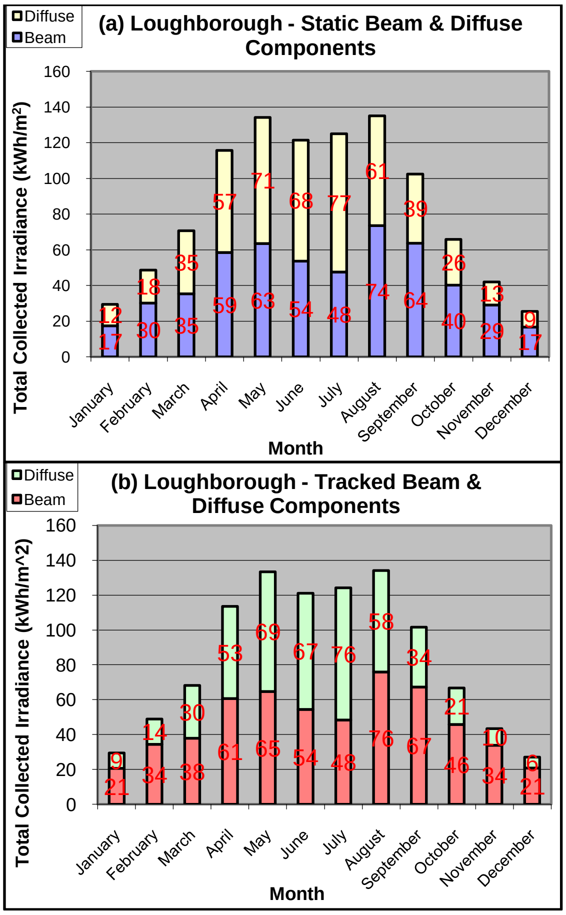
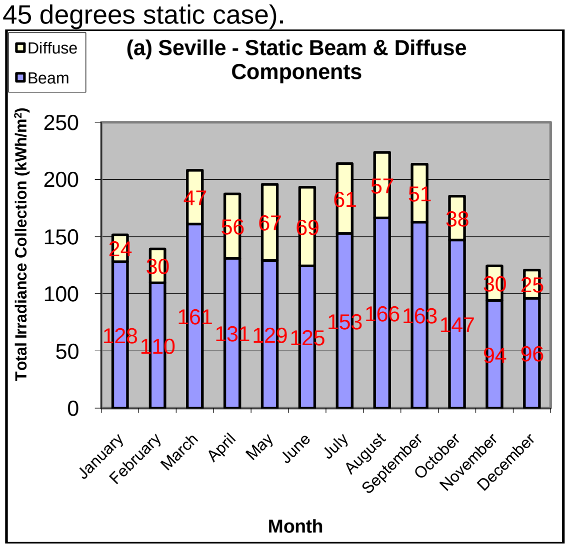


Figure 5. Monthly irradiance collection for (a) a static system, (b) a tracking system situated in Loughborough, UK, in 2007.

Figure 5 demonstrates that Loughborough receives a high proportion of diffuse irradiance. The introduction of tracking here results in a slight reduction in the yearly irradiance harvest (-0.4% compared with the 45 degrees static case).



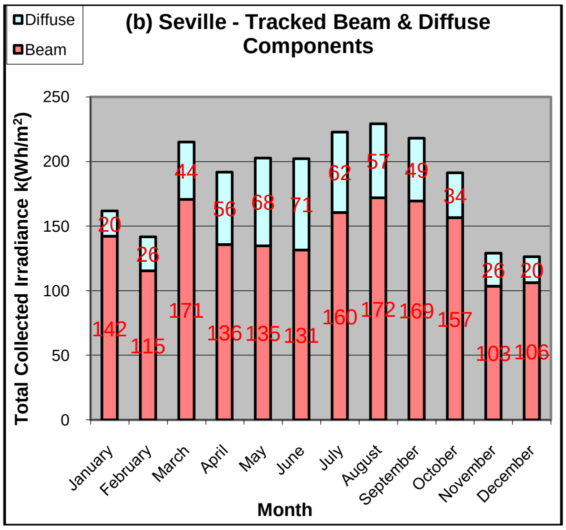


Figure 6 - Monthly irradiance collection for (a) a static system, (b) a tracking system situated in Seville, Spain, in 2007.

Figure 6 demonstrates that Seville receives a high proportion of beam irradiance. Here, tracking results in a slight increase in received irradiance (+3.4% compared with the static 45 degrees case).

Both figure 5 and figure 6 demonstrate that module tracking results in reduced diffuse and increased beam harvests.

Small tracking error effects were also checked. An average tracking error of 3 degrees results in a very slight, even insignificant, reduction in beam irradiance collection. It is important to note that the irradiance harvest in this simulation refers to that of a flat module with no associated optical devices. Tracking systems are most commonly used in CPV, where the use of optical devices ensures that tracking errors are more detrimental to irradiance harvest.

5. Conclusions

The facility of an irradiance collection calculation for every pixel in a proposed system design, where pixel size is user-defined, is extremely useful for PV energy and efficiency rating applications and also for realistic theoretical non-linear shading effect modelling. The sky-dome translation in this simulation leads to the production of a data set that is useful both as a reference for system installation notes and for quick yet effective analyses of relative system performance potentials in possible installation regions.

The generated data allows for an analysis of the adequacy of system design in a given installation region. Designs can not only be compared by their energy yields, but also by their performance relative to the available energy in the region. Accurate calculation of Sun position allows for the prediction of degenerative scenarios, such as the one described in Fig.3. Variables in proposed designs can be adjusted based on such predictions, proving the simulation a useful tool in the optimisation of system design.

The results show that too much of an increase in module packing density can fiercely adversely affect system performance, due to the resultant amplified shading effects, and also that changes in module inclination can have a dramatic effect on system performance.

The model can be used to conclude whether tracking systems are beneficial to system performance for any given location. Section 4.4 of this paper shows that elevation-only tracking is detrimental to system performance in Loughborough yet beneficial to the system in Seville, albeit without the consideration the energetic requirements of the tracking systems themselves.

However, the model is somewhat limited by the set of assumptions and approximations upon which it is currently based. An expansion of the model, eliminating some of the more restrictive and potentially inaccurate of these, such as the non-reflectivity of light, the lack of obstructions in the surrounding area and the isotropic distribution of diffuse irradiance, would no doubt improve the quality and accuracy of results, as well as the number of possible applications.

6. References

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