Performance of single-axis tracking photovoltaic systems in Europe

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ABSTRACT

In the past few years, a great deal of interest has developed in the use of sun-tracking mountings for normal flat-plate PV systems. Such systems deliver more energy for the same nominal PV power, but the cost of tracking is also higher than that of normal fixed-rack mountings. Tracking systems that have two axes and follow the sun closely at all times during the day are currently the most popular. However, systems that move the PV modules around a single rotating axis are simpler than two-axis tracking systems and can therefore be manufactured at a lower cost. This article presents research conducted by the authors on the performance of different tracking options. The results show that an optimized single-axis tracking system can deliver almost the same energy as a two-axis tracking system.

PV tracking systems

Photovoltaics has seen huge growth in several European countries recently, from those with hot and sunny conditions like Spain, southern Italy and Greece, to the more moderate conditions in Germany, the Netherlands and the Czech Republic.

In most cases these new PV installations have been constructed with the PV modules mounted in a fixed position, typically inclined at the local optimum slope and facing south, or integrated into buildings at whatever inclination and orientation is needed to fit in with the existing building shape. However, there is a growing interest in mounting the PV modules on moving supports to allow the modules to follow the sun during the day in order to maximise the amount of sunlight that arrives at the module surface. These mountings are known as *sun-tracking* systems.

Tracking systems can be made in a number of different ways. A system that always tracks the position of the sun perfectly is often called a *two-axis tracking* system, since it is not possible to track the position of the sun with a movement around a single axis of rotation. Up to recently, most of the industry interest has been in two-axis tracking systems, since these deliver the maximum energy for a given PV system size. This type of mounting is the only feasible option for concentrating PV (CPV) applications as the lenses or mirrors of the system must point straight at the sun disc at all times.

Figure 1. Photo of the tracking PV system installed by Raytracker, Inc. at the British Telecom US Headquarters, El Segundo, California.

Figure 2. The Solar Wings PV installation. 647kWp of modules are mounted on a single-axis tracking system with the rotation axis aligned about 15° away from north/south towards southwest, and inclined 23° from horizontal.

But this is not the only option available for flat-plate PV systems. A system that follows the sun imperfectly may receive almost as much energy as a true sun-tracking system. Simpler systems featuring one axis of rotation – henceforth known as *one-axis trackers* – may also significantly increase the amount of radiation received compared to the fixed systems. Such systems are less complex to construct and operate, and because the movements are simpler, they can be constructed at lower cost.

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The question then becomes whether the reduced cost can justify the reduced energy output. This in turn depends on calculating accurately the energy output from the various tracking options. This article will address a number of different tracking options and compare the estimated energy output between these systems and with the option of a fixed (non-tracking) system. On the other hand, no attempt will be made to assess the costs associated with the various tracking systems. With the industry in such rapid development, any information gleaned in relation to cost will undoubtedly be obsolete almost before this article is published. Nevertheless, the results should help potential investors to compare the different options on the market to find the one that gives the best price/performance ratio.

Examples of single-axis tracking systems

The number of PV systems using single-axis tracking is still rather small but increasing rapidly. The following is a brief selection of the systems that have been installed recently.

Raytracker, Inc. [1] produces and installs PV tracking systems upon which PV modules are rotated around a horizontal axis aligned north/south. Fig. 1 shows an installation of a 400kWp system installed above a parking lot at the British Telecom U.S. Headquarters in El Segundo, California. The trackers rotate the modules from east facing in the morning to west facing in the evening.

Another example is the Solar Wings design [2]. This 647kWp installation is in Waldshut, Germany and features steel cable-mounted modules that track the sun from east to west. The rotation axis is oriented slightly away from true north/south (about 15° towards southwest) and inclined 23° from horizontal. Fig. 2 shows a photo of the installation.

Calculation methods

Mounting types

There are several different options available for mounting flat-plate PV systems, including:

- Fixed mounting on a south-facing rack with the modules mounted at the yearly optimum inclination for the site.
- System with the PV modules rotating around a single axis placed in a north/south direction. The axis may be horizontal or lifted up at the northern end so it forms an angle with the horizontal plane. Modules are placed along the axis in the same plane as the axis, which is then rotated so the modules follow a path facing east in the morning to west in the evening. The examples shown in Figs. 1 and 2 are of this type.
- Single vertical axis system. The modules are mounted at an inclination angle relative to horizontal and moved around the vertical axis from east to west during the day.
- Two-axis tracking system that follows the sun path perfectly at all times.

Calculation methods

The methods used by PVGIS to estimate PV system output have been described in a number of papers [3,4,5,6]; therefore, only a brief description is required here.

The basis for the European part of PVGIS is a dataset with 10 years of data from 566 ground stations in Europe measuring global horizontal radiation and in some cases diffuse radiation. The station data were collected and processed as a part of the European Solar Radiation Atlas [7] and published as monthly averages of daily irradiation sums.

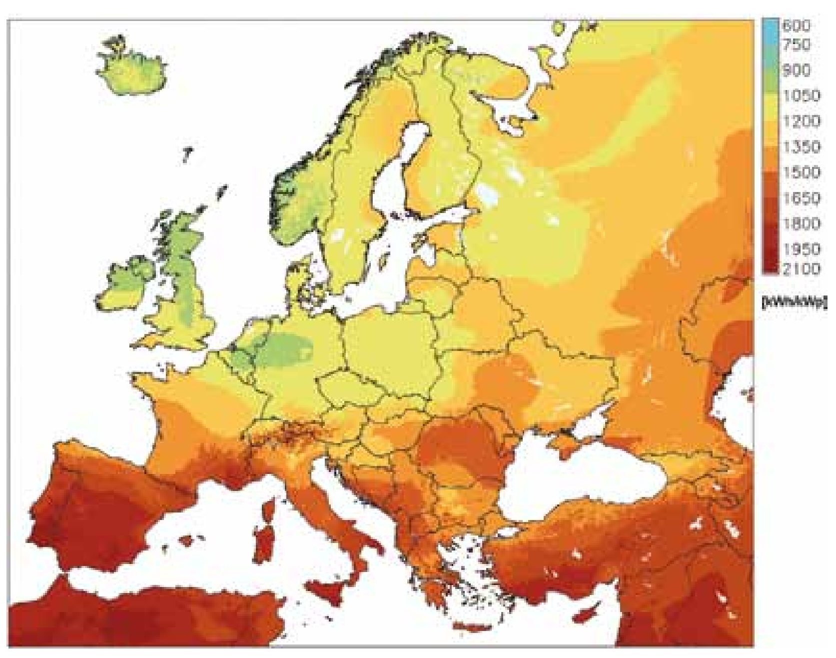

Figure 3. Map of PV performance in Europe showing the energy output of a 1kWp system mounted on a single-axis tracking system with a vertical axis and modules mounted at the local optimum angle.

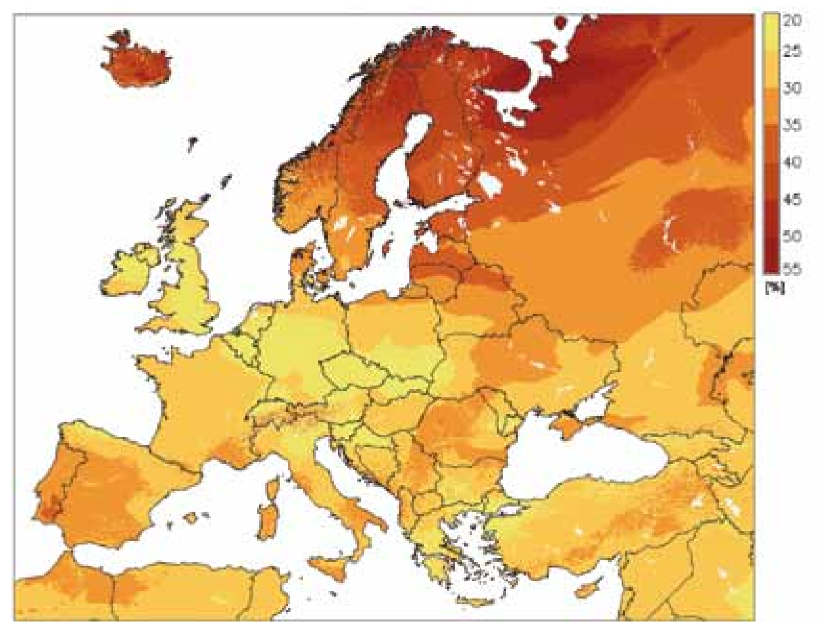

Figure 4. Percentage difference between the global irradiation arriving at the surface of a vertical-axis tracking system and a fixed system. Optimum angle is used both for the fixed and the tracking system.

Spatial interpolation methods were used to estimate the irradiation at geographical locations between the sites where ground station data is available [4].

Using the mathematical models described in Šúri and Hofierka [4] it is possible to reconstruct the average of the solar irradiance at any time during the day for a typical day in each month. This can be done for an arbitrarily placed plane, so it is possible to calculate the way the in-plane irradiance varies during the day also for a sun-tracking system. This method has been described for fixed and two-axis tracking systems [7].

From these daily values we calculate the yearly total irradiation on a given plane (fixed or moving), taking into account shadows from hills and mountains using a digital elevation map with a resolution of 100 x 100m.

The energy output of PV modules depends mostly but not solely on the irradiation level – elements such as the effects of temperature and reflectivity must also be taken into account [8]. Using monthly averaged data, it has been found that if one's interest lies only in the difference between the outputs of fixed and tracking systems, these effects tend to cancel each other out [7]. It follows that the relative difference in the PV output between fixed and two-axis tracking systems is almost the same as the relative difference between the respective in-plane irradiation values, an assumption that may not be fully valid when using real hourly data in the calculation. In addition, there are other losses in PV systems, such as losses in inverters, cables, losses due to dirt and snow and occasional shadows. The results presented in this paper assume that these 'other losses' amount to 14%, a fairly conservative value based on published data on PV systems' performance [9].

For some of the system types, the performance will depend on the chosen module angle. The authors have developed algorithms to find the optimum inclination angle for a given system, which will result in the highest annual output for the chosen location.

Performance comparison of various tracking options

Combining all the calculation methods yields maps of PV performance for Europe, such as that shown in Fig. 3, which shows the estimated PV output for a 1kWp PV system with crystalline silicon modules using a tracking system with a single vertical axis and the modules mounted with the optimum angle for each geographical location. The PV energy production in this map is the energy delivered to the grid, taking into account all losses. The energy output varies from about 1000kWh/year in North West Europe to ~1400kWh/year in Central France, Northern Italy and Hungary, and up to nearly 2000kWh/year in Southern Spain, Portugal and Sicily.

> "The relative difference in the PV output between fixed and two-axis tracking systems is almost the same as the relative difference between the respective in-plane irradiation values."

A comparison of this setup with a fixed system of the same nominal power is shown in Fig. 4, which shows the difference in the yearly in-plane irradiation between the vertical-axis system and the fixed system, in both cases using the optimum angle for the system. The difference is shown as a percentage increase for the tracking system over the fixed system. In this case there is no simple trend from north to south. In Southern

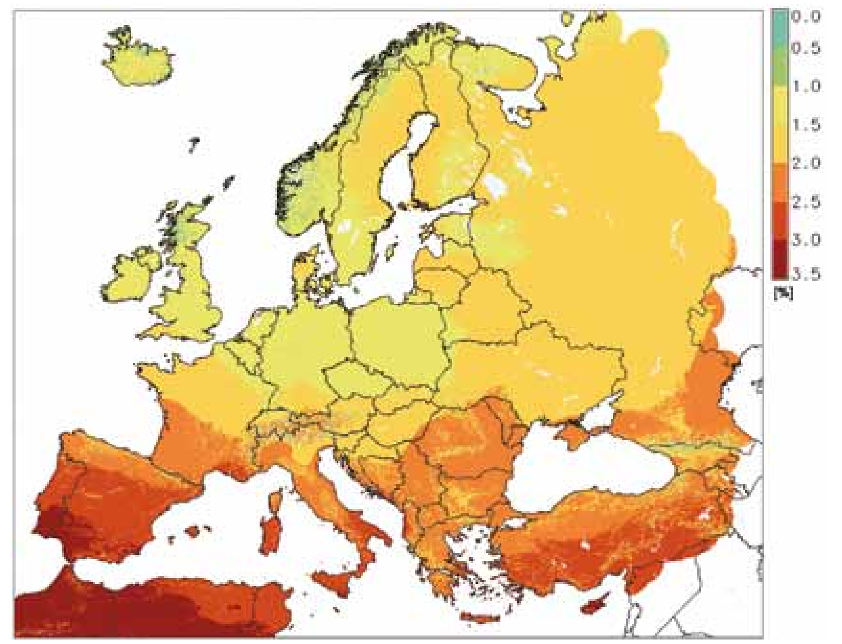

Figure 5. Percentage difference between the global irradiation arriving at the surface of a two-axis tracking system and at a vertical-axis system with optimum angle.

Europe and parts of the Balkans, the gain with tracking is generally around 30%; further north the gain is smaller, with values of 20-25% in much of Central Europe and the British Isles. Going even further north, the difference increases again and reaches more than 50% in Northern Scandinavia.

So far we have been looking only at vertical-axis systems. Repeating the calculation for inclined-axis systems aligned north/south we find that the two tracking options have almost the same performance, provided each of them uses the optimum inclination. The difference in output in most of Europe is less than 1%. Only in the far north will a vertical-axis system perform 2-3% better than the inclined-axis system.

The different single-axis tracking systems will only track the position of the sun imperfectly, so it is to be expected that a true two-axis tracking system would give higher energy output than any of the single-axis systems. But the discrepancy is surprisingly small. Fig. 5 shows the percentage gain in using two-axis tracking rather than the vertical-axis tracking with optimum angle. In Southern Europe the difference is around 3%, while in Central and Northern Europe the difference is smaller, typically around 1.5-2%. All these assumptions apply for areas that are not affected by shadowing of nearby terrain features or other obstacles.

> "A north/south-oriented horizontal tracking system performs better everywhere, normally giving 10-20% more energy than a fixed system."

To better illustrate the differences between all the discussed tracking options, we have calculated the PV output

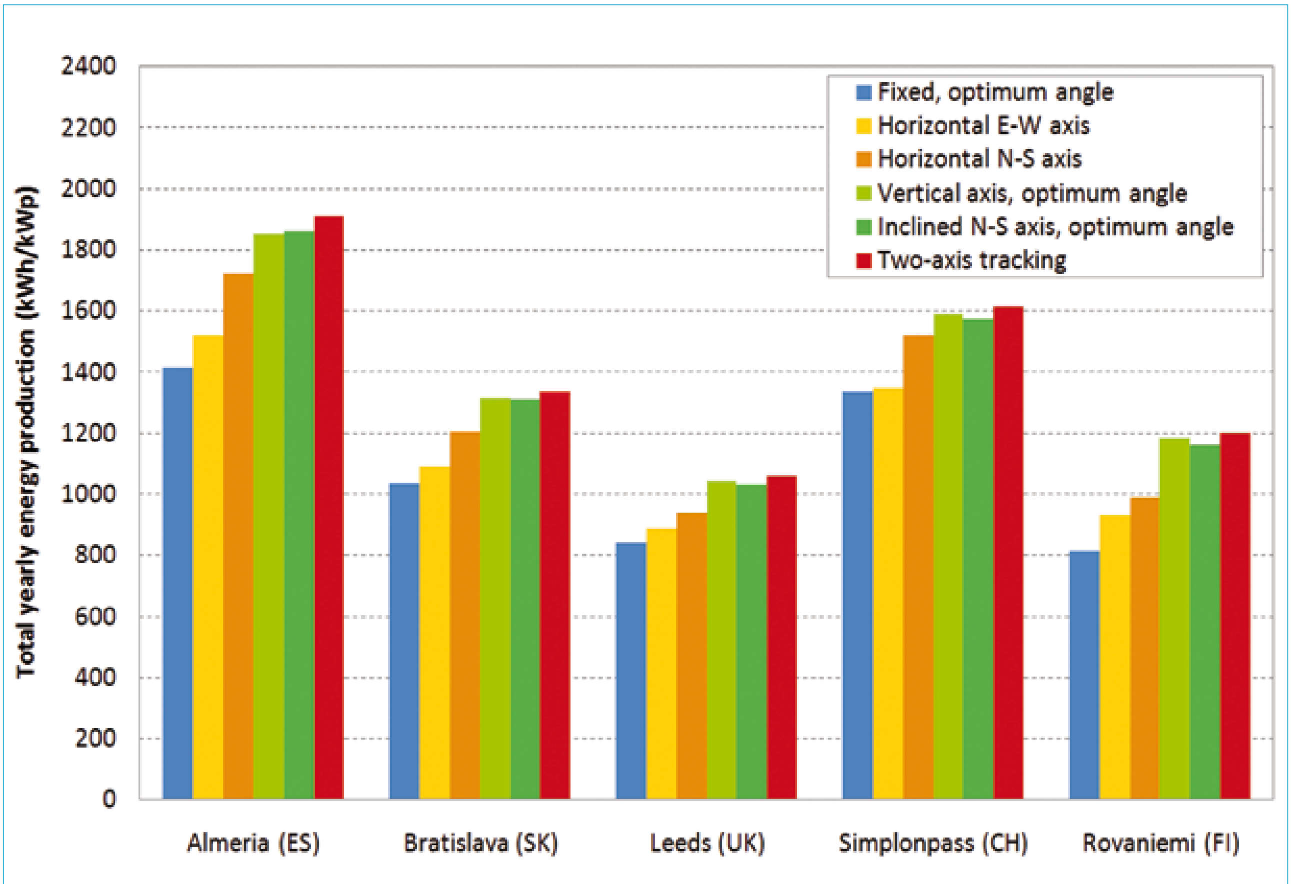

Figure 6. Comparison of the energy output from different system mountings for five locations in Europe. The comparison is made for a fixed system at optimum angle; for horizontal single-axis systems with axis pointing east/west or north/south; for vertical and inclined axis systems with optimum angle; and for a two-axis tracking system.

from a number of different tracking systems for five different locations in Europe representing different climatic zones. The results are shown in Fig. 6. In this case, the fixed system is compared to two different horizontal-axis systems (east/west oriented and north/south oriented), as well as to the inclined and vertical axis and the two-axis system.

The east/west horizontal-axis system has a slight advantage over the fixed system except where there is strong shadowing (Simplonpass), but this rarely reaches 10%. A north/south-oriented horizontal tracking system performs better everywhere, normally giving 10-20% more energy than a fixed system. A significant gain can be seen when moving to optimal angle for a single-axis system. Finally, the two-axis system performs slightly better than the optimized single-axis options.

One interesting feature is that by using tracking systems, the energy output is actually higher in the extreme north than in parts of North-Central Europe. This is only the case for tracking systems because they can follow the sun into the northern part of the sky in summer, unlike the fixed south-facing systems.

Conclusions

It is possible to gain a significant amount of energy when mounting PV systems on trackers. This gain depends on location, but will generally be 20-35% for a two-axis tracking system. Single-axis systems can perform almost as well as two-axis systems when the inclination of the modules is properly optimized. Given that single-axis systems are simpler in construction, this can make these systems attractive from a cost-benefit point of view.

One aspect of tracking systems that has not been discussed in this article is the problem of shadowing. In the morning and evening, the modules cast long shadows that may cover other modules, reducing the power output. For this reason it may sometimes be a better strategy not to let the modules track the sun all the way from sunrise to sunset, but to let them revert to a more south-facing position to avoid shadowing [10]. We are working on refining the calculation methods to take this effect into account.

The results that are based on the simulated average daily profiles of irradiation and temperature do not inherit specific local weather patterns such as convective clouds, thus giving an overview on the larger geographical scale. To calculate local site-specific differences of the tracking systems, data with higher spatial and temporal resolution may provide more realistic results.

Estimation of the energy output from various sun-tracking options is made available as a web application at the PVGIS site [11], where a user can request the calculations shown in this article for any location in Europe. Calculations based on the use of full time series of solar radiation and temperature data can be provided by the GeoModel Company.

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About the Authors

Thomas Huld holds an M.Eng. in electrical engineering and a Ph.D. in plasma physics, both from the Technical University of Denmark. He has worked for the last seven years in the fields of photovoltaics and solar radiation mapping, with particular involvement in mathematical modelling of PV performance and methods for estimating PV performance over large geographical areas. He maintains and develops the PVGIS web application.

Marcel Šúri holds an M.Sc. in physical geography and a Ph.D. in remote sensing and geoinformatics. From 2001 to 2008 he worked in the Joint Research Centre on geographical assessment of solar resources and PV potential mapping and is one of the co-authors of the PVGIS project. In 2008 he joined the GeoModel Company as the executive director. GeoModel develops solar radiation databases, simulation and control tools, maps, and web services to support the PV industry.

Tomáš Cebecauer received an M.Sc. in geography and a Ph.D. in geoinformation science. He worked on the technical development of solar radiation and geographical databases, algorithms, maps and web tools for the project PVGIS in the Joint Research Centre from 2005 to 2008. In 2008 he joined the GeoModel Company as the technical director to manage development of climate databases, tools and geoinformation services for solar energy industry.

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