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Maximum Collectable Solar Energy by Different Solar Tracking Systems

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The output energy from any solar energy system depends on the solar energy input to that system. Using different ways to track the solar energy system to follow the sun can increase solar energy input according to the type of the tracker. A practical study was carried out on different solar tracking systems. The layout of these systems are a fixed system facing south and tilted 40°, a vertical-axis tracker, a 6° tilted-axis tracker, and a two-axis tracker. All the trackers are microprocessor controlled systems, and all systems have photovoltaic arrays for electric energy production. The evaluation of the different systems is based on a complete year of measurements for solar radiation input to the systems and the electric power output from them. The study also includes the effect of some operating parameters on the tracker operation. These studies showed that the collected solar energy as well as the electrical output energy of the tracking solar system are more than that of the stationary system. These gains are higher in the case of the two-axis tracker and decrease gradually from the vertical-axis tracker to the tilted-axis tracker.

Keywords orientation, solar radiation, solar tracking.

At present, solar energy systems are used in many fields of life, especially for solar electric energy generation. In all solar applications, output from the solar energy system depends on the amount of solar radiation received by the system. The solar

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radiation received by the solar energy system varies with the angle that the sun's rays makes with the plane of the system. The sun tracker is a system that follows the sun and keeps the sun's rays almost normal to the plane of the solar system.

Baltas et al. (1986), Emslie and Dollard (1988), Gordon and Wenger (1991), and Guastella et al. (1993) carried out various investigations to study the operation of solar tracking systems to identify the optimum orientation according to their local sites and climatic conditions. They showed that the tracking solar systems increase the collected insolation by suitable gains over stationary systems. Jimenez et al. (1994), Pfeiffer (1985), Salim et al. (1988), and Shaltout and Hassan (1993) reported that these gains are relative to geographic location and weather conditions. In other words, the location of the plant is a very important factor in determining the output from any solar energy system.

The present work differentiates between different solar tracking systems with respect to the input solar radiation and the output electric energy measured from these systems for a complete year. The systems consist of a fixed system facing south and tilted 40°, a vertical-axis tracker, a 6° tilted-axis tracker, and a two-axis tracker. All the trackers are microprocessor controlled systems. The systems have photovoltaic arrays for electric energy production.

The objectives from the present work can be summarized in two main purposes: to compare stationary and tracking systems and to assess (1) the effect of the tracker reference position sensor on the tracker accuracy, (2) the effect of tracker accuracy on the system output, and (3) the factors affecting electrical power consumed by the solar tracker (El Shenawy, 1997).

System Descriptions

Here we describe the four systems, control, sensors, and data acquisition system. These systems are installed in Widderstall, Germany (test field of the Center of Solar Energy and Hydrogen Research, Stuttgart, Germany), latitude 48.58°N.

System A

System A is fixed on a wooden structure. The plane of the system is facing south and tilted by 40° horizontally, as this is the optimum tilt angle at the site for collecting more annual insolation. The system contains 120 commercial polycrystalline silicon modules arranged in 10 parallel strings forming one system with 4.8 KWp peak power and an operating voltage of 220 V. Each photovoltaic (PV) module has 40 WP as peak power at standard test conditions (STC) and an area of 0.5 m^2.

System B

System B rotates on one vertical axis (azimuth tracker). The plane of the system is inclined 33° horizontally. The system has 50 WP peak output at STC, and an area of 0.5 m^2 contains one AEG PV polycrystalline silicon module.

System C

System C rotates on a 6° tilted axis parallel to the north-south direction. This inclination was chosen to minimize environmental impact. The system contains

32 AEG PV monocrystalline silicon modules arranged in two parallel strings forming one system with 2.72 KWp peak power. Each PV module has 85 WP peak power at STC and an area of 0.75 m^2. System C contains a V-trough concentrator of a concentration ratio $2\times$. The reflectors consist of a crystal glass mirror, 4 mm thick, at an inclination of 60° on the module plane.

System D

System D is a two-axis, azimuth-elevation tracker. The structure of the system is mounted on a column 3 m above the ground. It is used for testing different light concentrations.

Control

Systems B and C use SOLARTRAK controllers for controlling motion. The controller computes the sun's position using the time, date, and site parameters and converts it to the tracker position using the coordinate transformations and derives transformation equations that can be linear for a geared system (like system B) or nonlinear for a screw jack system (like system C).

System D is a HELIOMAN solar module containing a microprocessor that takes the control commands via a digital signal from a PC. The computer computes the sun's position, by a specific software operating in real-time, and compares the actual position of the tracker with the calculated position. Once the difference reaches a certain threshold, the PC sends the digital control commands to the microprocessor. The tracker azimuth motion is linear by gears, while the elevation motion is nonlinear by self-locking lifting spindle.

Sensors

Several sensors are required by the open-loop control trackers, such as dual-turn count sensors to measure the motion and the direction, two limit switches to stop the tracker motion if it reaches the hard end in both sides, and an angle reference sensor to provide a fixed hardware reference to zero the internal position counters.

Data Acquisition System

Several parameters are measured, such as input solar radiation and output power from each system. The measured parameters are sampled every 10 sec and averaged every 1 min using a computer data acquisition system.

Results and Analysis

The results include two main parts: (1) comparison between the different systems with respect to the hourly measured input solar radiation and the power output, and (2) the effect of the sum of the operating parameters on the performance of the solar tracker.

Comparison Between Different Solar Tracking Systems

Figure 1 shows the solar radiation input to the different systems, while Figures 2 and 3 show the solar radiation input and the power output gained from the different systems over the fixed-tilt system.

From Figures 1–3, the following can be seen.

1. The fixed system, at the optimum tilt angle of 40°, receives annual solar radiation of 1149.02 KWh / m^2.
2. There is a gradual increase in the solar radiation input and the power output from the fixed-tilt system to the tilted-axis tracker to the vertical-axis tracker to the two-axis tracker.
3. The vertical-axis tracker gets more radiation than the fixed-tilt system for all months of the year, with higher radiation gains in summer months than in winter. The annual solar radiation input and the power output gained from the vertical-axis tracker over the fixed-tilt system are 18% and 21% (9 months only), with tracking accuracy of ± 0.15°.
4. The main part of the solar radiation input to the tilted-axis tracker is in summer, from the small tilt angle (6°) of the tracking axis. As a result, the system receives more radiation than the fixed-tilt system only in summer, with the inverse in winter. The tilted-axis tracker gets 11% more annual radiation than the fixed-tilt system, whereas the combination of the tilted-axis tracker and the V-trough concentration increases the input solar radiation and the power output gains to about 57% and 31%, respectively, with tracking accuracy of ± 0.56°.

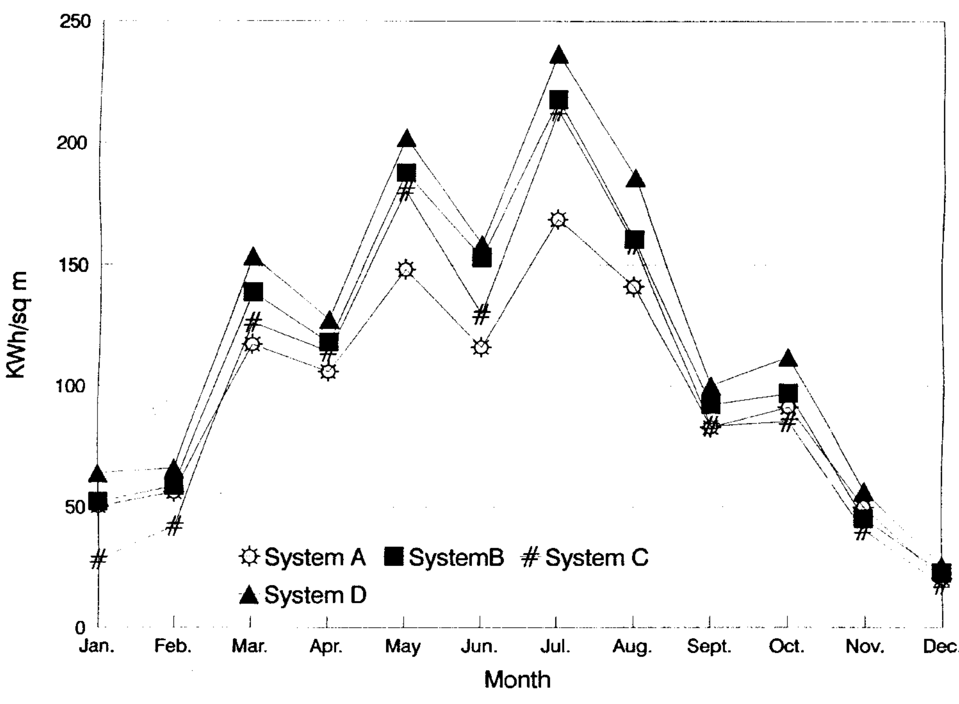

Figure 1. Solar radiation input to the different systems.

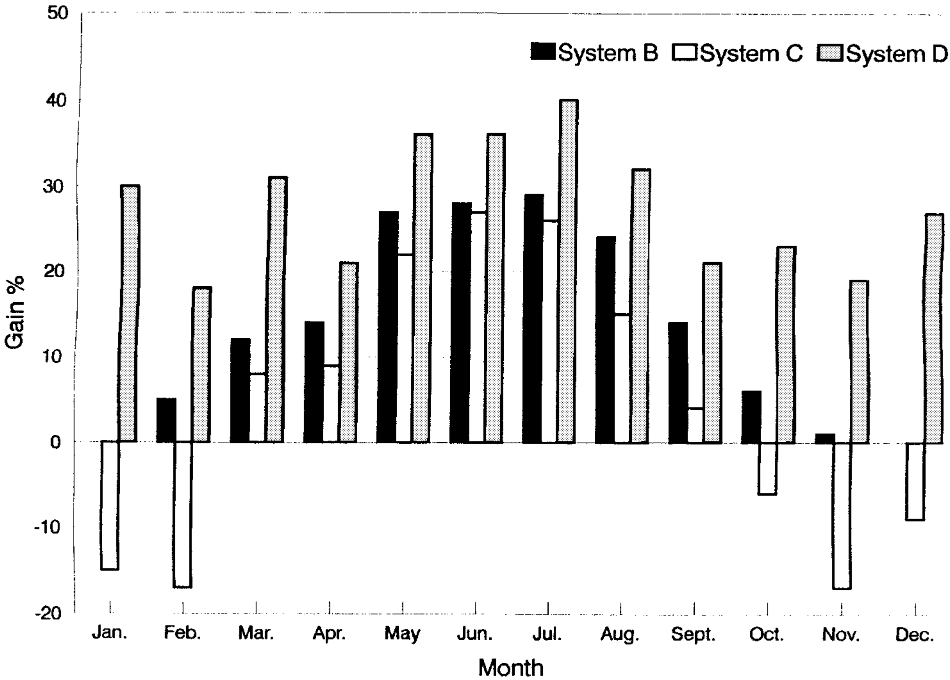

Figure 2. Solar radiation input gained from the different systems over that of system A.

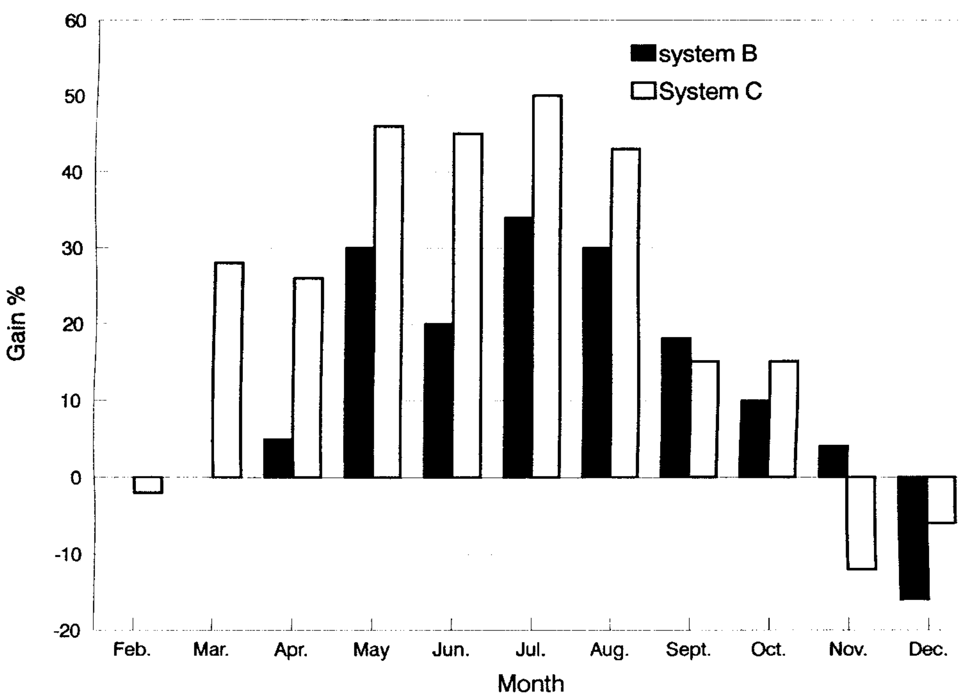

Figure 3. Power output gained from system B and system C over that of system A.

5. Since the two-axis tracker follows the sun in both daily and seasonal motions, it gets the highest radiation of all trackers. The annual radiation gained from the two-axis tracker over that of the fixed-tilt system is 30%, with tracking accuracy of $\pm$ 0.1° and $\pm$ 0.3° for the elevation and azimuth motions, respectively.

The previous section showed the advantages of the trackers in increasing the system's solar radiation input and power output under normal operating conditions. The next section outlines the effect of some operating parameters on the tracking operation. This includes effect of the reference sensor position on tracker performance and effect of tracking accuracy on the system output and electric energy consumed by the tracker.

Reference Sensor Position

Since the open-loop trackers do not sense the sun's position, they compute this position and convert it to a certain number of counts. The reference sensor is used to provide a fixed hardware reference to zero the internal position counter, which makes its position critical for tracking accuracy.

The two-axis tracker uses two reference position sensors, one for each direction of motion. Figure 4 shows the output of a concentrated PV module ($c = 21\,x$), using the two-axis tracker, versus error in azimuth motion only. From this figure it can be seen that the curve shown is not symmetric around the zero position. This is due to unequal outputs from the PV module for the same positive and negative

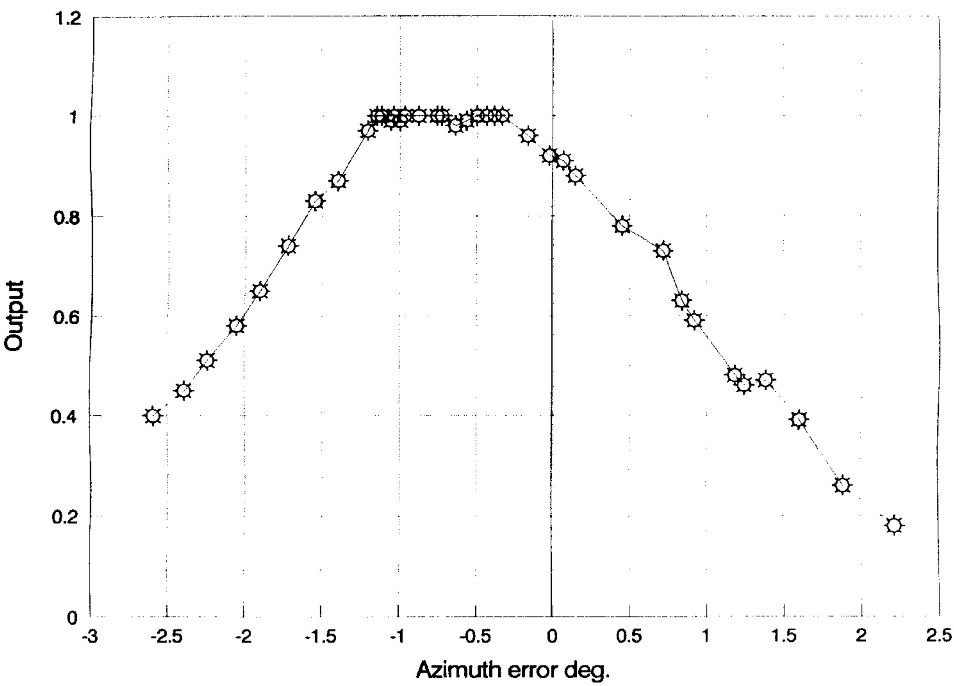

Figure 4. Output from the concentrated PV module ($c = 21\,x$) versus azimuth error in the two-axis tracker.

tracking errors. The main source of this error is the incorrect position of the reference sensor for azimuth motion. This error equals, in this case, about 0.7°. This error has a serious effect on the system output, especially for the small pointing error tolerance, concentrated PV modules. Consequently, accuracy of the reference position affects tracker accuracy.

Tracking Error

Two PV modules with high concentration ratios are installed on the two-axis tracker for studying the effect of tracking error on their outputs. Table 1 shows the main specifications of the two modules. The test is made by keeping the ideal operation in the elevation tracking, ± 0.1°, while the azimuth accuracy is decreased to 5°. Figure 5 shows the error in this case. The corresponding module outputs (the ratio between the module short circuit current to the total radiation) are shown in Figures 6 and 7.

The figures show that the effect of the tracking error is not the same on the module outputs at all times of day. For the same tracking error, the loss of module output is larger in the early hours of the day, decreases near noon, and then increases again at the end of the day. This result arises from the change in tilt angle of the tracker platform during the day. Near noon, the tracker platform has lower horizontal tilt angles. As a result, there is only a slight effect caused by changing the azimuth position, for some degrees, on the incidence angle of the sun's rays on the tracker platform.

Although the previous result is valid for the two modules, the losses in module output for the same error are different. At noon, although module ENTECH gives about 50% of its output at 5° azimuth error (Figure 6), module MIDWAY is almost unaffected by this error (Figure 7). This good performance from module MIDWAY continues for about 5 hours around solar noon. Since module ENTECH has a higher concentration ratio than module MIDWAY, it suffers more losses for the same error.

The same result can be drawn from the tilted-axis tracker (system C), as shown in Figure 8. It is clear from the figure that the tracking error has a different effect

Table 1
Main specifications of the concentrated modules used with the two-axis tracking system

Parameter	ENTECH module	MIDWAY module
Dimension	366 cm × 85 cm	193 cm × 51 cm
Concentration ratio	21 ×, line focus	170 ×, point focus
Short circuit current	19.9 A at 770 W/m^2	8.5 A at 850 W/m^2
Open circuit voltage	20.4 V	11.2 V
Output	302 W at 16.3 V and 18.6 A at 770 W/m^2 and 37°C	65 W at 8.12 V and 8 A at 850 W/m^2 and 25°C
Module efficiency	16%	9.2%

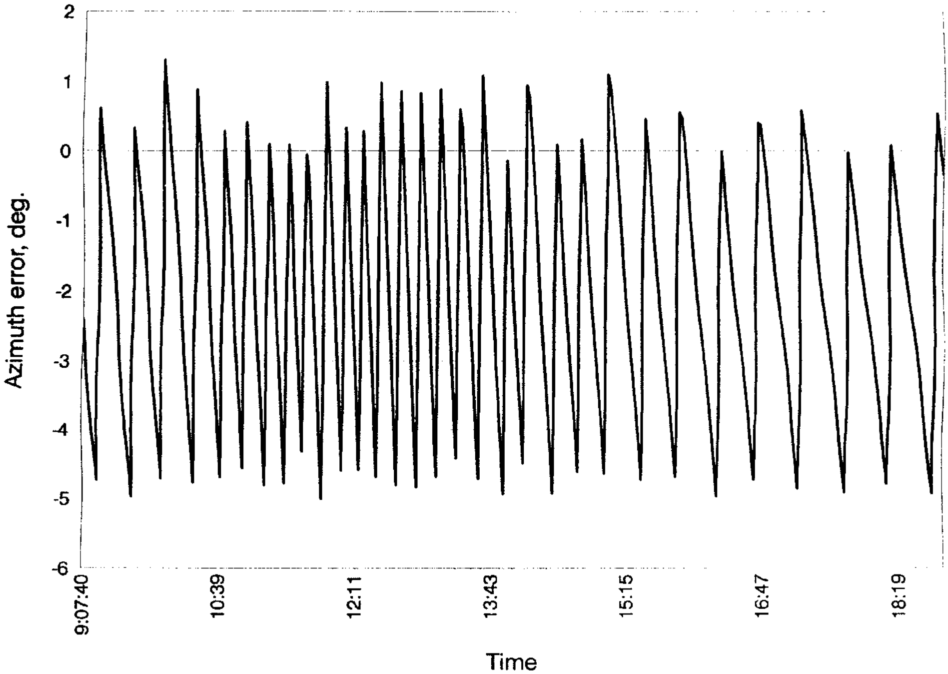

Figure 5. Azimuth error in the two-axis tracker versus time of day.

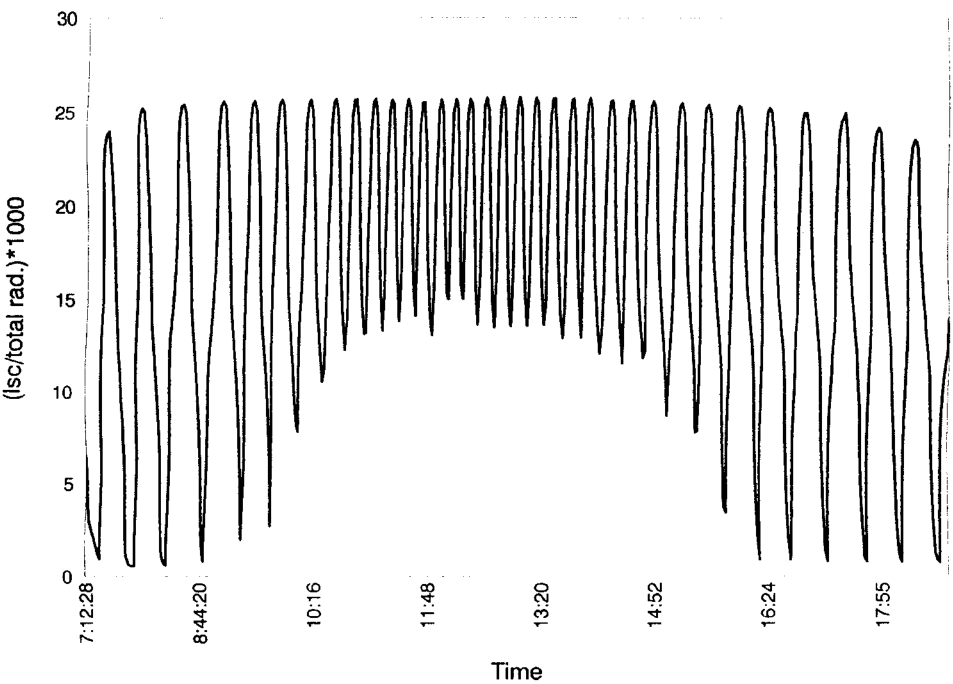

Figure 6. Output from ENTECH module versus azimuth error.

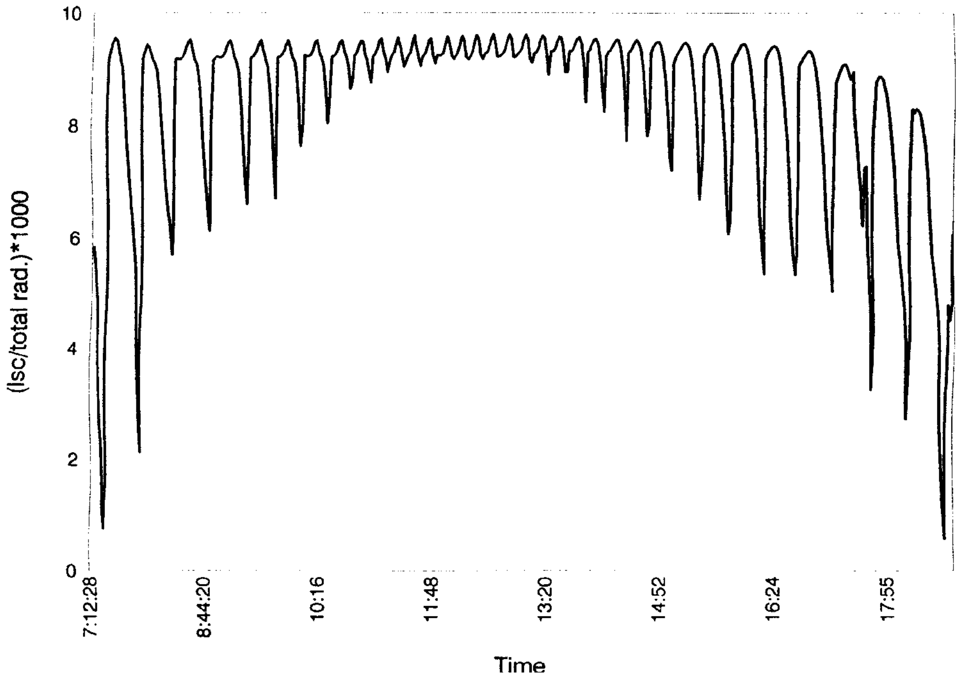

Figure 7. Output from MIDWAY module versus azimuth error.

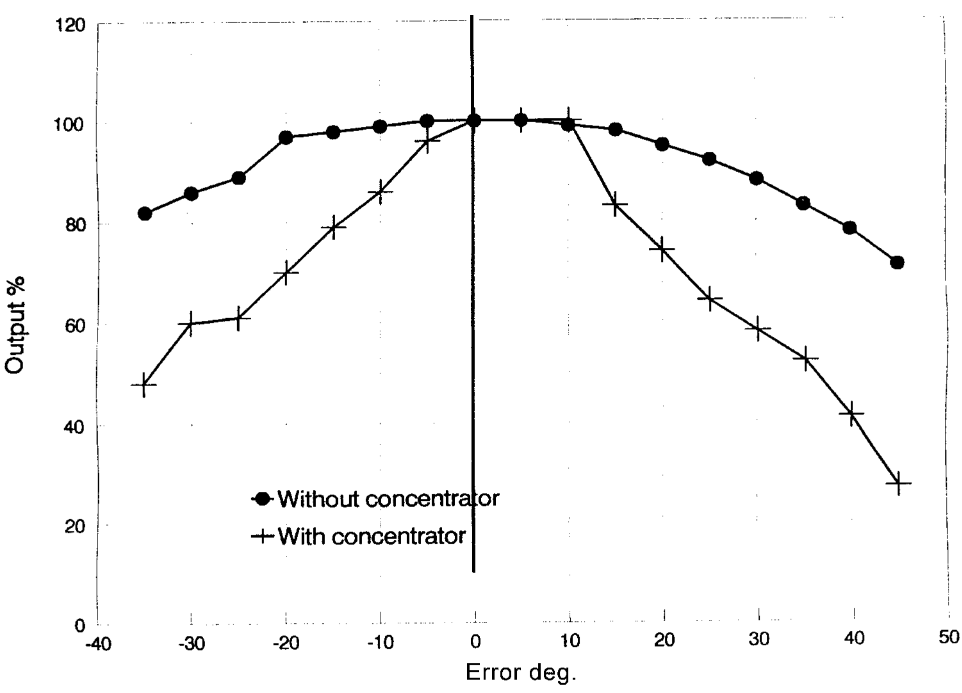

Figure 8. Solar radiation input to system C versus tracking error.

on the system radiation, with and without concentration. The concentrated radiation ($c = 2x$) can withstand the tracking error until $\pm 10^{\circ}$ with negligible losses, while without the concentrator, the system can withstand $\pm 30^{\circ}$ tracking error before it suffers noticeable losses.

From the above results, it is clear that the effect of tracking error on the output from any solar system mainly depends on two parameters. The first is related to the horizontal tilt angle of the system. The system tilt angle is referred to the season and the time of day. The second is related to the type of the module.

Electrical Power Consumed

There are many sources that consume electrical power from the system, such as microprocessors, electronic equipment, sensors, electrical switching, and driving motors. Figure 9 shows the effect of tracking accuracy on the electrical power consumed by the tilted-axis tracker (system C). The figure shows that the ideal operation of the system, in which the tracking error ranges between $\pm 0.56^{\circ}$, consumes 50 Wh/day. By increasing the tracking band (the larger the tracking band, the smaller the tracking accuracy), this power decreases. This decrease is due to longer stop periods of the motor due to comparatively higher deadband.

While Figure 8 shows that the tilted-axis tracking system can work at maximum efficiency until tracking error $\pm 10^{\circ}$, Figure 9 shows that the power consumed in this case is only about 22 Wh/day. In other words, for the tracking system that uses flat plate or even lower concentrated applications, the electrical power

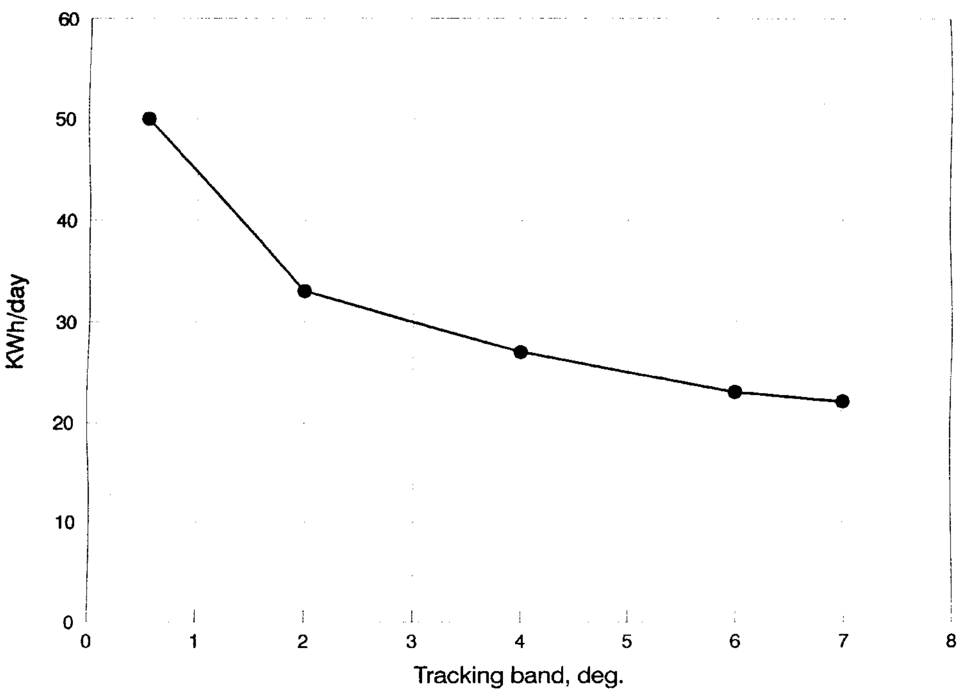

Figure 9. Electrical power consumed by the tilted-angle tracker versus tracking band.

consumed can be saved by increasing the tracker deadband to the permissible limit with no change in system output.

Summary and Conclusions

The method of tracking was studied by analysis of complete data measured from the different systems. These systems are a fixed system facing south and tilted 40°, a vertical-axis tracker, a tilted-axis tracker with V-trough concentrator, and a two-axis tracker. The study also included the effect of some operating parameters on the operation of the tracking, such as the effect of the reference sensor position on the accuracy of the open-loop tracker and the effect of tracking errors on the system output and electrical power consumed by the tracker.

Several interesting and useful conclusions were deduced from the present work, as follows.

1. The vertical-axis tracker receives 18% more annual solar radiation than the fixed-tilt system and produces 21% more output power in 9 months.
2. Tracking the solar system around a tilted-axis increases its annual solar radiation by 11% over the fixed-tilt system, while the combination of the tilted-axis tracker and the soft concentration receives 57% more annual solar radiation input and produces 31% more output power than the fixed-tilt system.
3. Moving the solar system around two perpendicular axes increases its radiation by 30% over the fixed-tilt system.
4. The microprocessor solar trackers can follow the sun with small pointing error, but they need more care in installation, especially the reference position sensors.
5. The effect of the tracking error on the system output depends on several parameters, such as type of application (flat plate or concentrated), tilt angle of the system plane, season, and time of day.
6. The electrical power consumed by the solar tracker is directly proportional to the tracking accuracy.

References

Baltas P., M. Tortoreli, and P. E. Russell. 1986. Evaluation of power output for fixed and step tracking photovoltaic arrays. *Solar Energy*, 37(2):147–163.

El Shenawy, E. T. 1997. Optimization of Electrical Solar Tracking Systems. M.Sc. thesis. Faculty of Engineering, Cairo University.

Emslie, W. A., and C. J. Dollard. 1988. Photovoltaic pilot plant. In *Twentieth IEEE PV Specialist Conference*, vol. 2, 1283–1288, 26–30 September, Las Vegas, Nevada.

Gordon, J. M., and H. J. Wenger. 1991. Central-station solar photovoltaic systems: Field layout, trackers, and array geometry sensitivity studies. *Solar Energy*, 46(4):211–217.

Guastella, S., A. Iliceto, and V. Piazza. 1993. Tracking versus fixed flat plate arrays: Experimental results of one year's operation at the Adrano pilot plant. In *ISES Solar World Congress*, 682–687, Budapest.

Jimenez, C., E. Lorenzo, and B. Yordi. 1994. 100 KWp tracking PV plant at the Toledo PV project. In *12th European Photovoltaic Solar Energy Conference*, 822–824, 11–15 April, Amsterdam, Netherlands.

Pfeiffer, H. 1985. Solar guided photovoltaic generators. In *6th Photovoltaic Solar Energy Conference*, 634–638, 15–19 April, London.

Salim, A. A., F. S. Huraib, and N. N. Eugenio. 1988. PV power—Study of system options and optimization. In *Eighth E. C. PV Solar Energy Conference*, vol. 1, 688–692, 9–13 May, Florence, Italy.

Shaltout, M. A. M., and A. A. Hassan. 1993. Photovoltaic performance for different solar tracking modes at Cairo. In *ISES Solar World Congress*, 337–342, Budapest.