A comparative study for assessing the effectiveness of solar trackers used in conjunction with photovoltaic power autonomous systems

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The aim of the present paper was to consider whether automatic guidance devices, also called solar trackers, used in conjunction with small autonomous monitoring systems, may lead to a reliable method in reducing the cost of generating electricity, by increasing the photovoltaic system output power production. In order to analyze the feasibility of installing a tracker on a small photovoltaic system, several factors such as the assessment of the solar flux, operation conditions, system maintenance, investment and operating cost, environmental issues and current legislation have been considered.

(Received April 30, 2013; accepted January 22, 2014)

Keywords: Solar tracker feasibility, Photovoltaic panel, Autonomous system

1. Introduction

In recent years, many innovations have been made in the field of photovoltaic (PV) technology. However, the cost of the electricity generation of such systems remains very high, mainly due to the high costs of investment and charging characteristics dependence of the climatic /meteorological factors.

One possible method for a faster investment recovery is to reduce the cost of generating the electricity by providing the panels with automatic guidance systems. Their purpose is to increase the photovoltaic system output power production, collecting a greater amount of solar energy by tracing the changes in the sun trajectory over the course of a day.

Solar trackers are complex devices consisting of mobile structures for orienting a day-lighting reflector, a photovoltaic panel or concentrating lens toward the radiation beam of the sun, with the aim of being always oriented perpendicular to the sun and consequently gaining efficiency. Photovoltaic cells work best when they are oriented towards the sun, therefore by changing the panel position, one may significant increase the performances up to 65% [1, 2, 3].

Depending on drive type, there are four different types of mechanisms used: active trackers, passive trackers, chronological trackers and manual trackers. Active trackers are oriented by motors and gear trains toward the sun by using electronic boards commanded by photosensors. Passive trackers use hydraulic mechanisms, usually operating by a low boiling point and compressed gas fluid that moves under the influence of solar heat, creating gas pressure and thereby moving the mechanism along [4, 5].

A chronological tracker operates based on the Earth rotation, by turning with an equal rate as the earth, but in the opposite direction, being very simple, yet potentially a very accurate solar tracker. Manual tracking has no automatic movement, as the drives have been replaced by operators who adjust the angles. The advantage of using passive solar trackers consists in the lack of energy consumption while active trackers have more accuracy, and thus develop better efficiency [1, 2].

Depending on the axial movement there may be single axis trackers or dual axis trackers. Single-axis solar trackers have a relatively simple mechanisms, rotation takes place only in one plane, around a single axis, and can be oriented upwards (called a polar axis) or lie flat (called a horizontal axis). Horizontal axis trackers are more stabile and more suitable for small latitudes, while polar axis is more suitable for larger latitudes.

Single-axis trackers benefits consists in simplicity, they are less expensive, horizontal single axis trackers being considered the most rigid and stable, and hence less likely to be damaged during storms. In addition to normal single-axis trackers, tubular solar trackers have been developed, the equipment having the same characteristics, but cylindrical shape, allowing the cells to capture the maximum amount of light [6].

Dual-axis solar trackers allow the system to position the solar cells directly perpendicular to the sun ray, being able to adjust continuously with reference to the Sun position. Regardless the guidance equipment used, generally the surface exposed to wind is very large, so the structure must be designed to resist strong wind loads, but without using a great amount of material [1].

As the apparent Sun angle changes throughout the year, in summer the Sun has a longer arc length than in winter.

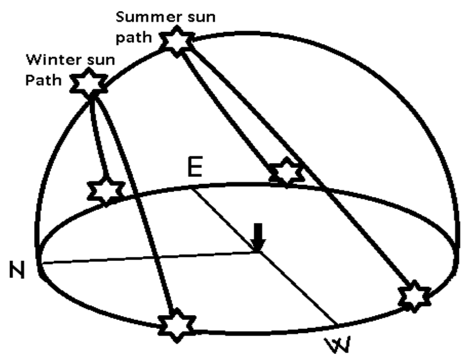

Fig 1. A simplified illustration of the Sun apparent path in summer and winter.

Combining simultaneously low cost trackers that adjust the PV position only at three fixed angles, on one axis with low concentration ratio reflectors, the power generation increases by approximately 56%. An economical analysis shows that price reduction could be between 20% and 30% [7].

The idea of a one axis simple sun tracker mounted on an individual sun tracking frame that adjusts the specific position only at three fixed angles has some advantages in terms of reducing the weight, minimizing cost and increasing system lifetime [7].

Another way of reducing the cost involves the use of two joined photosensors, separated by a diaphragm, called shading plate. When the shading plate, during sun movement, shadows one of the photosensing elements, the circuit detects the signal and will command the motor to move to the next position, which faces the sun more precisely [6].

Some alternatives to traditional trackers imply fixed frame photovoltaic panels and mobile light concentrators. Cheaper alternatives are made with concentrators mounted directly on panel, the light gain being generated by the special shape of the cell. These assemblies provide maximum efficiency, when expensive solar panels are used, replacing photovoltaic cells with reflective material [6, 8]. Another constructive solution consists in using a tracking mechanism which allows the panel to follow the sun as a 2-axis tracker, but using only one engine and hence a substantial reduction of the investment and operating cost [9].

Other studies are focused on designing and modelling irradiance databases, determining seasonal optimum tilt angles, or finding optimal distribution for photovoltaic solar trackers, in order to minimize power losses and maximizing power transfer [3, 10, 11, 12, 13].

Choosing the type of the photovoltaic panel is very important, especially in terms of technology used. One can choose a cheaper option, but with a smaller lifetime and less efficient, while an expensive option will ensure increased benefits like flexibility, transparency or special designed shapes [14, 15, 16].

Monocrystalline solar panels are made of monocrystalline silicon cells and are the most efficiently in absorbing sunlight and converting it into electricity, but are also the most expensive. These panels perform well in low-light conditions when other panels are less productive.

Polycrystalline solar panels, the most common solar panels, are less efficient than the single crystal ones, but they are cheaper and can endure large differences in temperature without losing their efficiency.

Amorphous solar panels are less efficient than other silicon based panels, but they do very well when shading phenomenon occurs. Solar panels suffered a process of degradation in time, the most stabile being amorphous solar cells, whose output may fall with an annual rate of 1%, unlike monocrystalline or polycrystalline, whose degradation is 3% - 5% annually [14].

From a financial perspective, the additional capital costs for the procurement and installation of the tracking systems may vary from 250EUR/kW to 700 EUR/kW. In addition, operation and maintenance costs are added for the moving parts, and large tracking systems may require cranes to install, increasing also the installation cost [9].

In terms of operation and maintenance, expensive photovoltaic panels come with a 25 year performance warranty but the inverters, have only 2-5 year warranty and would be expected to last 10-15 years. An economic analysis has to take in consideration an annual operation and maintenance cost around 0.17% of the total installation cost. However, there may be advantages for using solar systems in terms of renewable energy certificates (RECs), witch are commodities for producing energy from eligible renewable energy resources [14].

Tracker cost-effectiveness and reliably are strongly influenced by the environment, wind loads, temperature, dust and humidity may damage the electric motors [7].

2. Materials and methods

The equipment used for evaluating the photovoltaic panel characteristics consisted of a 40 W FVG Energy photovoltaic panel (Italy), a 12V/24Ah Caranda Solar Lead Acid battery (Romania), a Steca PR1010 controller (Germany), a 50 Ω/50 W variable resistor, IPRS Baneasa (Romania). The current and voltage generated by the photovoltaic panel at different charges were measured using two DT830B digital multimeters (China). The system was coupled with a SAD Power Inverter (Italy) and various fixed values power resistors (electrical bulbs of 75W, 60W, 40W, and 15W). To measure the solar flux, a Voltcraft Pyranometer PL-110SM (Germany) was used. The IMAX B6 Charger was used to display the variation in time of total capacity, the battery terminal voltage and drawn current. The experimental layout for the determination of the photovoltaic panel characteristics is presented in Fig. 2. By changing the resistor value, one may obtain a series of voltage and current pairs and hence one may have a polarization curve of the solar panel.

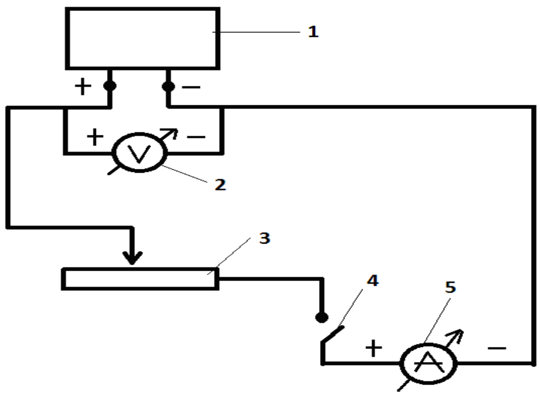

Fig. 2. A 40W photovoltaic panel evaluation.
1. Photovoltaic panel. 2. Voltmeter. 3. Potentiometer.
4. Circuit breaker. 5. Ammeter.

The integrated photovoltaic power autonomous system, consisting in photovoltaic panel, a controller, a lead-acid rechargeable battery, an inverter and the electrical bulb is depicted in Fig. 3.

The controller ensures that the charging voltage is maintained within the limits of the optimal values, acts as a safety breaker when the solar flux drops below the acceptable limit, fact that will prevent the battery to discharge through the photovoltaic panel in the absence of the Sun and also as a battery regulator, breaking the circuit when the battery is fully loaded to prevent transforming the rechargeable battery into an electrolysis cell. In addition, the controller has an energy meter included, displays continuously the battery state of charge (SOC), the charging current and voltage and has also the function for optimal battery maintenance and control.

The FVG 40 M is a 40 W photovoltaic panel, designed for stand-alone systems, build of 36 photovoltaic cells and having maximum voltage per module of 17,3V and the short-circuit current of 2,56A.

The SAD Power Inverter is a 200W 12V DC to 220V AC inverter and providing also an integrated protection against overload, low battery, overvoltage, short circuit and high temperature possible events.

The rechargeable battery, designed specifically to be used in conjunction with photovoltaic devices, can withstand high temperatures, having also good recovery characteristics after deep discharge cycles.

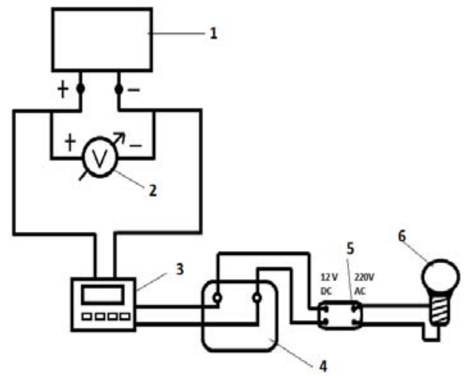

Fig. 3. State of charge monitor of a rechargeable battery connected to the photovoltaic panel
1. Photovoltaic panel. 2. Voltmeter 3. Controller 4. Battery 5. Inverter. 6. Resistor.

3. Results and discussion

The current, voltage and the total electrical power yielded by the photovoltaic panel, recorded versus the ohmic load are presented in Figs. 4, 5, and 6.

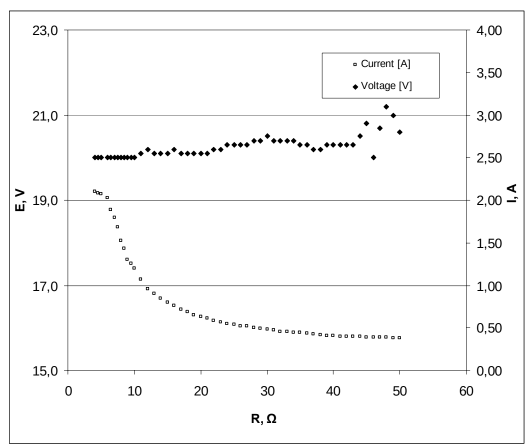

Fig. 4. Current and voltage variation of a photovoltaic panel with variable resistor.

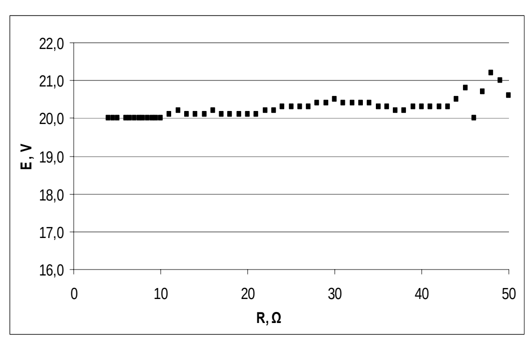

Fig. 5. Voltage variation versus ohmic load.

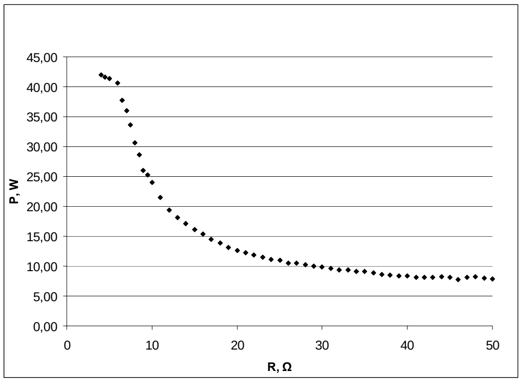

Fig. 6. Power variation versus the ohmic load.

By simultaneously measuring both the solar flux and the charge current one determined by linear regression a linear relationship between the incoming solar flux and the generated current, Fig. 7. The controller contribution can be seen when one plots the variation of the generated current versus solar radiation flux, the controller eliminating the current spikes and averaging the curve (Fig. 8).

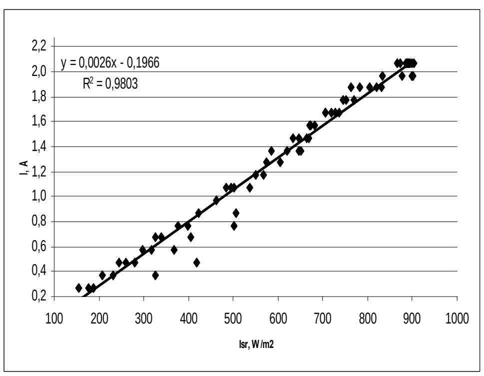

Fig. 7. Charging current versus energy flux (insolation).

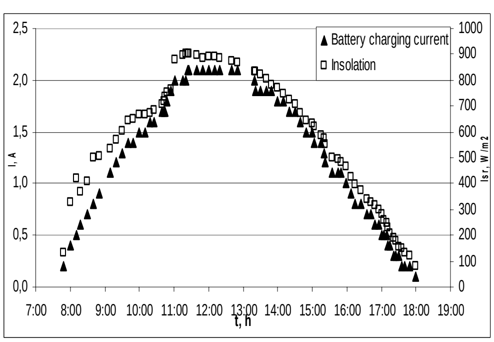

Fig. 8. Solar flux, measured with a Voltcraft PL-110SM pyranometer and the charging current, varied by Steca PR1010 controller.

By comparatively assessing the performances of the photovoltaic system with and without the solar tracker and superimposing the curves (Fig. 9), one may notice that the solar tracker positively increases the PV panel performance especially at the beginning and end of the day, where a fixed panel, inclined at 45 degrees angle, has poor performances comparing to the case when a tracker is used.

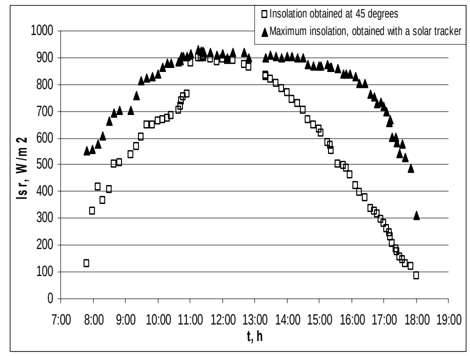

Fig. 9. Solar flux measurements comparison of a photovoltaic system with and without the dual axis solar tracker.

However, the main issue is whether by introducing a certain tracking systems, long-term gains can be achieved, due to the increased energy output or the cost of purchasing the tracker overcomes the benefits in energy gain. In this way one has to quantify the daily extra gained by using a solar tracker in comparison with a fixed system. By converting the experimental data presented above in percentage and plotting them, and considering that this is the most favourable case (summer time) it appears that the most increase one can get is limited to no more than 29% (see Fig. 10) while the measurements carried out during the winter time (the least favourable case) indicating only a 19% increase.

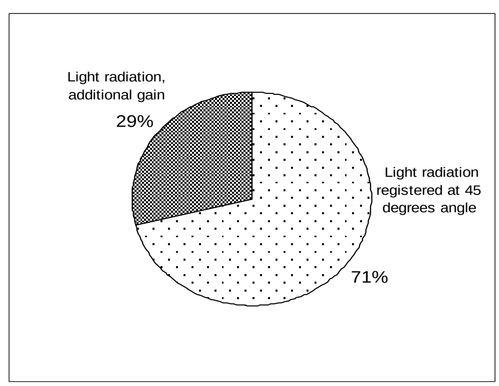

Fig. 10. Light radiation additional gain by using a dual axis solar tracker.

In Bucharest, Romania, September illustrates best the average monthly solar radiation potential, (Fig. 11) and hence this month can be used a reference towards the determination of PV panel average performances.

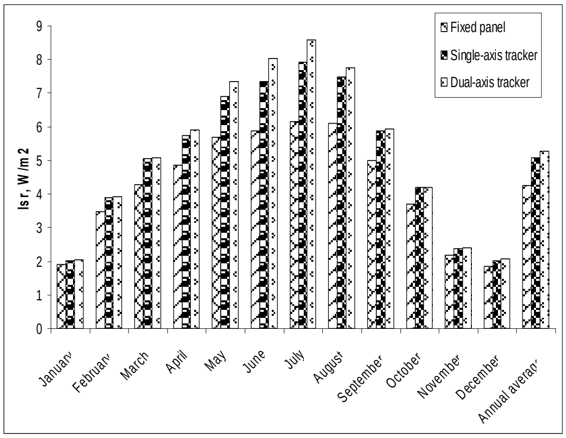

Fig. 11. Monthly average solar radiation, comparison between fixed, single axis tracker and dual axis tracker.

As can be seen in Fig. 12, the daily photovoltaic panel current variation, between hours 8-18, varies from 0.1 A to 2.1 A. This does not reflect however the daily average current charge on September, but rather an indication the maximum current that can be achieved in a day of this month.

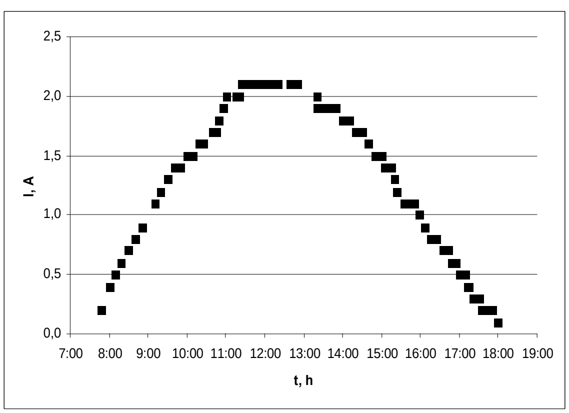

Fig. 12. Photovoltaic panel charge variation, via Steca PR-1010 controller.

Fig. 13 shows the energy gained by using a dual-axis solar tracker, compared to a fixed panel, in a significant timeframe for September, between 7 a.m. and 6 p.m. The largest gain is achieved during the afternoon hours.

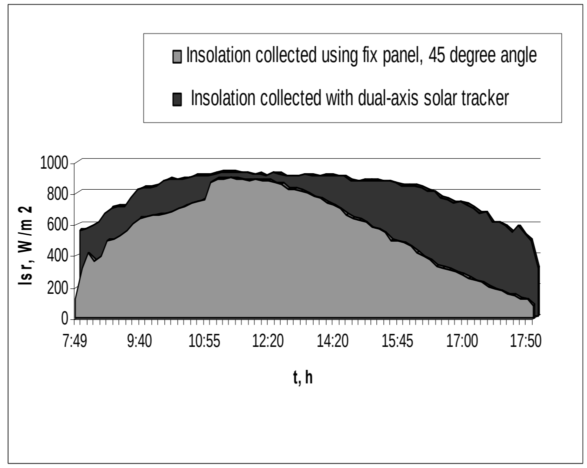

Fig. 13. Energy gained using a dual-axis solar tracker, compared with a fixed panel.

Fig. 14 shows the power yield versus the solar flux, particularly useful in choosing the correct photovoltaic system on the basis of the average current consumption criterion.

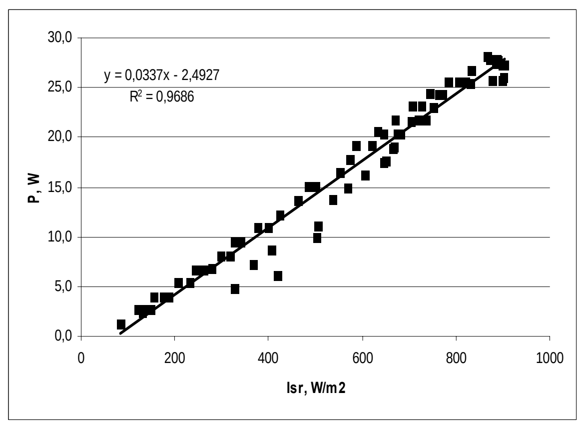

Fig. 14. Photovoltaic power variation depending on insolation.

However, one must consider also that there are as well daily weather variations (see Figs. 15, 16 and 17) and one must make adequate provisions for this, considering the least favourable case. The energy surplus could be at any time feed into the national grid using a smart grid system.

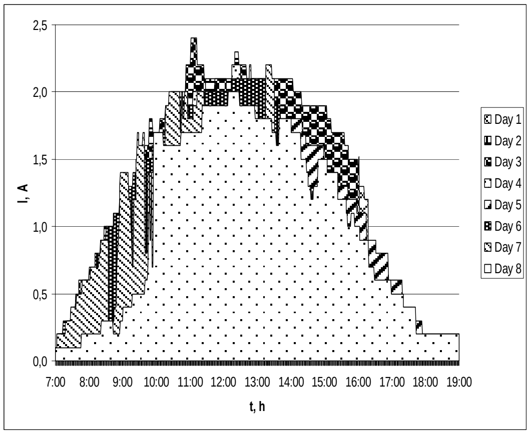

Fig. 15. A depiction of daily current variation in august.

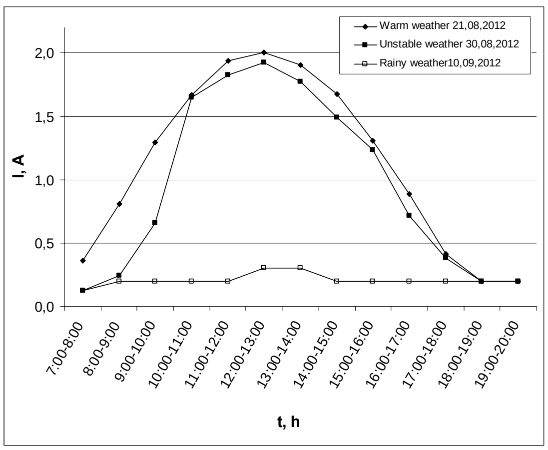

Fig. 16. The hourly average current yielded by the photovoltaic panel via Steca PR1010 controller, for three different weather conditions in august.

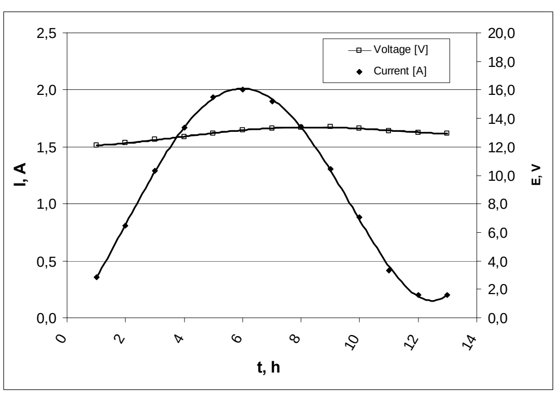

Fig. 17. Daily voltage and current variation.

By using literature data and various software freely available [7, 8, 10, 22,] one may estimate the solar flux and hence the energy production for various geographical coordinates, powers and different types of trackers. In Fig. 17 one may see that the efficiency of using a tracker increases with the installed PV power, the maximum efficiency being obtained for the dual-axis trackers.

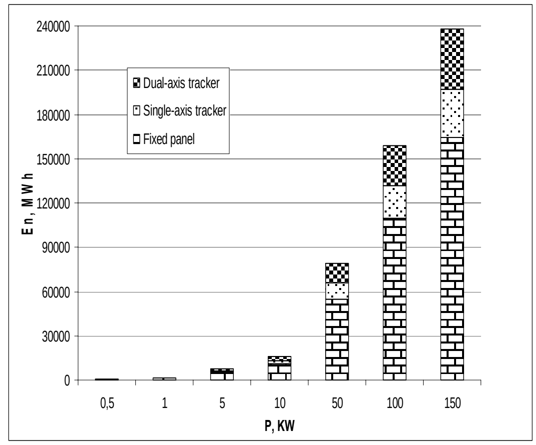

Fig. 18. Comparison fixed panel, single-axis tracker and dual-axis tracker.

Fig. 19 shows that energy gained per month by using an autonomous guidance system, which increase proportionally with the installed power.

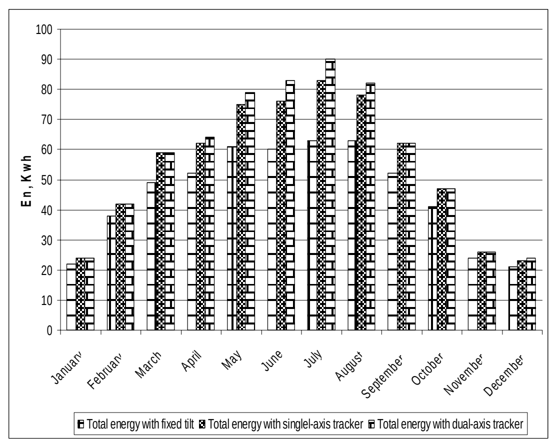

Fig. 19. A 500 W PV system, annual energy yield, comparison between fixed tilt, single axis tracker and dual axis tracker.

At high state of charge values, over 94%, the controller STECA PR 1010 protected the battery, reducing the charge current, as seen in Fig. 20. Similar corrections are made during charging process regarding voltage; a consumer was operated in parallel, case in which the controller redirected the excessive power.

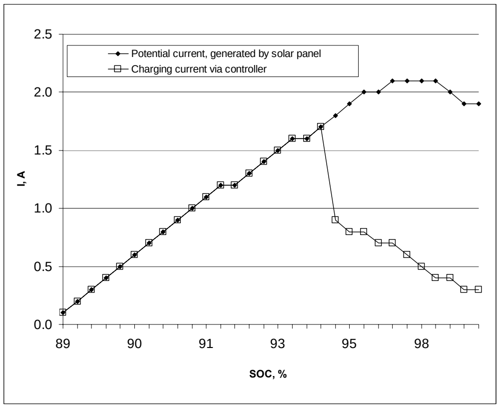

Fig. 20. Charging the battery via Steca controller, at high State of Charge values.

In order to evaluate the gain due to the installed dual axis tracker, one has to consider the followings:

-a 2-axis orientation system, that can support one photovoltaic panel, with maximum size up to 2m x 1m, and average power up to 230W, the maximum wind speed accepted by producer is 130km/h. the average price of such a guidance system is 500 EUR, for our 40W PV panel, the total energy consumed by the motors during the day, in order to repositioned the panel was 5.84Wh, (measured for operating for 16 hours) and hence in one hour it will consume 0.365 Wh from the PV panel;

- the energy produced by a 40W stationary panel in October 2012, hours: 8:00-18.00, sunny weather was 181.5 Wh;

- using a tracker a 29% energy surplus, E_e is gained;

$$Ee = \frac{29}{100} \cdot 181.5Wh = 52.63Wh$$

- tracker energy consumption in 11 hours will be:

$Tec = 11 \cdot 0.365Wh = 4.015Wh$ (7.6% of energy gain)

- net energy gained by using a solar tracker:

$$En = 52.63Wh - 4.015Wh = 48.61Wh$$

- electricity price in Romania is 0.108 EUR/ kwh. The monthly financial gain by using a solar tracker will be:

$$Mfg = \frac{0.108}{1000} \cdot 48.61 \cdot 30 = 0.157EUR/Month$$

- the 40W panel will yield an annual gain of:

$$Ag = 0.66 \cdot 12 = 7.87EUR$$

- the return on investment:

$$Ir = \frac{500}{7.87} = 63 years$$

4. Conclusions

The energy balance resulting from the experimental data shows that the energy consumption by the auxiliary orientation photovoltaic panel represents only 7.6% from additional energy gained by using such a system.

However, the usage of such equipment is recommended only for high power systems, or if there are restrictions regarding network size. In this case, the increased efficiency can reduce the initial investment by decreasing the number of panels used and by purchasing a cheaper controller, able to master more than one PV panel at once. Maintaining the orientation independence, the daily charge current will have a steady high value, especially in warm climates.

For a small autonomous power device, like in this case, the variable orientation system is not profitable, the investment being recovered in a long period of time. In addition, the manufacturers of such systems impose limitations regarding wind speed, maximum weight (which can increase with ice and snow storage), maximum operating motor temperature, all these restrictions being in opposition to the notion of autonomous monitoring system.

Moreover, the advanced solar trackers require some software applications and a sensor system in order to be able to control the rotation angle, speed, position and synchronism, features which increase the complexity and the probability of something going wrong and increasing as well the additional maintenance and operating cost.

Acknowledgements

This work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement OSDRU/107/1.5/S/76903.S.

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