NEW BIFACIAL SOLAR TRACKERS AND TRACKING CONCENTRATORS

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Abstract

A very simple solar tracker and tracking concentrator are described in the paper as well as the tracking strategy which enables high collectible energy surplus at medium tracking accuracy. A new low cost tracking soft ridge concentrator together with the solar tracker and bifacial PV panels can double photovoltaic energy harvest in comparison with fixed panels and substantially reduce price of PV energy.

Fundamental aspects of the energy production

In last years the permanently sustainable development is well discussed theme. Some experts hope that it is possible, some experts don't believe it. Renewable energy usage is an actual problem in connection with limited reserve of classical energy sources and with ecological aspects. In addition to the widely discussed arguments we would like to emphasise that exhaust heat, dust and fly ash, sulphur-, carbon- and nitrogen oxides aren't produced in the case of energy production in solar power stations, hydro-electric power plants and wind-power plants. Exhaust heat is usually two times higher than produced electric energy in the case of energy production in thermal power stations and nuclear power plants and mentioned oxides cause hothouse effect. Atmosphere heating and climate changes are well known problems. From the point of view of the permanently sustainable development, the energy production from the renewable energy sources is the only way for mankind.

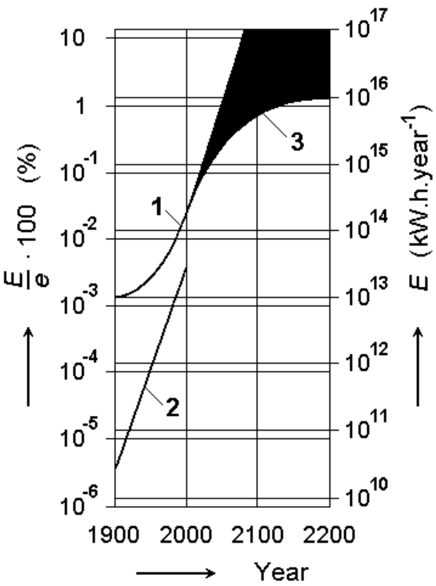

Fig.1 The development in the energy production (1 - total energy production, 2 - electric energy production, 3 - forecast of the development, e =7.2x10^{17}kW.h.year^{-1} - solar energy falling on the Earth surface)

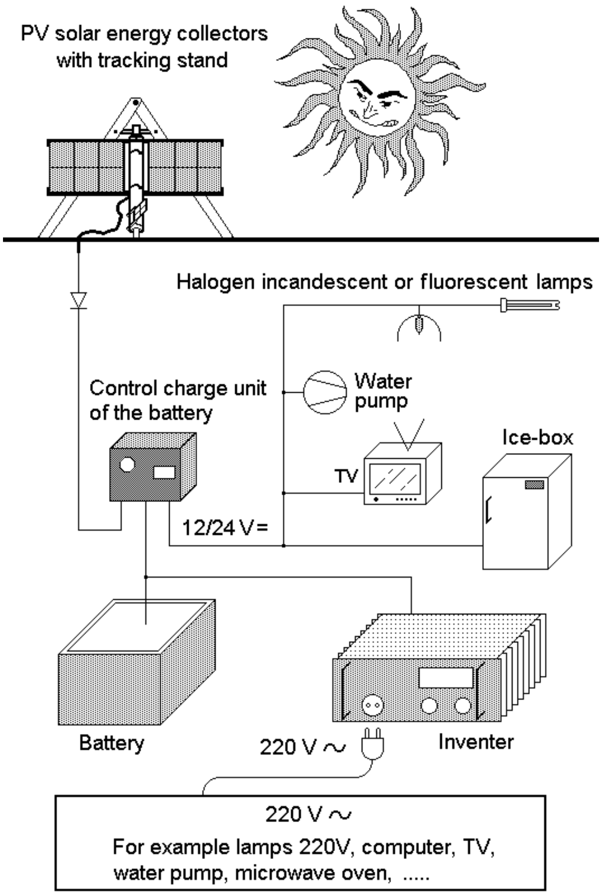

Fig.2 Example of the solar power supply in a house

Fig.1 shows the development in the energy production in the last century and the forecast for next two centuries. The curve 1 corresponds with the total energy production, curve 2 corresponds with the electric energy production and the area 3 shows the forecast of the development. The permanently sustainable development will be possible only in the case of the limiting curve with limited value $E = 10^{16}$ kW.h.year^{-1}.

This chapter speaks about solar energy. The direct photovoltaic (PV) energy transformation is effective enough and it can be used for example as power supply for portable solar pumping systems in agriculture. Especially in outlying places the long electric connection is expensive as well as petrol for combustion engine driving the generator. Fig.2 shows one example of the power supply in a house. There is possible to use equipment for voltage 12/24 V= or change the voltage by inverter. The battery levels the discontinuity in the solar radiation.

There is possible to use more simple arrangement for solar pumping system in agriculture with direct connection between solar PV panels and water pump without battery. In the night isn't possible to pump in this case. In most applications the night pumping isn't necessary.

The solar constant $I_s = 1367\ \mathrm{W/m^2}$ is the average radiation intensity over the earth atmosphere in the middle Earth distance from the Sun. The maximum radiation intensity is up to $I_{max} = 1100\ \mathrm{W/m^2}$ on the Earth surface during the sunny day. The efficiency of the best semiconductor photovoltaic solar panels based on the monocrystalline silicon is over 20% and the efficiency of the best solar panels based on the polycrystalline silicon is up to 15%. We can calculate, that it is possible to obtain the maximum power $P = 160 – 200$ W from the area $S = 1\ \mathrm{m^2}$ in this case. The other solar panels based for example on GaAs, CdTe, CdS, CdSe, InP and so on have some advantages, but the main disadvantage is the much higher price. That is the reason, that these panels are used in special applications, where the price isn't the limiting parameter. Especially in space applications in power supply of the satellites the limiting parameter is the highest efficiency and not the price. For example GaAs has higher resistance to the hard radiation in addition to the efficiency over 25% and the efficiency decreasing with the temperature increasing is very small.

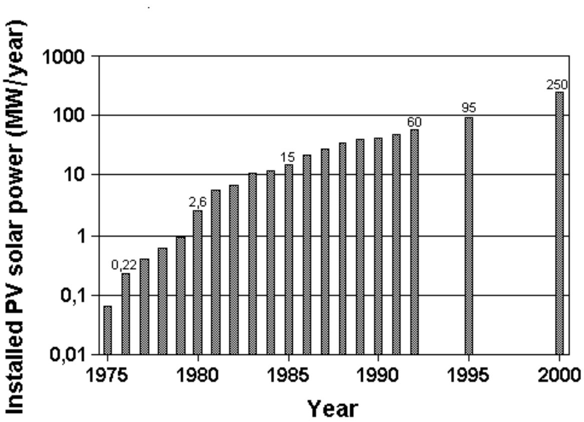

Fig.3 Production, sale and installation of the photovoltaic solar panels

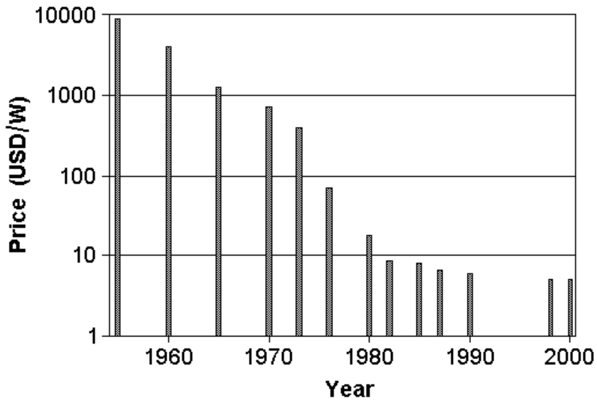

Fig.4 Development of the photovoltaic solar panels prices

Fig.3 shows the development of the solar PV panels production and sale during last 25 years. We can approximate the last years by linear dependence in the semilogarithmic scale and it really corresponds with the exponential dependence. Fig.4 shows the development of the solar PV panels prices. We can see the substantial price decreasing during 1970-1980. Today the average price of the solar panels based on the crystalline silicon is approximately 5 USD per watt and it is nearly constant during last ten years. We can see on Fig.5 that most of PV solar energy is produced in Japan and in the USA. This fact is logical because these countries have high level of industry and low level of classical energy sources and they must import especially crude petroleum.

They are existing solar power stations with maximum power higher then 1 MW. But we can't calculate that the solar power station can replace a classical power station with the same maximum power. The utilisation of the thermal power station and nuclear power plant is approximately 85-90%, but utilisation of the solar power plant is only 30% in desert places with the best solar conditions. Nevertheless $1\ \mathrm{km^2}$ of the solar panels based on polycrystalline silicon with down mentioned tracking stands can yield energy $4.3\mathrm{x}10^8\ \mathrm{kW.h.year^{-1}}$. The area don't corresponds with $1\ \mathrm{km^2}$ of the power station area because there must be distances between panels and areas for inverters! The energy production in the whole world was $10^{14}\ \mathrm{kW.h.year^{-1}}$ in the year 1997 [1]. Comparison of these two values shows, that it would be theoretically possible to produce the energy only in the solar power stations. There are desert areas enough on the Earth surface for example in north Africa, south USA, Mexico, Chile, Mongolia west Australia, Kazachstan and so on. The energy would be transported in the form of electrical energy by classical wires or by superconductive wires or would be produced liquid hydrogen and the energy would be transported in this form. We must calculate some energy lost during the transport. Production of 1 kg liquid hydrogen needs energy approximately 50 kW.h (water electrolysis and liquefaction) but in this case we must calculate some energy for water transport and liquid hydrogen transport.

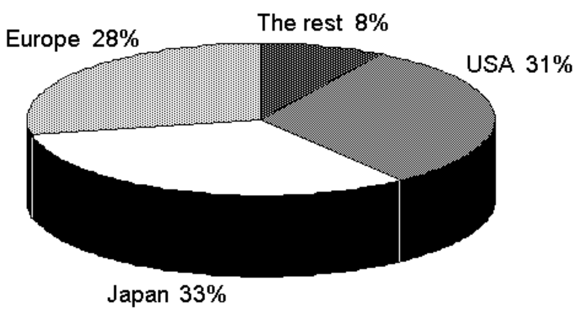

Fig.5 Electric energy production by photovoltaic solar panels

The tracking strategy

The solar radiation consist of three parts. The direct solar radiation includes most of energy. It is coming only from the sun circle in defined direction. Smaller amount of energy is in diffuse circumsolar radiation which is diffused by atmosphere but it keeps some direction in major angle. Only low energy is in isotropic diffuse radiation which don't depend on the direction and it dominate in the case of cloudy weather. Fig.6 shows the iso-curves of radiation intensity in dependence on the direction from the cloudless sky. The dotted line corresponds with diffuse circumsolar radiation, the full line corresponds with isotropic diffuse radiation. The sun is 30° over horizon and we can see, that the radiation intensity from the opposite side is constant for the most part of the sky. The increase near the opposite horizon causes the reflection.

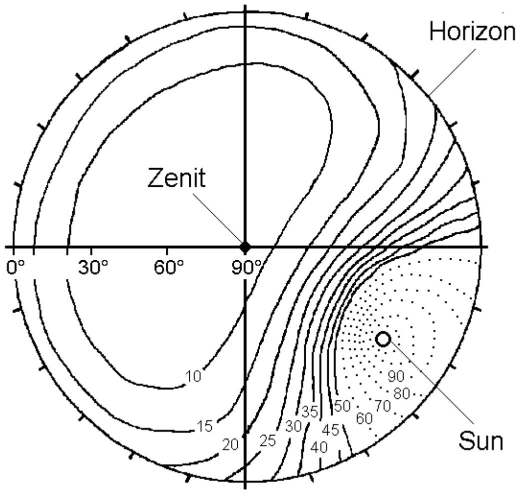

Fig.6 Iso-curves of radiation intensity in dependence on the direction

Sun is moving cross the sky during the day. In the case of fixed solar collectors the projection of the collector area into the plane, which is perpendicular to the radiation direction, is given by function cosinus of the angle of incidence (Fig.7). The higher is the angle of incidence φ, the lower is the power. The solar tracker, a device that keeps photovoltaic or photothermal panels in an optimum position perpendicularly to the solar radiation during daylight hours, can increase the collected energy by up to 40%. This increase is raised to 80% when solar energy is used for water pumping because during the day the pump is longer time over the limit power value.

Theoretical calculation of the energy surplus in the case of tracking collectors is as follows: We assume, the maximum radiation intensity $I = 1100\ \text{W.m}^{-2}$ is falling on the area which is oriented perpendicularly to the direction of radiation. We assume the day length $t = 12\ \text{h} = 43200\ \text{s}$ as well as the night length and we compare the tracking collector which is all the time optimally oriented to the sun with the fixed collector which is oriented perpendicularly to the direction of radiation only at noon. We mark the collector area S_o.

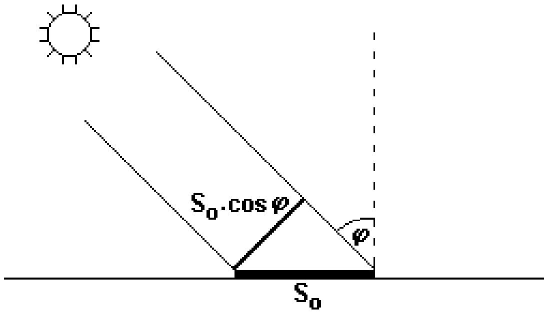

Fig.7 Angle of incidence φ of the solar radiation

a) *For fixed collector we calculate*: The projection of this area on the area which is oriented perpendicularly to the radiation direction is equal $S = S_o \,.\cos\varphi$ and the angle φ is changing in the interval $\varphi \ni \left\langle \frac{-\pi}{2}; \frac{+\pi}{2} \right\rangle$ during the day. The angular velocity of the sun moving cross the sky is equal $\omega = 2\pi / T = 7{,}27\,.10^{-5}\ \text{s}^{-1}$ and the differential of the falling energy is equal $\text{d}W = I\ S\ \text{d}t$. When we don't consider the atmosphere influence, we can calculate the energy, which is fallen on the collector area $S_o = 1\ \text{m}^2$ during one day

$$W = \int_{-21600}^{+21600} I\ S_o\ \cos\omega t\ \text{d}t = I\ S_o \left[\frac{\sin\omega t}{\omega} \right]_{-21600}^{+21600} = \frac{2\ I\ S_o}{\omega} = 3{,}03\,.10^7\ \text{W.s} = 8{,}41\ \text{kW.h}\,. \quad (1)$$

b) *For the tracking collector which is all the time optimally oriented to the sun we calculate*: When we don't consider the atmosphere influence, we can calculate the energy, which is fallen on the collector area $S_o = 1\ \text{m}^2$ during one day

$$W = I\ S_o\ t = 4{,}75\,.10^7\ \text{W.s} = 13{,}2\ \text{kW.h}\,. \quad (2)$$

Comparison Eq.(1) and Eq.(2) shows the energy surplus 57% when we don't consider the atmosphere influence. We would really obtain this surplus for example on the Moon surface. On the Earth surface the sun is shining cross thick atmosphere layer after sunrise and before sunset. In the morning and in the evening the radiation intensity falling on the area which is oriented perpendicularly to the radiation direction is much lower than at noon is. On the other hand the day can be longer than 12 h at higher latitude. That is the reason, that the energy surplus can be really as much as 40% on the Earth surface. The addition of the down mentioned soft concentrator can increase the energy surplus up to 100%.

Fig.8 shows the dependence of the energy lost on the maximum tracking angle in comparison with the ideal tracking. $\pm 0^\text{o}$ corresponds with the fixed stand. We can see, that the tracking angle more than $\pm 60^\text{o}$ don't yield energy surplus and also it has no sense. That's why our down mentioned solar tracker TRAXLE™ was constructed for tracking angle $\pm 60^\text{o}$.

Solar trackers

Although solar trackers can boost energy gain of PV arrays by up to 40% and pumping capacity by up to 80% their applications wasn't frequent at present. Why? Relatively high prices and medium reliability prevent widespread use of solar trackers. Reliability and cost/performance ratio will decide about the future trends of solar trackers.

Active trackers : Electrooptical solar trackers are usually composed of at least one pair of antiparallel connected photoresistors or photovoltaic solar cells which are, by equal intensity of illumination of both elements, electrically balanced so that there is either no or negligible control signal on a driving motor. By differential illumination of electrooptical sensors differential control signal occurs which is used to drive the motor and to orientation of the apparatus in such direction where illumination of electrooptical sensors is equal and balance is restored. Such trackers with high accuracy are intended mainly for concentrator solar systems. These trackers are complex and, therefore, expensive and unreliable. Further exist active solar trackers based on clockworks or combining both principles.

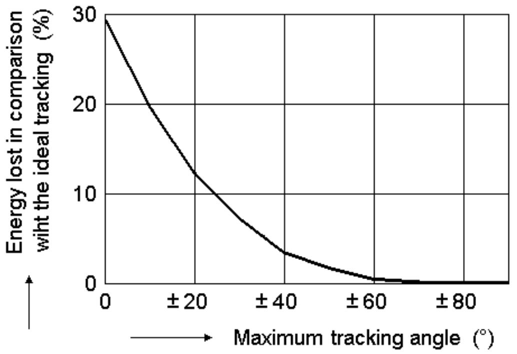

Fig.8 Energy lost in dependence of the maximum tracking angle in comparison with the ideal tracking

Passive trackers : Passive solar trackers are based on thermal expansion of matter (freon) or on shape memory alloys. Usually are composed of couple of actuators working against each other which are, by equal illumination, balanced. By differential illumination of actuators unbalance of forces is used for orientation of the apparatus in such direction where equal illumination of actuators and balance of forces is restored. Passive solar trackers, compared to active trackers, are less complex but they are working with low efficiency and at low temperatures are not working at all.

New solar tracker

The construction of the new tracking stand TRAXLE™ for solar devices is original and patented [2, 3, 5]. The apparatus enables backtracking within 5 minutes. It is important advantage in comparison with popular passive trackers where backtracking times as long as one hour are usual. The tracker works also at low temperatures down to –40°C

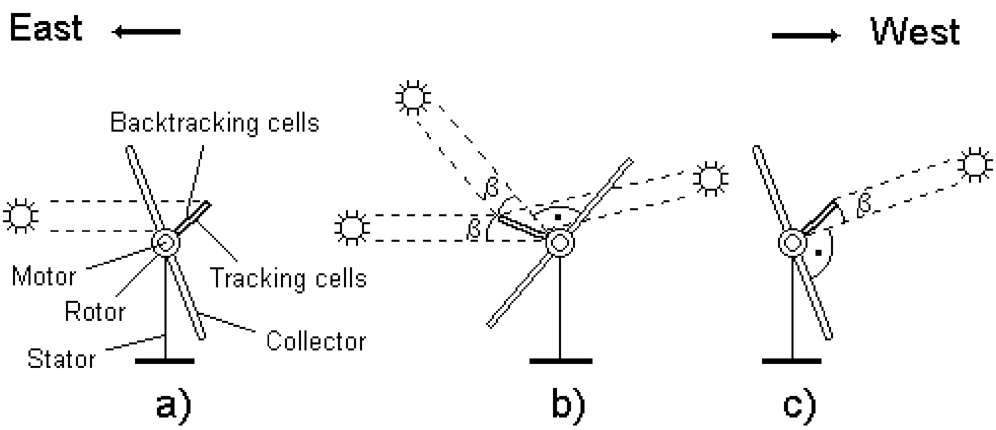

Fig.9 The principle of the new solar tracker

with average tracking accuracy $\pm 5^{o}$. The low cost solar tracker is based on a new arrangement of solar cells connected directly to a reversible DC motor. Solar cells both sense and provide energy for tracking. Costly and unreliable electronics has been completely eliminated.

Fig.9 shows the principle of the tracker. Two antiparallel sensing/driving solar cells are connected to reversible DC motor, the transmission is self-locking. When solar collectors are oriented eastwards and the sun moves from the east to the west (Fig.9b), the angle β between solar radiation and sensing/driving cells increases until the power of the driving DC motor is high enough to move solar collectors. Then the collectors start to move and the angle β starts to decrease until the power of DC motor is lower than what is necessary to move solar collectors. Step by step the collectors

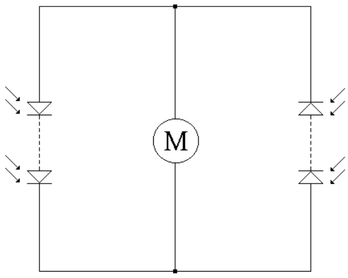

Fig.10 Complete wiring diagram of the tracker

moves westwards during whole day. Additional antiparallel solar cell enables backtracking of the tracker in the morning. In Fig.9b it is seen that the sun can move the collectors from any position when it is cloudy weather a part of the day and the sun start shining for example in the afternoon. Backtracking is possible from any position. The plane of the sensing/driving cells is inclined from the plane parallel to the axle and perpendicular to the collectors approximately by 20° eastwards. This angle is important due to prompt morning backtracking and accuracy of tracking. Fig.10 shows the complete wiring diagram.

Backtracking time of the new tracker is only a few minutes even in cold climate (-40°C) due to the higher efficiency of the semiconductor solar cells. Backtracking time of the passive trackers (either freon and shape memory) is more than 1 hour [4] at the same temperature. The area of the auxiliary solar panel with sensing/driving cells is about 1% of the area of the moved solar collectors. Good balance is necessary. The above mentioned tracking accuracy $\pm 5^{o}$ is sufficient, because the values of the function cosinus are equal approximately 1 in this interval ($0.996 \div 1$, see Fig.7).

Recently we developed solar tracker with 360° tracking angle and with vertical tracking axle [12]. Unlike standard trackers with 120^{o} tracking angle it can work in higher latitude in regions above polar circle, for example in Russia, Canada, Alaska, Scandinavia, Antarctica and so on, where sun can shine 24 hours a day.

The tracking concentrator

Our new tracking soft ridge concentrator (C=1.6 -1.7) [6] can double photovoltaic energy harvest in comparison with fixed panels and substantially reduce the price of PV energy. The new system combines the simple low-cost tracker [5] with flat booster mirrors but unlike V-trough concentrator [7, 8] by the new ridge concentrator the "outer" mirror has been eliminated (Fig.11). On single axis trackers the mirrors have to be extended beyond PV panels to ensure uniform illumination of panels at seasonally variable elevation of the sun. On polar axis trackers with seasonally adjustable slope of the axle the extended mirror is not needed.

It is advantageous that soft concentrators for photovoltaics does not need highly specular expensive mirrors. Weather resistant (at least 10 years) mirrors with high total reflectance are needed. The mirror can be made of rolled stainless steel sheet with special surface finish [9], of rolled aluminium alloy sheet (plated with pure aluminium) protected by a weather resistant polymer (PVF) film [9, 10], of silver coated polymer (acrylic) film [11] or sheet, of aluminium coated polymer (acrylic) film [9] or sheet, of silver coated hardened glass.

The new tracking soft concentrator is very compact, simple and reliable. Proven existing tracker hardware is used. Unlike V-trough concentrators no additional mirror supporting structures are needed and wind induced torque is strongly reduced. Application of the ridge concentrator on different tracking system is also very easy. It can be used on polar or horizontal single axis trackers, two axis trackers as well as on down mentioned 360^{o} trackers for space and terrestrial applications.

Concentration ratio (1.6-1.7) reduces temperature of PV panels, increases efficiency consequently and avoids degradation of the encapsulant. The new design also improves (against V-trough) air flow around PV panels (improved cooling). Concentration ratio (2-2.4) of standard V-trough concentrators frequently caused browning of the EVA encapsulant while elevated temperature reduces efficiency of semiconductor PV panels.

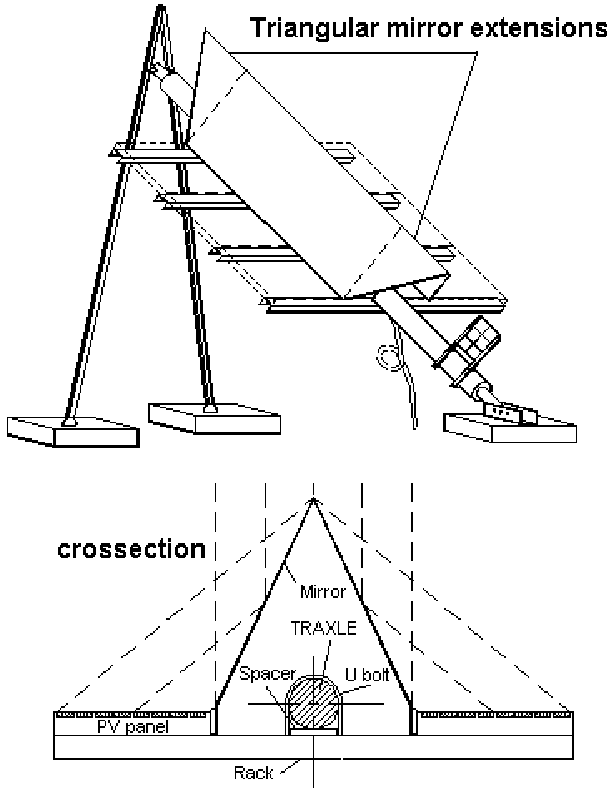

Fig.11 The tracking ridge concentrator.

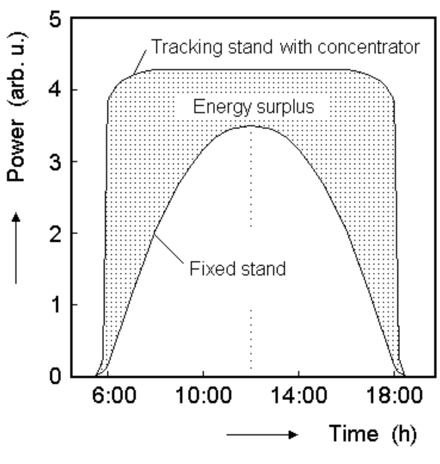

Fig.12 Idealized dependence of the power on the time

The new tracking ridge concentrator can double annual energy harvest (100% energy surplus) in comparison with fixed panels and pumping capacity surplus can be as high as 150%, because during the day the pump is longer time over the limit power value (see Fig.12). Fig.12 shows the idealised dependence of the power on the time during the day for collectors with fixed and tracking stand. Produced energy corresponds with the area below the curve, because it is given by Eq. (3)

$$E = \int_{\Delta t} P.dt \,, \qquad (3)$$

where *P* is the power and *t* is the time.

Two years comparison of energy production between fixed tilt PV panels and PV panels mounted on polar axis tracking ridge concentrator was started in May 1999 (Prague region, 50^o N). The results show that e.g. on clear (6.8 kWh/m^2) day in June the energy surplus of 107% was observed.

BIFACIAL PV PANELS IN SOLAR TRACKERS AND TRACKING CONCENTRATORS

Bifacial PV modules (Fig.13) are recently delivered by several manufacturers. Because there is either no or low price difference in the price of such bifacial and monofacial modules it is reasonable to use bifacial modules which could produce 5-20% more energy (in comparison with monofacial PV module with the same nominal output power).

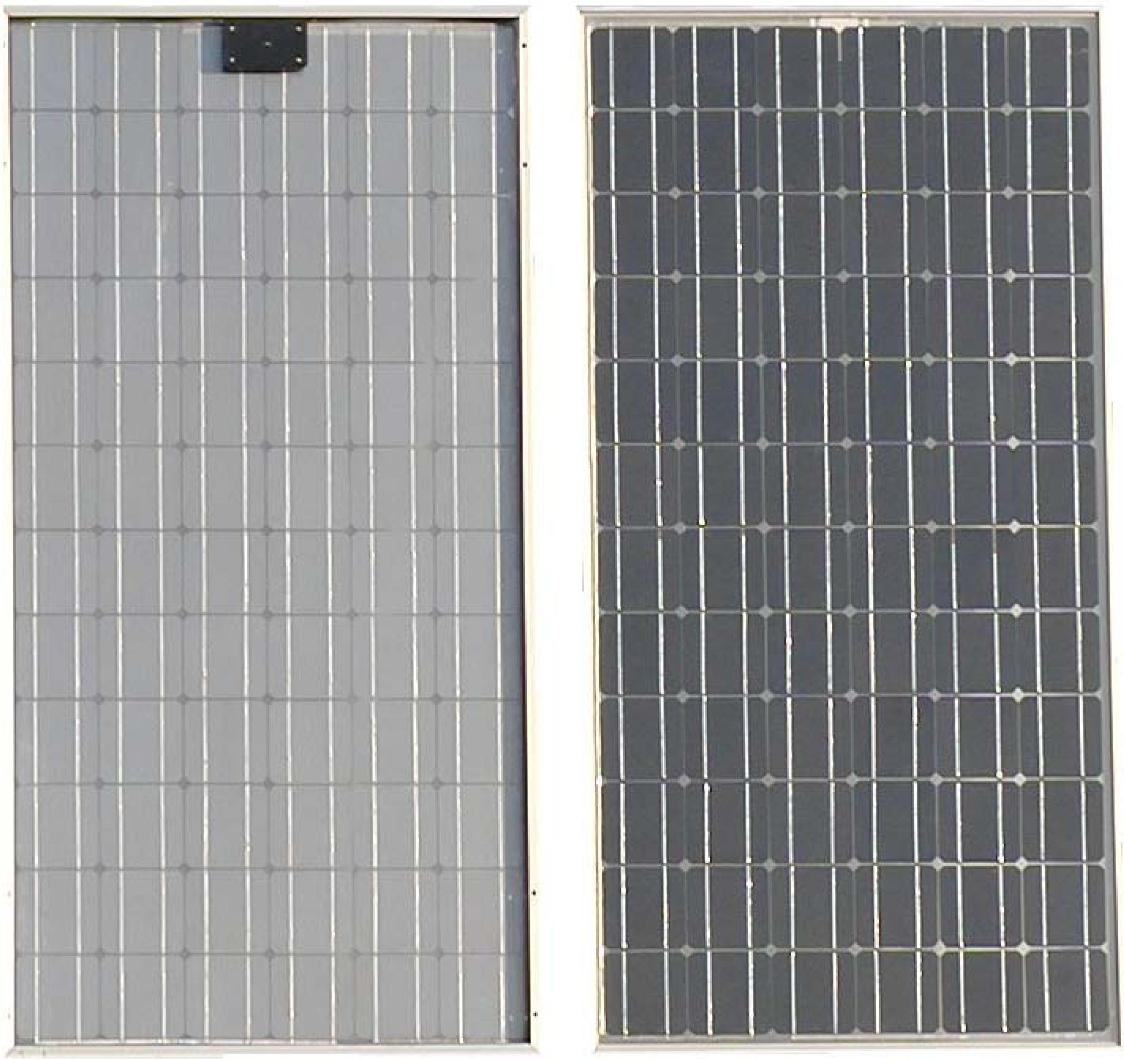

Fig. 13. Bifacial PV panel 100W

Polar axis solar tracker and/or tracking concentrator is always mounted on high support structures (to avoid contact of the rotating PV array with the ground). It improves back side energy collection in comparison with fixed PV arrays or even roof integrated PV modules. The energy gain can be in the range 10-15% (for typical albedo 0.3).

Additionally solar trackers/concentrators are usually oriented to the west, before backtracking, in the morning. The bifacial modules enable to collect direct back side solar radiation before backtracking. According to local climate the resulting energy gain could be 2-5%.

It is also very advantageous that bifacial PV modules (fixed), transparent for infrared radiation, has lower operating temperature against monofacial ones (about 5-9^{o}C). It is especially advantageous by solar trackers and tracking soft (C = 1.6) concentrators where PV modules are exposed to higher solar radiation than on fixed racks. As indicated above solar trackers/concentrators are always mounted on high support structures which improve cooling of PV modules by air flow. Measured temperature of bifacial c-Si PV modules on the tracker was usually lower (by 5-8^{o}C) than that of roof integrated monofacial c-Si modules.

Even in soft concentrators (C = 1.6) with bifacial PV modules there is very low temperature difference against roof integrated monofacial modules (lower than 5^{o}C). The reduced temperature of bifacial modules can also increase the energy gain by 2-5%.

The reduced temperature is also very important for lifetime of PV modules in soft (C = 1.6) concentrators. It should help to avoid degradation of polymer encapsulants of modules cased by higher temperatures (of monofacial modules).

The new bifacial PV modules with reduced temperature sensitivity (HIT) can further increase the system energy gain by up 10%. A synergic combination of all above effects can boost energy gain by 15-25% in comparison with the same tracker/concentrator with monofacial modules.

The polar axis solar tracker with c-Si bifacial PV modules will therefore deliver by about 50% more energy than fixed c-Si monofacial PV array with the same rated output power. The tracking bifacial soft concentrator will even double the energy gain [13] against fixed monofacial PV array (Fig.14). Concerning the PV pumping systems there is 100% and 150% pumping capacity surplus for tracks and tracking concentrators respectively.

The customer e.g. in Spain will therefore get the support 0.4 EUR per kWh of the 5 kWh systems. The 5 kW tracking bifacial system will deliver energy equivalent to 7.5 kWh fixed system, but for 7.5 kW system the support

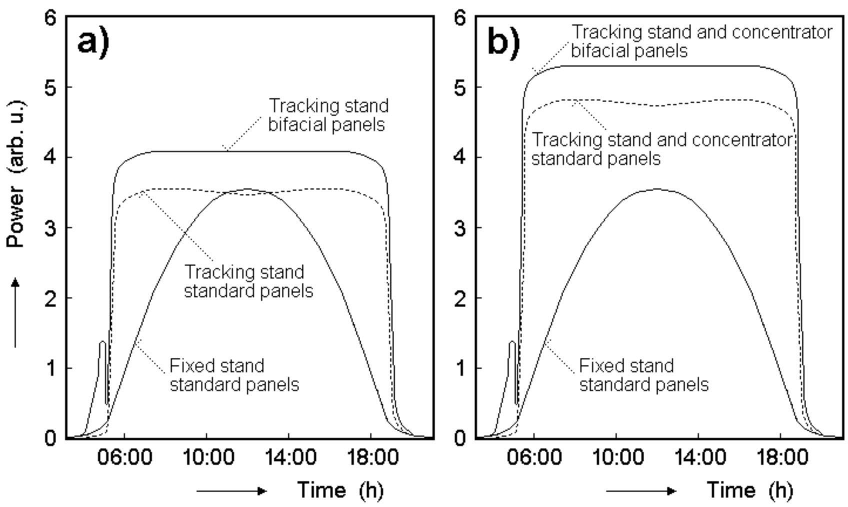

Fig.14. Idealised dependence of the power on the time

would be only 0.2 EUR per kWh. There is 5 kW limit for the 0.4 EUR/kWh support in Spain, for bigger systems the support is 0.2 EUR/kWh.

The same facts are valid also for tracking ridge concentrators where the energy gain is about 100% (i.e. 5 kWh tracking bifacial concentrator gives the same energy output like the 10kWh fixed monofacial system).

Another calculation shows that 5 kW tracking concentrator is by about 2,700 EUR more expensive than 5 kW fixed mono stand but the double energy gain will pay back the price within less than 6 months (5 kW x 0.4 EUR x 10hrs. x 180 days = 3,600 EUR) in sunny arid climate.

Operating temperature measurement of bifacial modules

Bifacial as well as monofacial reference PV modules were delivered by the same manufacturer. The design of both modules has been very similar. The only difference is back surface grid of bifacial cells and back surface glass encapsulant of the bifacial module. Cell temperatures were calculated using the temperature dependence of the open circuit voltage.

Our measurements of both bifacial glass/c-Si/glass and monofacial glass/c-Si/foil flat plate PV modules indicate that the operating temperature $T_{op} = 41^oC$ of bifacial modules was by 12^oC lower than that of monofacial ones $T_{op} = 53^oC$ at AM 1.5 solar radiation, wind speed below 1 $m.s^{-1}$ and ambient temperature $T_{amb} = 22^oC$.

Another measurement indicate that bifacial PV modules at soft concentrators ($C_{geometrical} = 1.5$, $C_{optical} = 1.35$) are still by about 3^oC less hot $T_{op} = 50^oC$ than monofacial modules at one sun radiation.

The study shows that main reasons are as follows:

1) Bifacial Si PV cells are transparent for the infrared part of the solar radiation. As the infrared radiation above 1,100 nm represents more than 20% of the solar energy a proportionally lower energy is absorbed in the bifacial module in comparison with non transparent monofacial one.

2) Opaque back surface protection foil also contributes to the higher temperature of monofacial modules. Typical packing density of c-Si PV modules is about 0.85. It means that 15% of the module area, not covered by PV cells, can absorb substantial quantity (about 50%) of the incident solar radiation while there is negligible absorption in the bifacial modules.

The experimental results are in good agreement with our calculation as well as with soft concentrator (C = 1.6 and 2.2) measurements [14] of PV modules (both glass/Si/glass and glass/Si/foil) with monofacial cells only.

In conclusion using soft concentrators ($C_{geometrical} = 1.5$-1.7 , $C_{optical} = 1.35$-1.45) with bifacial PV modules the over heating of modules is eliminated. Additionally module mounted on high pedestal solar trackers/concentrators can be well cooled by air while fixed modules are frequently roof integrated so the natural air flow is substantially restricted.

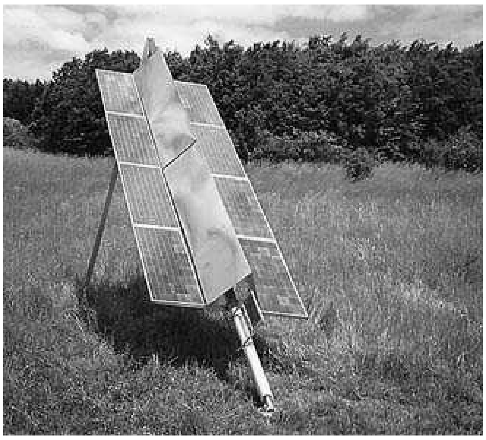

Fig 15. Solar tracking system with the soft ridge concentrator (600 W)

Conclusions

The described newly designed and patented device [2, 3, 5] for automatic orientation of the solar energy collectors with the soft concentrator of radiation can double the solar energy harvest and substantially reduce price of PV energy. It has range of advantages in comparison with existing devices. First of all its simplicity has positive influence to the reliability and price. In the near future we will use our device for the construction of the solar pumping systems which can be used above all in agriculture for irrigation, feeding and so on. We expect the pumping capacity surplus up to 150% which corresponds with our experiments. The new solar tracking concentrator has been scaled up to 5kW unit for industrial applications. Both standard (monofacial) and bifacial solar photovoltaic modules can be used in our tracking concentrators. Mono c-Si, poly c-Si as well as a-Si PV panels can be used.

Some examples of our solar tracking systems are on next figures. Fig.15 shows the solar tracking system with the soft ridge concentrator (600 W). Fig.16 shows the photovoltaic solar pumping system 3 kW installed in Great Britain and Fig.17 shows the PV solar tracking system 1 kW installed in Spain (Canary Islands).

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Fig.16 The solar pumping system 3 kW installed in Great Britain

Fig.17 The solar tracking system 1 kW installed in Spain (Canaria Islands)

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