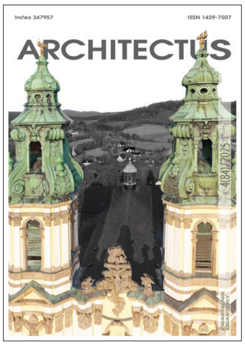

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Przemysław Andrzej Stobiecki*

Mobile vertical photovoltaic system

Abstract

The aim of the article is to present an original alternative technical solution enabling the multiplication of solar energy receiving stations processed by photovoltaic panels or solar collectors, with minimal involvement of the plot or roof area intended for this purpose. The new proposal makes it possible to use and arrange solar energy panels not only in a way that absorbs the surface of the plot for panel development as little as possible, but at the same time in an aesthetic and optimal way by using the structure of movable panels placed in a specific order. The proposed technical solution presented by the author allows the panels to track the movement of the Sun in the sky at different latitudes in different seasons of the year, which is of particular importance in the temperate zone. The proposed solution will also enable the possible cooling of photovoltaic panels, with the forced air movement of installations operated in conditions of extremely high temperatures during summer days. The technical solution is to be a cheap alternative to the existing solutions that absorb costs, space, and prevent proper maintenance and upkeep of above-ground or roof installations. Thanks to it, it will be possible to further increase the efficiency of modern installations drawing energy from sunlight. In order to validate the designed solution, the dependence of the inclination of the selected photovoltaic panel in relation to the Sun and its power was tested.

Key words: photovoltaics, solar panels, two-axis solar tracker, moderate zone, municipal installations

Introduction

The Sun is a gigantic thermonuclear reactor. It is of course a trivial simplification and unfair pigeonholing of a gorgeous space phenomenon which is the Sun and the planets circling around it. We owe our life to this star. Similarly, all the energy comes from it. In the past and today, it was produced from minerals, and all forms of renewable energy obtained come from solar energy – it was trapped millions of years ago indirectly, in various forms, such as coal or hydrocarbons from the prehistoric world of plants and animals.

Trapped solar energy can be obtained on ad hoc basis from fuels processed from plants that are currently living and cultivated. Energy sources can come from the sun's energy transferred to water and atmospheric air, manifesting in the form of sea currents and tides, river water flow, and wind. Finally, since the 2nd half of the 20th century, it can be obtained directly from solar heat and light radiation. This is the purest and simplest form of solar energy – the plant world has been using it since the dawn of life on Earth. In the 20th century, attempts were also made to use geothermal and nuclear energy. Work is also underway to ignite a local energy source: a "miniature sun" trapped in a thermonuclear reactor. However, the use of the latter three sources is still associated with technological shortcomings, risks caused by the unreliability of modern technologies, and extremely costly environmental consequences of possible failures. Today, electricity is the most efficient carrier of energy. And photovoltaics is the most interesting and cleanest option for obtaining it directly from the sunlight.

Current state of the development of solar power engineering

Over the last 10 years, we have seen steady development in photovoltaic cells (often referred to using the PV abbreviation). They are no longer a scientific curiosity used in space exploration research programs and are becoming increasingly popular as components of terrestrial solar power plants. In small formats, they are used as a tourist, cheap, and increasingly efficient source of electricity during vacation trips through the wilderness. They are also used in

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households. Photovoltaic cells are produced in increasingly larger numbers in handy kits and modules installed on the roofs of single family homes, set up in orchards and gardens. More and more often they are incorporated in the national energy network. They are slowly appearing in larger cities as roof installations or as a source of energy for individual street lamps, electronic measuring devices, and electronic municipal equipment.

Cells are still being developed and are becoming increasingly efficient. Currently, cells with efficiencies above 40% are already in use; these that are industrially manufactured and popular have the efficiency of around 20%. Research is also being conducted on polymer and organic cells or the cells with structures similar to the mineral ones called perovskites ("Wikipedia: Ogniwo słoneczne" 2024). Solutions in the form of double-sided cells using reflected and diffracted light are also being used (Szymański 2023).

In order to increase the efficiency of the systems, the programs tracking the Sun's movement across the sky and rotate the photovoltaic panels are also being developed to get the optimal position for harvesting solar energy throughout the year. Mechanical devices called solar trackers which rotate the panels on one or two axes constitute additional equipment for solar panel systems but due to the additional costs associated they are not very popular. Their manufacturers report an expected increase in energy yields on an annual basis. Single-axis solar tracker – an installation moving along a single axis, vertical or horizontal – according to manufacturers' data, provides up to 20–30% higher yields than those recorded for stationary photovoltaics. dual-axis solar tracker allows photovoltaic panels to move in two axes, horizontal and vertical, which makes it much easier to position them perpendicularly to the axis of the sunlight. The greater range of movement means that energy production can be increased by up to approximately 40% compared to a traditional, static structure (Biernaciak 2024).

The development of photovoltaic cell technology should be accompanied by the simultaneous development of the most appropriate methods of exposing them to the sunlight. Panel rotation systems should be popularized and their design modified in order to reduce costs continuously.

State of research

The latest publications in the international specialist literature on solar energy harvesting focus on the properties and efficiency of photovoltaic panels themselves, as well as their construction and chemical composition (Zobaa, Bansal 2011) and electrical instrumentation (Szymański 2023; Zobaa, Bansal 2011; Luque, Hegedus 2011; Dubey, Sarvaiya, and Seshadri 2013). They also discuss alternative ways of obtaining energy from the sun (Prinsloo, Dobson 2015). They describe the optimal exposure conditions for solar energy devices, building on previously acquired knowledge and verifying long-term experience in the operation of solar farms.

A review of several well-known publications from international literature and online sources leads to the following conclusion: while we are seeing the progress in the development of increasingly efficient and durable photovoltaic cells, there is virtually no progress in terms of methods of exposing them to the sunlight and the results achieved so far seem to be generally satisfying. In this situation, it is necessary to propose renewed attempts to develop systems for exposing photovoltaic panels to the Sun in order to reduce their costs and increase the efficiency of the installations used.

Below there is a brief overview of selected current bibliographic items on renewable energy sources (hereinafter: RES). They present advanced solar technologies, state-of-the-art achievements driving solar innovation and techniques for optimizing the efficiency and effectiveness of energy harvesting.

In the publication by the Częstochowa University of Technology, *Kierunki i perspektywy rozwoju odnawialnych źródeł energii. Wybrane aspekty* [Directions and Prospects for the Development of Renewable Energy Sources. Selected Aspects] (Gawlak 2022), it was pointed out that it was the European Union's consistent policy on curbing adverse climate changes related to carbon dioxide emissions that forced member states to take various measures, including the development of the renewable energy sector. The current geopolitical situation is causing raw material prices to rise sharply and energy independence is becoming a key objective for Europe. There is no doubt that renewable energy sources play a key role in this energy transition. Eco-energy solutions guarantee zero carbon dioxide emissions which is usually seen as the main advantage of renewable energy. Currently, energy-importing countries attach great importance to locally sourced renewable energy.

Among the new publications addressing the issue of renewable energy sources and their development in Poland, an important place is occupied by a unique publication devoted to technical and organizational issues related to photovoltaic installations, including descriptions of their potential uses and integration into the country's power system: *Instalacje fotowoltaiczne w systemie elektroenergetycznym* [Photovoltaic Installations in the Power System] (Piątek, Hanzelka 2023). It focuses on the problems of photovoltaic (PV) installations working with the power grid, especially on the impact of these sources on the quality of electricity supply in power systems. The theoretical basis for the operation of both solar installations (PV cells, inverters) and the issue of connecting PV installations to the distribution network were also discussed. The technical conditions for connecting PV installations in Poland and abroad were compared and the principles of forecasting energy generation by solar power plants were explained. The book contains numerous examples and references to the practical use of renewable energy sources. In addition, the appendix presents a sample functional and utility program for a 500 kW PV installation.

Similar issues are discussed in a more recent publication: *Podstawy elektroenergetyki* [Fundamentals of Electrical Power Engineering] (Kacejko, Pijarski 2024), which is a compendium of electrical power engineering knowledge with a particular focus on photovoltaics and wind energy. It also describes important issues related to the energy transition and electrical power security in Poland. The paragraphs devoted to the basics of protection automation and the control and management of power systems, as well as the quality of the electricity obtained are noteworthy. Examples of computer software currently used in the power industry are cited and described here.

The book *Designing and Installing Solar PV Systems* (Warmke 2022) is a guide to designing commercial installations and large residential solar systems – at an advanced level. It extends the knowledge of photovoltaic installations in homes to the field of commercial project installations. It also addresses project management issues. The guide has been updated in accordance with the changes introduced in NFPA 70: National Electrical Code 2020, binding in the United States.

In turn, the publication *Fundamentals of Solar Cells and Photovoltaic Systems Engineering* (Victoria 2024) covers all topics relevant to understanding of photovoltaic technology, including: the principles of solar cell operation, modelling and measurement of solar radiation, the manufacturing processes of solar cells and photovoltaic modules, the design and operation of rooftop installations and large-scale power plants, the economics of such systems, and the role of photovoltaic solar energy in the ongoing energy transition. It also examines innovative PV system designs, including agrivoltaics and energy communities based on PV installations on shared roofs. This outstanding publication is intended to serve as a guide and handbook on photovoltaic solar energy and is addressed to engineers and engineering students at university level in Spain and around the world.

Solar Energy (Botwright 2024), a book promoting the use of solar energy, addresses extremely important issues related to photovoltaics in several chapters. It is an ideal starting point for anyone ready to use renewable energy, as well as for those who want to minimize costs and reduce their carbon footprint.

Inspirations from the world of plants

When it comes to industrial energy harvesting from sunlight, it is worth emulating the solutions tested and invented by the plant world, which draws its life energy from photosynthesis – this is undoubtedly the most effective solution possible.

In the world of plants originating from temperate zones (e.g., sunflowers, soybeans, cotton), heliotropism is a popular ability is (Fig. 1), it is sometimes called sun tracking – the ability of leaves or flowers to change their orientation in response to the Sun's position. Often, plant's leaves position themselves so that the sun's rays fall perpendicularly on them, regardless of the time of the day, which increases the absorption of sunlight energy.

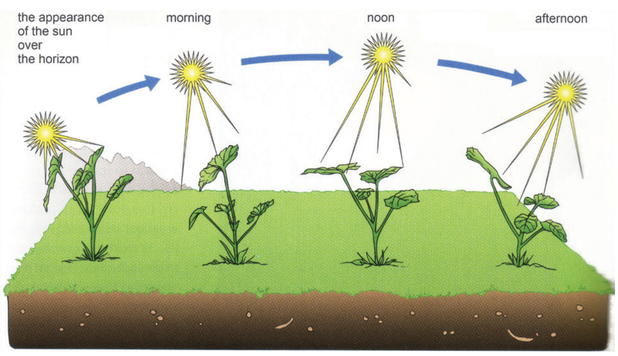


Fig. 1. Plant heliotropism (Salomon, Berg, and Martin 2007, 696)

Il. 1. Heliotropizm roślin (Salomon, Berg i Martin 2007, 696)

Designing the ways of photovoltaic panels exposition we should be inspired by the solutions from the world of nature.

Development of power engineering in recent years

The statistical data showing the actual degree of utilization of solar photovoltaic cells in the global energy balance are worth reviewing. The charts below allow you to assess possible trends in the development of modern energy sources in the coming years (Figs. 2, 3).

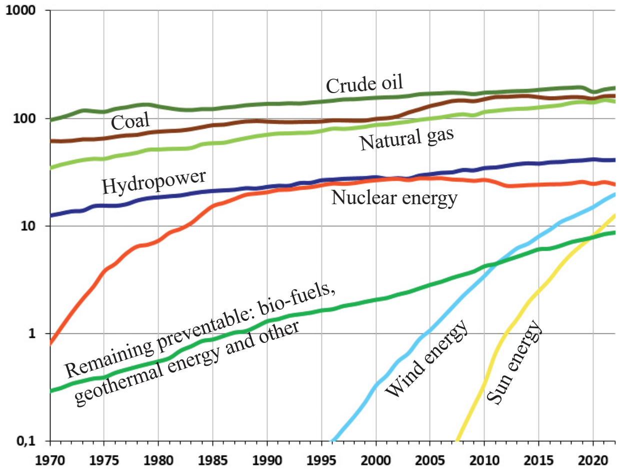


Fig. 2. Energy [Mtoe] obtained from various sources worldwide between 1970 and 2022. Logarithmic scale (source: Wikimedia Foundation. "Wikipedia: Odnawialne źródła energii." Accessed September 13, 2024, https://pl.wikipedia.org/wiki/Odnawialne_%C5%BAr%C3%B3d%C5%82a_energii#cite_note-bp19-7)

Il. 2. Energia [Mtoe] uzyskana z różnych źródeł na świecie w latach 1970–2022. Skala logarytmiczna (źródło: Wikimedia Foundation. "Wikipedia: Odnawialne źródła energii." Dostęp 13 września 2024, https://pl.wikipedia.org/wiki/Odnawialne_%C5%BAr%C3%B3d%C5%82a_energii#cite_note-bp19-7)

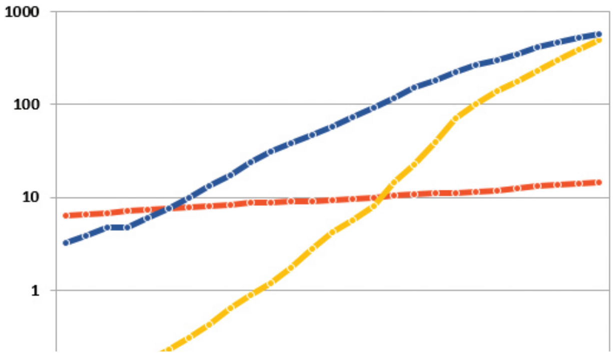


Fig. 3. Capacity [GW] of wind (blue), solar (yellow) and geothermal (red) wind farms in the world in 1992–2018. Logarithmic scale (source: Wikimedia Foundation. "Wikipedia: Odnawialne źródła energii." Accessed September 13, 2024, https://pl.wikipedia.org/wiki/Odnawialne_%C5%BAr%C3%B3d%C5%82a_energii#cite_note-bp19-7)

Il. 3. Moc [GW] elektrowni wiatrowych (niebieski), słonecznych (żółty) i geotermalnych (czerwony) na świecie w latach 1992–2018. Skala logarytmiczna (źródło: Wikimedia Foundation. "Wikipedia: Odnawialne źródła energii." Dostęp 13 września 2024, https://pl.wikipedia.org/wiki/Odnawialne_%C5%BAr%C3%B3d%C5%82a_energii#cite_note-bp19-7)

Mtoe is a megaton of oil equivalent, toe is the energy equivalent of one metric ton of crude oil with a calorific value of 10,000 kcal/kg. This unit is used in the energy sector to describe large amounts of energy ("Wikipedia: Ton of oil equivalent").

The charts from recent years show the most dynamic growth in solar energy sources.

The state of photovoltaic solar power engineering in Poland

The installed capacity of photovoltaics in Poland at the end of September 2022 amounted to over 11 GW (Urząd Regulacji Energetyki 2024). On April 30, 2024, the President of the Energy Regulatory Office published an annual report on electricity generation in small renewable energy installations in 2023. According to the report, approx. 3.5 GW was obtained from so-called small photovoltaic installations (Energy Regulatory Office). Currently, photovoltaics in Poland accounts for more than half of the total installed capacity of renewable energy sources. The examples of some of the largest Polish photovoltaic farms are presented below (Urząd Regulacji Energetyki 2024).

PV Sun farm in Zwartowo

The power plant in Zwartowo (West Pomeranian Voivodeship is the largest solar farm in Poland. Its capacity is 204 MW. It is also the largest solar installation in Central-Eastern Europe. The farm covers the area of 300 ha (equivalent to 422 full-size soccer fields). It was built by Respect Energy S.A. in cooperation with the German company Goldbeck Solar. The first stage of the farm, with a capacity of 204 MW, was completed in September 2022. The planned second stage aims to increase the total capacity to 290 MWp, which will allow the farm to maintain its leading position. The Zwartowo farm will produce approximately 230 GWh of green energy per year. This will power 153,000 households – the total number of households in Gdańsk.

PV powerplant in Brudzewo

The Brudzewo power plant (Wielkopolskie Voivodeship) with a capacity of 70 MW was built by the ESOLEO consortium for the ZE PAK group. The construction was completed in October 2021. The farm consists of 155,554 photovoltaic modules with a capacity of 450 Wp (this abbreviation refers to the amount of electricity at peak production) each and covers the area of approximately 100 ha. Previously, the area was used by the Adamów mine for opencast lignite mining. In addition to the modules, 306 inverters and over 900 km of cables and fibre optics were used to build the power plant. There are 31 transformer stations on the power plant premises, each with a capacity of 2 MVA.

PV powerplant in Witnica

A 64 MW solar power plant is located in Witnica (Lubuskie Voivodeship). The facility was built by BayWa r.e. Electricity production began in early 2021. The Witnica farm consists of over 150,000 Jinko Solar polycrystalline modules with a maximum efficiency of 20.13%. The cables have a total length of 900 km. The farm's annual efficiency is 68 GWh, which corresponds to the annual electricity consumption of approximately 22,500 average households in Poland. Currently, the Witnica solar farm belongs to the Irish company Alternus Energy Group.

PV power-plant in Wielbark

In October 2022, the construction of a 62 MW photovoltaic farm located near Wielbark (Warmian-Masurian Voivodeship) was completed. It will supply energy to over 30,000 households. Approximately, it consists of a total of 140,000 panels with a unit capacity of up to 530 W. The installations are operated by 337 inverters. The construction of the farm required 56 permits and the use of almost 2,500 tons of steel. The farm was built on an area of 119 ha, mainly low-grade arable land. The project was implemented by Energa Wytwarzanie, a subsidiary of Energa from the ORLEN Group. Wielbark solar farm began operating at full capacity in the first quarter of 2023. There are plans to expand it with additional transformer stations, increasing its connection capacity and enabling the safe reception of the energy generated. At an earlier stage of the investment in the farm, commercial production was carried out using 12 MW panels connected to the transmission grid.

PV powerplant in Stepień

In October 2022, the construction of a 58 MW photovoltaic farm in Stępień (Warmian-Masurian Voivodeship) was completed. The investment was carried out and will be managed by Wento, a company owned by Equinor (formerly Statoil). The solar farm consists of 100,000 solar panels spread over an area of 65 ha. It will produce 61 GWh of energy per year, which corresponds to the demand of approximately 31,000 Polish households.

PV powerplant in Czerników

The solar power plant in Czerników near Toruń has an installed capacity of 3.77 MW. The PV power plant covers an area of approx. 7.7 ha. The installation consists of nearly 16,000 panels, with the capacity of 240 W each, covering an area of over 22,500 m^2, which corresponds to the size of several football fields. The annual electricity production in Czerników is estimated at 3,500 MWh, which is sufficient to meet the needs of approx. 1,600 households. The power plant has a container transformer station consisting of a low-voltage switchgear, a transformer chamber, and a medium-voltage switchgear with a control room and an underground cable connection to the 15 kV MV line.

Sun power-plant in Bierutów

The solar farm in Bierutów (Lower Silesian Voivodeship) was built in the second half of 2018. Its installed capacity is 2.059 MW. The installation consists of 7,920 photovoltaic panels, with a capacity of 260 Weach. The owner has been granted a license to generate electricity until the end of 2030.

Sun power-plant in Cieszanów

In 2014, a solar power plant was built in Cieszanów near Lubaczów (Podkarpackie Voivodeship). The solar power plant, located on a 4.5-hectare plot, has 8,333 polycrystalline photovoltaic panels, each with a rated power of 240 Wp (kWp kilowatt-peak). The total power of the plant is 2 MW.

Sun power-plant in Ostrzeszów

The solar farm in Ostrzeszów has a capacity of 2 MWp. It was built on an area of 3.33 ha. The surface area of the photovoltaic modules is 11,155 m^2. The farm consists of 8,064 monocrystalline photovoltaic modules with a peak capacity of 250 Wp.

None of the above-mentioned power plants uses rotating sun-tracking systems and occupies a large area of poor soil with high bonitation value.

The description of own research

Materials and methods

The measurement tests were limited to examining the impact of the inclination of solar panels on the direct current values appearing in them. No tests were conducted on sets converting direct current into alternating current. When describing the illumination conditions for the panels, the focus was on European conditions. Particular attention was paid to the latitude of the author's hometown, Wrocław (Lower Silesian Voivodeship). Wrocław is located at approximately +51°06′0″ north latitude (N+, S–) and –16°46′0″, in a time zone with an UTC offset of –1. The calculations and diagrams do not take into account daylight saving time changes. The measuring station was set up at a height of 7 m above ground level in Wrocław, at an elevation of 119.55 m above sea level. On December 21, 2020, between 11:45 a.m. and 12:15 p.m., i.e., during outdoor measurements, the ambient temperature was +4°C. Weather conditions were favourable: it was a sunny day with visibility exceeding 10 km. Atmospheric pressure was 1046.4 hPa. The temperate illumination zones of the Earth almost coincide with the geographical temperate zones, or rather the temperate latitudes (Fig. 4). They are located in areas in both hemispheres, between the tropics and the polar circles. They are adjacent to the polar zones and the inter-tropical zone. The intensity of solar radiation throughout the year varies at different latitudes on Earth. The northern and southern temperate zones receive the most radiation when the days are long, i.e., in the spring and summer months.

In the areas of moderate illumination there is no polar day or polar night and the sun never reaches its zenith. On the summer solstice the sun reaches an altitude of almost 90° above the horizon near the Tropic of Cancer. At this time near the Antarctic Circle the Sun reaches just over 0°. In Wrocław the Sun reaches an altitude of 62°40′1″. During the winter solstice the Sun is at the Tropic of Capricorn. At this time, it shines almost 43° above the horizon at the Tropic of Cancer and only 16°0′6″ in Wrocław. This causes a large variation in the length of day and night. In Poland the longest day (the first calendar day of summer) lasts from 4:10 p.m. in the south to 5:20 p.m. in the north. The shortest day (the first day of calendar winter) in the north is more than 10 hours shorter and in the south of Poland – almost 8 hours shorter. Additionally, regardless of the season, on sunny days from dawn to dusk, the sun "wanders" across the sky from a position of 0° above the horizon at dawn to 0° above the horizon at dusk. At noon it reaches its maximum height above the horizon. Every day (in one of the two halves of the year) this height is always different.

Based on data collected from the Sun position calculator (Global Monitoring Laboratory) curves of its position in the sky above Wrocław were determined on the days of measurement: December 21, 2020, and June 21, 2021. These are the days of the lowest and highest position of the sun at noon above the horizon as seen from Wrocław.

When preparing analyses for other illumination zones and locations with different geographical coordinates different measurement results and sun positions in the sky should be expected.

When looking for the best placement and tilt of the panels for known sun positions above the horizon the angle of the sun above the horizon from 90° should be subtracted. For the most common photovoltaic installations in Poland, i.e., those mounted on roofs or on fixed pedestals in gardens and fields, the recommended angle of the panels, measured from the ground level, should range from 30° to 40° (according to companies installing stationary photovoltaic panels; Byś 2023), which translates into the optimal positioning of photovoltaic panels for the sun at an altitude of 50° to 60° above the horizon. As shown in Figure 5 for the latitude of Wrocław this is the correct inclination in the middle of the day at the end of spring, summer, and the first weeks of autumn. Unfortunately, for the rest of the year – when the days become shorter, colder, and cloudier – the recommended panel setting does not allow for the full power of the photovoltaic installation to be achieved, even during sunny spells. These panels occupy a relatively large area – to achieve 1 kW of peak power the required cell area is approx. 7 m^2 (Byś 2023).

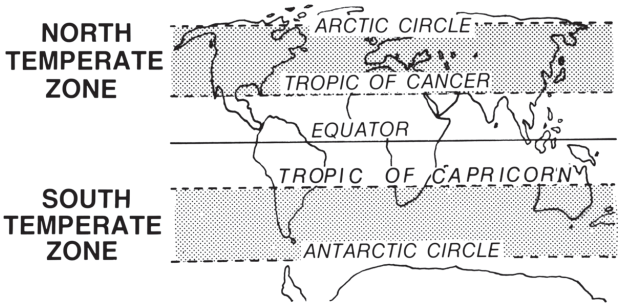
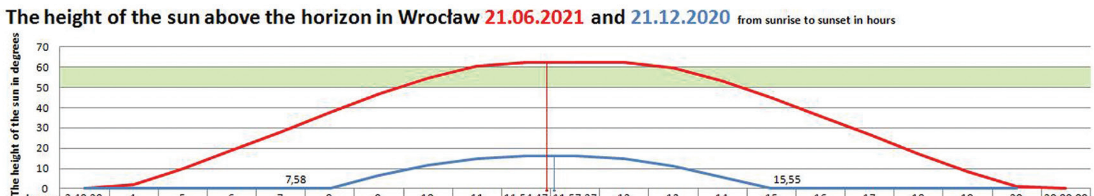


Fig. 4. Zones of moderate illumination of the globe and zones of temperate zones latitude (source: https://commons.wikimedia.org/wiki/File:Temperate_zone_(PSF).png)

Il. 4. Strefy umiarkowanego oświetlenia kuli ziemskiej oraz strefy umiarkowane szerokości geograficznych (źródło: https://commons.wikimedia.org/wiki/File:Temperate_zone_(PSF).png)



hours	3,40,20	4	5	6	7	8	9	10	11	11,54,47	11,57,37
The height of the sun in degrees (red)	0	2,14	10,03	18,86	28,15	37,54	46,6	54,63	60,44	62,41	62,40
The height of the sun in degrees (blue)	0	0	0	0	0	0,17	6,56	11,74	15,01	16,05	16,06

hours	12	13	14	15	16	17	18	19	20	20,09,09
The height of the sun in degrees (red)	62,39	59,66	53,35	45,07	35,92	26,51	17,28	8,57	0,96	0
The height of the sun in degrees (blue)	16,05	14,76	11,26	5,89	0	0	0	0	0	

Fig. 5. The height of the Sun above the horizon in Wrocław, from sunrise to sunset in hours. The slope of fixed photovoltaic panels recommended by producers in Poland is marked in green (elaborated by P. Stobiecki)

Il. 5. Wysokość słońca nad horyzontem we Wrocławiu od wschodu do zachodu słońca co godzinę; na zielono zaznaczono nachylenie stałych paneli fotowoltaicznych rekomendowane przez producentów w Polsce (oprac. P. Stobiecki)

On December 21, 2020, between 11:45 a.m. and 12:15 p.m., tests were conducted in Wrocław to measure the direct currents occurring in a new photovoltaic panel manufactured and sold in 2020, constructed from monocrystalline cells (4 pcs. × 9 pcs. = 36 pcs.).

The panel manufacturer provided the following specifications:

– flexible solar module,
– module type: HNPV-100M,
– peak power (PMP): 100 W,
– manufacturing tolerance: ±3%,
– open circuit voltage (VOC): 21.6 V,
– maximum power current (MP): 6.05 A,
– maximum power voltage (VMP): 18.00 V,
– short-circuit current (Isc): 5.56 A,
– maximum system voltage: 1000 V,
– product dimensions: 1200 × 550 × 2.5 mm,
– all technical data under standard test conditions,
– AM = 1.5 E = 1000 W/M^2 TC = 25°C,
– CE ISO 9001 – 2008 ROHS.

The study was designed to determine the efficiency of the tested panel which is exposed to sunlight at various angles and the characteristics of these relationships as well as to assess the values of the obtained voltages, intensities, and DC currents when changing the position of its plane in relation to the light source, i.e., the Sun. A voltmeter was used to measure the DC voltage while an ammeter and a system with a light bulb drawing current from the photovoltaic panel were used to measure the DC current. The results obtained do not exceed the maximum values, taking into account the ±3% tolerance guaranteed by the manufacturer.

Results

The results obtained are presented in the graphs (Figs. 6–8). The *y*-axes (vertical) show the measured and calculated values: DC voltage, DC current, DC power. The *x*-axes (horizontal) show the slope of the tested photovoltaic panel during the measurements in degrees and tenths of degrees. The inclination of 163.94° means that the panel is facing downwards with its photovoltaic plane lying in the plane determined by the position of the Sun on December 21, 2020, at 12:00 p.m. in Wrocław. Similarly, the angle of inclination is –16.06° but for the panel facing upwards. On that day and at that time in Wrocław, the Sun's rays fell perpendicularly on the plane panel positioned at an angle of 73.94°. Detailed values are also listed below the graphs.

The recorded results allow for the calculation of the direct current generated in the photovoltaic panel.

The red colour indicates the levels of direct current produced by the panel and lost due to poor orientation of the panel relative to the Sun. The total amount of lost energy reaches 22–35%.

Conclusions

The actual levels of profit or loss generated by fixed panels and sun-tracking panels can be determined by comparing installations with identical parameters installed close to each other, in an identical environment over a longer period of time, e.g., a year or several years. The results of research and analyses clearly indicate the advantage of sun-tracking panels throughout the year. As already mentioned, research shows that immobilizing modern photovoltaic panels leads to unnecessary losses. Not only the further development of photovoltaic cells is necessary but also is the widespread use of dual-axis devices that move the panels commonly known in Poland as trackers. All this aims at making fuller use of the Sun's energy reaching the Earth.

The analyses carried out enable us to propose new, original solutions which are presented below.

Reduction of costs of rotating systems that track the sun's movement across the sky should be the main goal of designers. Stacking photovoltaic panels on a single rotating device may be an interesting method of reducing the costs of planned installations. Detaching photovoltaic farms from the ground and placing them on poles will free up between one-third and two-thirds of the space they currently occupy. One can imagine multi-story installations spaced at certain distances from each other in such a way that the shadow of the high-placed panels wandering across the Earth's surface will not interfere with the vegetation of low and medium-sized plants growing around them. This makes it possible to build photovoltaic farms not only on wasteland but also on farmland. Such solutions erected in sunny locations on lawns, squares or along existing streets, may become a popular alternative to urban rooftop photovoltaic installations.

When correctly positioned, rotating systems can not only provide solar energy but also provide welcome shade on summer days in urban areas and streets. By creating screens

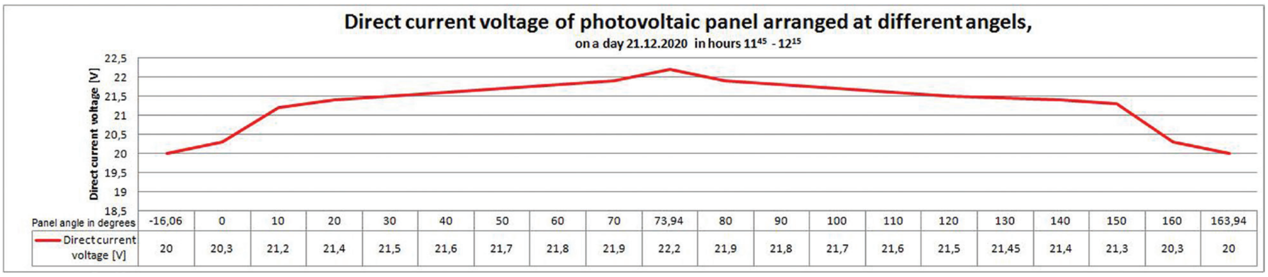


Fig. 6. The voltage of direct current, a photovoltaic panel laid at different angles, on a day 21.12.2020, in hours 11.45–12.15 (elaborated by P. Stobiecki)

Il. 6. Napięcie prądu stałego, panel fotowoltaiczny ułożony pod różnymi kątami, 21 grudnia 2020 r., godz. 11.45–12.15 (oprac. P. Stobiecki)

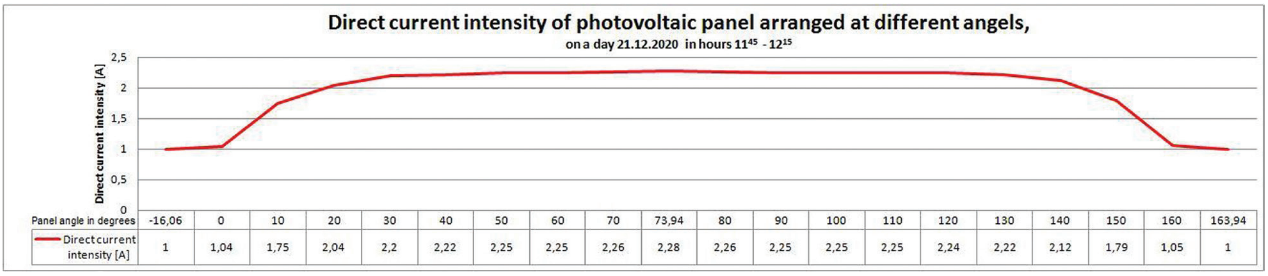


Fig. 7. The intensity of direct current, a photovoltaic panel laid at different angles, on a day 21.12.2020, in hours 11.45–12.15 (elaborated by P. Stobiecki)

Il. 7. Natężenie prądu stałego, panel fotowoltaiczny ułożony pod różnymi kątami, 21 grudnia 2020 r., godz. 11.45–12.15 (oprac. P. Stobiecki)

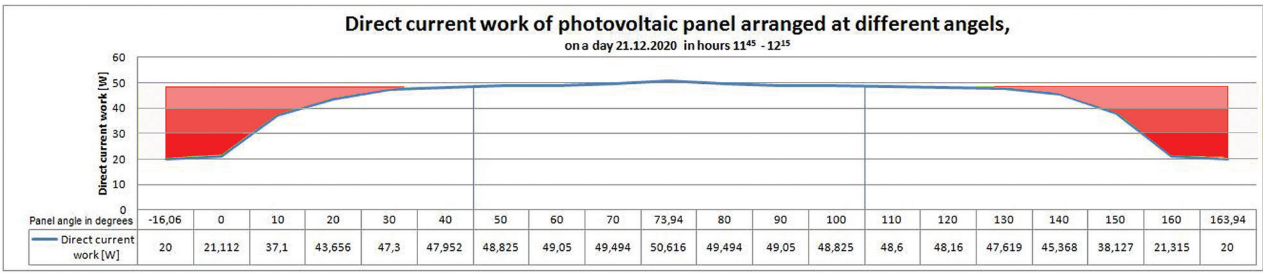


Fig. 8. The work of direct current, a photovoltaic panel arranged at different angles, on a day 21.12.2020, in hours 11.45–12.15 (elaborated by P. Stobiecki)

Il. 8. Praca prądu stałego, panel fotowoltaiczny ułożony pod różnymi kątami, 21 grudnia 2020 r., godz. 11.45–12.15 (oprac. P. Stobiecki)

from photovoltaic panels placed high on rotating poles an additional cooling effect can be expected in urban areas during the summer months. Figure 9 shows the author's proposal for a new type of tracker solution.

The proposed solution is equipped with additional sprinkler and cooling systems for the panels during the summer months. Placing several panels vertically above each other on a single rotating pole makes this solution more economically viable. The panels in the lowest position should be located approximately 2.5 m above the ground. They are arranged in such a way that at no time of the day or year do they obscure those located above and below. The total height of the solution shown is approximately 10.5 m. The presented variant, provisionally named type "A", consists of 8 identical photovoltaic panels with an example power of 280 W. The total power of such an installation is 2.24 kW. Solutions for a larger number of panels attached to the same mast are in preparation:

– "B" for installations with 12 panels with a total power of 3.36 kW,

– "C" for installations with 17 panels with a total power of 4.76 kW,

– "D" for installations with 18 panels with a total power of 5.04 kW,

– "E" for installations with 22 panels with a total power of 6.16 kW,

– and a slightly larger "F" for installations with 36 panels with a total power of 10.08 kW.

Fig. 9. A proposal for a new type of vertical, rotating, biaxial photovoltaic system solution: a) side view; b) frontal perspective; c) axonometry side. 1 – photovoltaic panels, 2 – axis of rotation of panel hangers, 3 – panel hanger, 4 – hanger tie rod motor, 5 – main rigid tie rod of hangers, 6 – steel tube of the rotating column structure, 7 – steel foundation tube with a motor rotating the pole, 8 – reinforced concrete footing, 9 – sprinkler water system, 10 – cooling air supply system (designed by P. Stobiecki)

Il. 9. Propozycja rozwiązania wertykalnego, obrotowego, dwuosiowego układu fotowoltaicznego nowego typu: a) widok boczny, b) perspektywa od przodu, c) aksonometria boczna. 1 – panele fotowoltaiczne, 2 – osie obrotu wieszaków paneli, 3 – wieszak panelu, 4 – silnik cięgna wieszaków, 5 – sztywne cięgno główne wieszaków, 6 – stalowa rura konstrukcji obrotowego słupa, 7 – stalowa rura fundamentowa z silnikiem obracającym słup, 8 – żelbetowa stopa fundamentowa, 9 – instalacja wody do tryskaczy, 10 – instalacja nawiewu chłodzącego (projekt: P. Stobiecki)

In urban areas such as Wrocław, there are streets that are almost ready for the installation of photovoltaic panels in vertical arrays. Plac Grunwaldzki is a spectacular example. It extends from southwest to northeast. Existing street lamp posts, approximately 12 m high and spaced every 25 m, can be used to install suitably adapted vertical rotating panel installations. Separate new-type tracker poles with panels can also be added.

The northern side of this street (on the right in Fig. 10) seems to be particularly well suited for the installation of vertical photovoltaic systems. This is due to the shape of the low and high greenery, the appropriate urban development, and the favourable solar exposure.

Advantages of the proposed solution

The new type of dual-axis tracker has several significant advantages. Some of them are the advantages of all dual-axis low trackers used to date. However, the proposed solution will save more costs, space, and energy losses. Among the advantages, the following are worth mentioning:

– increasing the efficiency of sunlight capture, leading directly to improved performance of the photovoltaic installation (average annual energy production is by 29% higher compared to traditional photovoltaic installations; Energetyka-Sloneczna.Net),

– installation is an important step towards energy self-sufficiency, but also serves the environment protection,

– movement of solar panels reducing the likelihood of dust and other contaminants settling on them (Biernaciak 2024),

– support for the system with sprinkler and ventilation installations,

– more convenient access to the panels (e.g., if cleaning, repair, or maintenance is required, a photovoltaic installation with a tracker can be easily positioned in a convenient location, which is a great convenience, especially in the case of panel failure inside the installation; Biernaciak 2024),

– movable panels enabling automatic snow removal in winter,

– benefits and savings arising from the reduction of land and acreage occupied,

– vertical arrangement of panels on a single rotating pole resulting in reduced costs compared to previously used solutions in the form of single-story trackers,

– the function of shading selected urban areas leading to lowering the temperatures in summer.

The advantages listed above can significantly reduce the costs associated with planned investments.

The costs as well as a certain sensitivity to damage to the drive systems are the main disadvantages of the proposed sun tracking systems which are exposed to weather conditions. Final decision on the cost-effectiveness of the proposed solutions must be preceded with appropriate research in this area. Without it is difficult to estimate how profitable will be the proposed solution compared to less complicated immobile systems. However, the economic aspect was not the focus of this study. Such research needs to be conducted as part of a separate project.

Nevertheless, there is hope that this study will encourage solar system designers and all those interested in this topic to work hard to promote inexpensive, effective vertical photovoltaic systems in urban and rural areas.

Summary

The study conducted and the results obtained are of a general nature. The conclusions drawn from them may be applicable to other positions of the Sun in the sky or other days of the year for the selected location. The losses shown are actually multiplied and translated into the annual performance of photovoltaic panels, which are traditionally fixed on pedestals without the possibility of changing their position in relation to the Sun. With various poor panel settings electricity is lost according to the percentage breakdown shown in Table 1.

The percentages in the table cells at the border between the white and red rows reach the level of value loss measured in the range of 3–5%. They can be considered the margin of error of the measurements obtained in the experiment. The area of obvious losses resulting from the mismatch between the inclination of the photovoltaic panels and the maximum, optimal sunlight conditions is marked in red. The colour code

Fig. 10. The perspective of Plac Grunwaldzki street in Wrocław and its favourable arrangement for municipal vertical photovoltaic installations (photo by P. Stobiecki)

Il. 10. Perspektywa ulicy Plac Grunwaldzki we Wrocławiu i jej korzystne ułożenie dla miejskich pionowych instalacji fotowoltaicznych (fot. P. Stobiecki)

also corresponds to the data obtained in the scheme in Figure 8. At photovoltaic panel inclinations of –16.06° and 163.94°, voltages of 20 V and currents of 1 A were recorded.

These inclinations are extremely unfavourable for the operation of the photovoltaic panel on December 21, 2020, at 12:00 p.m. and prevent the absorption of direct sunlight. Nevertheless, the recorded voltage and current values are different from zero and indicate the appearance of current values in the system caused by light reflected from the environment and scattered water vapor in the atmosphere during the test. Currents from scattered light nearly always appear.

The energy generated by sunlight reflections is used in double-sided photovoltaic panels. Their efficiency can be

Table 1. Percentage loss of direct current work, photovoltaic panel laid at different angles, on a day 21.12.2020, in hours 11.45–12.15* (elaborated by P. Stobiecki)
Tabela 1. Procentowa strata pracy prądu stałego, panel fotowoltaiczny ułożony pod różnymi kątami, 21 grudnia 2020 r., godz. 11.45–12.15* (oprac. P. Stobiecki)

Panel tilt downward from 73.94°	Panel tilt upward from 73.94°	% work related to maximum	% decrease of efficiency related to maximum
73.94	73.94	100.00	0.00
70	80	97.78	2.22
60	90	96.91	3.09
50	100	96.46	3.54
40	110	94.74	5.26
30	120	93.45	6.55
20	130	86.25	13.75
10	140	73.30	26.70
0	150	41.71	58.29
–16.06	163.94	39.51	60.49

* The optimal angle of the panel on December 21, 2020, at 12:00 p.m. from the horizon: 73.94°; it allows sunlight to fall perpendicularly to the panel surface. Position of the Sun in Wrocław: 16.06° above the horizon.

increased by up to 25% (Szymański 2023). To fully utilize the effects of reflected light double-sided panels should be placed at considerable heights above the ground or roofs.

In the experiment the efficiency losses of the tested system for angles ranging from –16.06° to 40° and from 110° to 163.94° correspond to the losses that occur in permanently installed photovoltaic panel systems in the morning and evening hours. Such losses are particularly severe in the summer months when the normal operation of photovoltaic panels is disrupted by high ambient temperatures and the heating of the panel. According to experiment, losses caused by temperature increases in the daily energy balance reach 0.4% per 1°C (Dubey 2013). The balance can be improved by tracking the position of the Sun with a dual-axis tracker which will ensure maximum power supply in the morning and evening on a summer day (with moderate temperatures).

Research shows that the immobilization of modern photovoltaic panels leads to losses. These losses, regardless of the level of atmospheric light, are a year-round, common and unnecessary phenomenon. Given the current popularity of solar energy which draws energy from photovoltaics as well as the trends in the development of this type of energy production every effort should be made to reduce the cost of devices that track the Sun's movement in the sky which will allow for their widespread use. This, in turn, will eliminate energy losses resulting from the misalignment of the panels.

Numerous studies on the intensity of sunlight show that during the winter months and in the early morning and late afternoon hours in summer, the intensity of sunlight is only seemingly lower. The intensity of sunlight can be around 60% of its maximum value when the Sun is 15° above the horizon, around 50% at 10°, and 25% at just 5° above the horizon. Therefore, if trackers can follow the Sun from sunrise to sunset their rotating solar panels can collect a significant amount of additional energy ("Wikipedia: Solar tracker").

Translated by
Agata Haglauer

Patents

Patents for the above-mentioned designs of vertical dual-axis trackers of types "B", "C", "D", "E", and "F" are planned to obtain.

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Streszczenie

Ruchomy pionowy system fotowoltaiczny

Celem autora artykułu było przedstawienie oryginalnego alternatywnego rozwiązania technicznego umożliwiającego multiplikację stanowisk odbioru energii słonecznej przetwarzanej przez panele fotowoltaiczne lub kolektory słoneczne, przy minimalnym zaangażowaniu powierzchni przeznaczonej na ten cel działki lub powierzchni dachowej. Nowa propozycja pozwala na wykorzystanie i ułożenie paneli gromadzących energię słoneczną równocześnie w sposób estetyczny i optymalny poprzez wykorzystanie konstrukcji ruchomych paneli umieszczanych według określonego porządku. Rozwiązanie to może być alternatywą także dla połaciowych dachowych przydomowych instalacji fotowoltaicznych lub kolektorów słonecznych.

Propozycja rozwiązania technicznego przedstawiona przez autora pozwala na śledzenie przez panele ruchu słońca na nieboskłonie pod różnymi szerokościami geograficznymi w różnych porach roku, co ma szczególne znaczenie w strefie umiarkowanej. Możliwe są także obrót paneli i optymalizacja ich położenia w trakcie każdego dnia roku, od świtu do zmierzchu. Proponowane rozwiązanie umożliwi ponadto ewentualne chłodzenie paneli fotowoltaicznych wymuszonym ruchem powietrza instalacji eksploatowanych w warunkach ekstremalnie dużych temperatur podczas dni letnich.

Proponowane rozwiązanie ma być tanią alternatywą dla dotychchzasowych instalacji naziemnych lub dachowych, absorbujących koszty i powierzchnię oraz uniemożliwiających należyte utrzymanie i konserwację. Dzięki niemu możliwe będzie dalsze zwiększanie efektywności nowoczesnych instalacji pobierających energię ze światła słonecznego.

W celu uwiarygodnienia projektowanego rozwiązania przeprowadzono badania zależności nachylenia wybranego panelu fotowoltaicznego względem słońca i jego uzyskiwanych mocy.

Słowa kluczowe: fotowoltaika, panele solarne, tracker słoneczny dwuosiowy, strefa umiarkowana, instalacje miejskie