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An analysis of the economic and technological potential of solar-driven generation in renewable energy development

Abstract: The development of solar generation is an integral part of evaluating renewable "green" energy in accordance with the concept of sustainable development. This study focuses on the specifics of the implementation of solar energy in the context of the USA, the EU and China, taken as an object in connection with the specifics of the geographical-territorial and climatic-natural situation. The originality of the research lies in the approach of modelling the implementation of solar power generation with consideration to the main economic, technological, and resource factors. This study

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aims to assess trends in the development and implementation of regional solar power generation. Solar energy development is performed exclusively at the expense of private investment and state support is minimal. Therefore, the power of installed solar power plants relative to the amount of invested investments shows a high correlation. From the perspective of economic activity, solar energy in the analyzed regions is used by households in small amounts. The highest use of solar energy by households is in the USA, where this indicator is 8.3%, and the lowest is in China (0.13%). The analysis indicates that currently, solar energy is not a priority for developing the energy sector but is only a supplement. Further solar energy development is possible owing to technological innovations that will increase the efficiency of solar radiation use. The analysis also revealed the conclusion that the most powerful use of solar energy appears in China, with a figure of 19.6%, while the US has only 4.04% and the EU has almost 9%. According to the criterion of economic and technological influence on solar energy development, China occupies a leading position (9.89%), whereas the EU has only 0.03%. Thus, solar energy is currently not an attractive area for business and needs to prioritize the development of the EU economy, which is confirmed by insignificant investment flows compared to China and the USA.

KEYWORDS: solar energy, sustainable development, economic and technological model of solar generation, solar radiation, solar installation

Introduction

The activation of the transition to renewable energy sources, mainly wind and solar energy, is determined by the growth trends in their use as it contributes to the preservation of resources for future generations and the emphasis on environmental friendliness, including electricity (Sribna et al. 2023). The attractiveness of solar energy is dictated by its natural ecological source, which is constantly active and has infinite potential in the solar system.

An essential aspect of the activation of solar energy is the technological progress in producing solar panels, which helps reduce the cost of producing electricity from this source. Technological innovations have made it possible to increase the efficiency of solar power plants and reduce their dependence on weather conditions. For many countries, the transition to solar energy is becoming a strategic decision in order to reduce dependence on traditional energy sources such as coal and gas. It also helps reduce greenhouse gas emissions and improve the quality of the environment. Governments actively implement incentive programs, subsidies, and other measures to support solar energy use. According to Ember's Global Electricity 2023 report (2023), wind and solar power generation has reached 12% of the world's total electricity generation capacity. This has increased the share of low-carbon electricity to almost 40% of the total production. Wood Mackenzie (2023) expects 270 GW of new global PV capacity in 2023, up 33% year on year. However, the annual growth rate is anticipated to fall to 1% in 2024 and to increase again by 5% in 2025. Global manufacturing capacity is forecast to reach 1,100 GW by the end of 2024, and significantly exceed demand (IEA 2024).

Despite all the positive aspects, specific challenges are associated with integrating solar energy into energy systems, including ensuring stability and saving excess energy. Addressing these challenges requires an integrated approach and collaboration among governments, research institutions, and the private sector. In the context of modern trends, solar energy is a crucial direction for ensuring sustainable development, especially in the European Union (EU), China and the United States of America (USA). These countries have set the pace for implementing the global concept of sustainable development by introducing alternative energy, particularly solar energy. In particular, the EU must achieve the ambitious goals of reducing emissions and dependence on low-carbon energy sources. China, the world leader in the production and use of solar panels, continues the rapid development of the sector and has set new records for the number of installed solar capacities. In the United States, where solar energy has become a strategic direction in the framework of the clean energy strategy, a large-scale program is being implemented to increase the production and consumption of solar energy.

Despite the above, the potential use of solar radiation is quite uneven and is dictated by various political and economic factors, which determine the actual state of its development. Although solar energy represents a huge potential for sustainable development, its successful implementation is determined by various factors, ranging from geographic location to political acceptance and economic feasibility.

The purpose of the study is to assess the trends in the development and implementation of solar generation using the examples of the USA, the EU and China. In accordance with the goal, the following hypotheses are proposed:

1. The feasibility of world energy development is based on the use of solar energy. In accordance with this, its development should be intensified in areas with optimal solar provision.
2. The introduction and use of solar energy by households should be maximal in the areas of the best solar supply.

The manuscript's novelty lies in its comprehensive analysis of solar energy trends across the USA, the EU and China, integrating technological, economic, and policy perspectives. It uniquely combines the latest data on solar capacity, technological advancements in solar panels and the impact of government incentives on the adoption of solar energy. This study offers fresh insights into the strategic importance of solar energy in the global energy mix, emphasizing the role of technological progress and policy support in overcoming challenges related to solar energy integration and sustainability.

1. Literature review

Research efforts in the field of renewable energy have been widely recognized by the global community (Holechek et al. 2023; Kabeyi and Olanrewaju 2023; Aparupa et al. 2022; Maka and Alabid 2022; Kumar 2020). The most popular research investigations include a wide range of global assessments of renewable energy opportunities and analyses of modern energy technologies which reveal significant opportunities and challenges in the field of energy (Bordin et al. 2021; Asim et al. 2022; Zhang et al. 2023). These form the foundation for the development of sound strategies and decision-making processes at various levels, including policy (Peidong et al. 2009; Norberto 2023; Agrawal et al. 2023; Tiruye et al. 2023) and energy planning (Chu and Majumdar 2012; Tsangas et al. 2023; Laveneziana et al. 2023), and investments (Shinwari et. al. 2022; Grabara et al. 2021; Liu et al. 2019) and global energy conservation efforts (Żywiołek et al. 2021; De la Cruz-Lovera et al. 2017). The scientific achievements determine the future of energy policy, contributing to the transition to the more sustainable and environmentally-friendly use of energy for the entire world.

The greatest attention in research on the development of renewable energy concerns the dynamics of "green" energy development, including solar energy (Soundarrajan and Vivek 2016; Saba and Ngepah 2022; Androniceanu and Sabie 2022; Zhou and Li 2022; Fang 2023). These studies analyze technological advances and various aspects such as economic impacts and environmental benefits and challenges.

Sun et al. (2022), Eichenauer and Gailing (2022), Igliński et al. (2023) and Siala et al. (2021) studied solar energy development dynamics at regional and national levels. It is crucial to consider the context and specifics of different markets when assessing the dynamics of solar energy development at the regional and national levels. Different parts of the world have unique conditions for introducing solar energy, which is determined by climatic features, economic opportunities and technological development. An example of this is that developed countries may actively use modern technologies to produce solar energy, whereas developing markets focus on more straightforward and affordable solutions. Considering these factors makes it possible to better adapt solar technology implementation strategies to the specific conditions of each region, contributing to the efficient and sustainable development of solar energy worldwide.

Assessment of the impact of solar energy on the environment related to the problems of the disposal of spent solar power plants is of distinguishable importance (Bošnjaković et al. 2023; Tawalbeh et al. 2021; Abid et al. 2023; Gulaliyev et al. 2020; Lay et al. 2023; Sharma et al. 2023). By analyzing the impact of solar power plants on the environment, these authors identified problems associated with the disposal of installation that were already in operation. This covers the issue of the efficient recycling of old solar panels including communication with battery electric vehicles and the management of waste resulting from their use (Koval et al. 2023; Olczak et al. 2023).

Innovative solutions for solar power plants require both automation and digitalization (Kangas et al. 2021; Borowski 2021; Constantino et al. 2022; Podolchak et al. 2023). The authors pointed out that the use of digital technologies such as sensors, Internet of Things (IoT) systems, artificial intelligence (AI) and data analytics can provide accurate measurement and real-time analysis of the efficiency of solar power plants, allowing plant operators to quickly respond to changes in energy production, to maximize its use and to ensure optimal functioning.

State subsidies for solar energy systems also stimulate its development (Ntanos et al. 2018; Kumar and Majid 2020; Agbo et al. 2021; Wen et al. 2021; Farghali et al. 2023). Studies note that an essential component of the success of public policy and the transition to solar energy is the stability and long-term nature of stimulants. These will both create the stability of investment conditions and the development of renewable energy in the future.

These studies provide the foundation for developing sound strategies and decision-making fundaments necessary to create a stable, efficient and environmentally-friendly energy system. Despite these achievements, social aspects, technical innovation, global cooperation, disposal efficiency and other issues remain open for further research.

2. Methods

The object of the research is the solar energy market in the USA, in the EU and in China. Several factors determine the choice of the countries of analysis:

1. Economic potential: The USA, the EU and China are the world's economic leaders and occupy a crucial place in the global energy markets. The high level of economic development makes them attractive for study in the context of the transition to solar energy.

2. Policy strategies and regulation: The US, the EU and China are actively defining their energy strategies and adopting regulatory measures to promote the development of solar energy. Understanding the political context is the key to analyzing and forecasting the sector's future development.

3. Technological progress: Observing technological advances in solar energy in the US, the EU, and China is essential in order to determine the direction of innovation and its impact on the global market.

4. Consumer demand: The high demand for energy in these regions creates the basis for introducing solar energy as an essential source for meeting energy needs.

The data for analysis was meticulously sourced from government agencies, such as the U.S. Energy Information Administration (EIA), Eurostat, and China's National Bureau of Statistics, alongside scientific and industry databases like Scopus, Web of Science, IRENA, and IEA, as well as satellite and geospatial data from NASA's Power Data Archive and the European Space Agency's Copernicus program. This diverse collection has provided a robust foundation of official statistics, academic research, technological advancements and solar intensity metrics. Once collected, the data underwent rigorous cleaning to correct errors and perform normalization in order to ensure comparability across different units of measurement, and appropriate aggregation or disaggregation to align with the study's analytical goals. These preparatory steps, combined with a detailed statistical analysis, laid the groundwork for a comprehensive evaluation of the development of the solar energy market across the USA, the EU and China, emphasizing the sector's potential for growth and the challenges it faces.

The analysis of these countries allows us to understand the current state of solar energy and predict its future contribution to the global energy system. To assess the development of solar energy, an economic and technological model of solar power plants was developed. The model considers a significant number of factors influencing solar energy development, as highlighted by Mikhno et al. (2022):

- Economic factors play a key role in the development of solar energy, considering their impact on financial profitability, costs and the efficiency of projects. The efficiency of solar power plants largely depends on the cost of producing solar energy compared to other energy sources. In turn, the cost of installing and maintaining solar power plants and their profits affect the attractiveness of investment in this industry.
- Technological factors including aspects related to technical and production issues, the improvement of technologies and the development of new technical solutions in the field of solar energy. In particular, this includes the development of solar panel production technologies and their design to maximize solar energy collection; the use of new materials and technologies to increase the efficiency of converting sunlight into electricity; the implementation of monitoring systems that allow real-time monitoring of the efficiency of solar power plants and the detection of possible malfunctions; improving energy management schemes to maintain the stability of electrical networks with a high percentage of solar energy.
- Environmental factors such as the absence of greenhouse gas emissions and pollution, the use of renewable resources, the preservation of biodiversity, the minimization of the use of water resources and the reduction of the impact on natural ecosystems.
- Political factors including the adoption and implementation of favorable legislative and regulatory mechanisms, the provision of financial incentives and the formulation of energy strategies aimed at spreading and integrating solar technologies into national energy systems.

Considering all these factors in the economic and technological model makes it possible to effectively assess the potential for solar energy development in different regions or states. However, in modelling solar energy development, these factors must be simplified to a minimum number. The resource factor has its specificity and is manifested in the form of solar radiation, a potential energy source for solar technologies; the amount of solar energy used determines the possibility of the efficient operation of solar power plants and their contribution to electricity production.

The technological factor manifests itself, first of all, as the development of the technological process, which ensures the maximum productivity of converting solar radiation into electricity or heat. Additionally, the technological process is related to the possibility of ensuring the arrival of solar rays for an extended period due to the possibility of acting with electromagnetic pulses and chemical compounds on the lower and middle levels of the Earth's airspace. This is the application of technologies that allow the dispersal of cloudiness and ensure stable, clear weather in certain areas of the Earth's surface. Furthermore, the investment factor should approach the minimum financial expenses, and the resource part should be maximized. There should be clear sunny days for an extended period, regardless of seasonal periods. The economic and technological model of solar generation is presented in Figure 1.

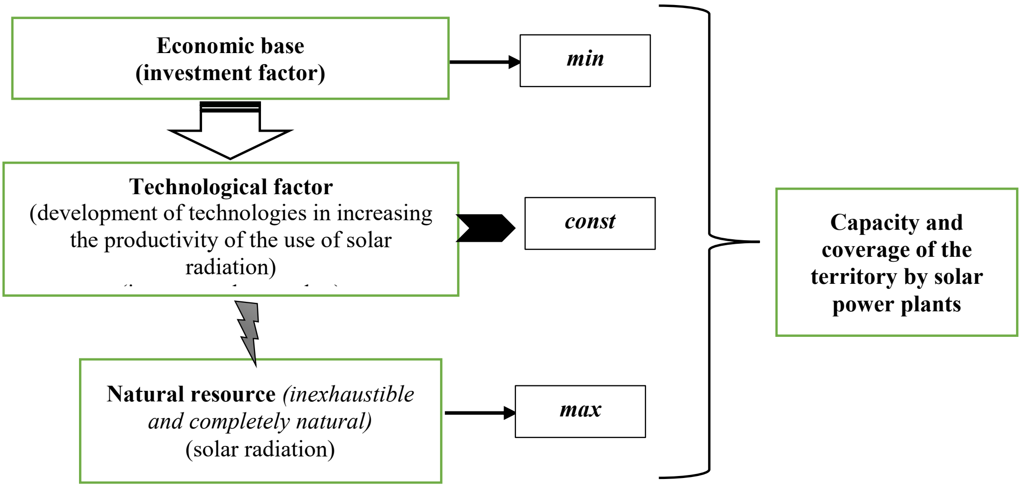

Fig. 1. The concept of the economic and technological model of solar generation

Rys. 1. Koncepcja modelu ekonomiczno-technologicznego generacji energii słonecznej

In mathematical form, this model will be formed:

$$\begin{cases} \sum_{1}^{n} I \to \min \\ \sum_{1}^{n} S \to \max \\ \sum_{1}^{n} P \to \max \end{cases}$$

where:

I – investments;
S – solar energy resource;
P – power.

Investments (I) – this variable represents the financial resources allocated to solar energy projects, including the costs of technology, installation, and maintenance.

Solar energy resource (S) – this captures the potential of solar energy available for conversion into electricity or heat, which is influenced by factors such as geographical location, weather patterns and technological efficiency in harnessing solar radiation.

Power output (P) – the amount of electricity or heat generated by solar power systems. This is a direct measure of the system's productivity and efficiency.

The total power P = $\int(I;S)$ and the technological factors remain constant. For the mathematical solution of this model, the approximation method is applied to simplify the model effectively. In mathematics, the approximation method is an approach to the approximate expression of complex mathematical objects, such as functions or numbers, by other simpler objects that are easier to examine or calculate. The main idea is to replace a complex object with a simpler but close enough value. This is done in order to facilitate mathematical calculations and analysis, mainly when the exact solution or expression for the object consists of complex formulas or does not have an analytical expression. In mathematics, the approximation method is an approach to the approximate expression of complex mathematical objects, such as functions or numbers, by other, simpler objects that are easier to examine or calculate. The main idea is to replace a complex object with a simpler but close enough value. This is done to facilitate mathematical calculations and analysis, mainly when the exact solution or expression for the object consists of complex formulas or when it does not have an analytical expression.

The model is built for optimization purposes, aiming to identify the most efficient and cost-effective strategies for solar energy generation. It seeks to inform decision-making in the deployment and management of solar power technologies by illustrating how different levels of investment and resource management can impact power output.

A few publications have evaluated the development of renewable energy, particularly solar energy, from the perspective of a critical approach (Lu et al. 2020; Zachary and Goldberg 2023; Maka and Alabid 2022). Our research is an element of assessing the vision of the development of solar energy from the perspective of using a potential natural resource (solar radiation). In general, several authors have noted that the use of this source is only 2% (Vostriakova 2021; Podolchak et. al. 2023). This study evaluated this problem in comparison with the invested and implemented investments. In accordance with this, a vision was formed in which solar energy was being introduced rather slowly and was not generally available.

3. Results

The solution of the model is identified through the determination of the relevant economic and technological indicators, which is calculated based on the initial data (Table1).

Several indicators can be calculated based on the initial data. In particular, the indicator of the capacity of solar power plants per invested dollar. The technological indicator is the power of solar power plants per unit of solar energy. According to our prediction, the power per dollar should be minimized and the power per solar energy unit should be maximized. Therefore, these coefficients are correlated through the difference (coefficient of economic and technological impact on the development of solar power plants). The corresponding calculations are presented in tabular form, with states ranked according to this indicator in Table 2.

Table 1. Characteristics of solar energy in 2022

Tabela 1. Charakterystyka wykorzystania energii słonecznej w 2022 r.

Region	Total area [mln km^2]	Population [mln]	Solar installation [GW]	Number of residences powered by solar energy [mln]	Money invested in solar sector [$ bln]	Solar radiation [kWh/m^2/day]
EU	4.233	446.7	41.4	12.4	0.132	4.65
China	9.597	1425.9	87.4	1.864	44	4.45
USA	9.834	333.3	20.2	27.5	25.5	5

Source: own study based on Wasson and Novak (2023); Eurostat (2023); IRENA (2023).

Table 2. Evaluating the interplay between economic and natural factors in creating solar energy development in 2022

Tabela 2. Ocena wzajemnego oddziaływania czynników ekonomicznych i naturalnych w kształtowaniu rozwoju energetyki słonecznej w roku 2022

Region	Power indicator of solar power plants per invested dollar	Power indicator per unit of solar radiation	Coefficient of economic and technological impact on the development of solar energy
EU	8.903	313.64	0.03
China	19.64	1.99	9.89
USA	4.04	0.79	5.10

Source: own study.

The most significant trends in solar energy development in quantitative terms are observed in China, including the capacity of solar energy, the number of households and the level of invested funds. However, the quality characteristics vary considerably across the three world regions. China has the lowest share of households using solar energy, although this indicator is unreliable because a large part of China's territory is highlands, deserts and mountain ranges (80% of the population lives in 10% of the country's territory). The use of areas for solar energy is highest in the US States and lowest in China, indicating uninhabited areas. US households use solar energy the most (8.3%), while only 2.8% use solar energy in EU countries. For China, this figure is 0.13%.

Regarding the power of solar radiation, China occupies a leading position with an indicator of 19.64. In EU countries, this indicator is 8.9. In the USA, this is the lowest indicator (4.04). The solar activity in the USA averages 5 kWh/m^2/day, which is the highest among these regions. The EU and China are more or less the same geographical area for providing solar radiation with indicators of 4.45–4.65 kWh/m^2/day. The return on investment in energy capacity is the highest in the EU (3313.64) and the lowest in the USA (0.8). China reached an indicator of 2 and this means that EU countries use solar energy with the lowest investment amount.

Table 3. Share of solar energy use by households in 2022

Tabela 3. Udział energii słonecznej w podziale na gospodarstwa domowe w roku 2022

Region	Population [mln]	Number of Residences Powered by Solar [mln]	Coefficient of economic and technological impact on the development of solar energy	Share of households that use solar energy [%]
EU	446.7	12.4	0.03	2.776
China	1,425.9	1.864	9.89	0.131
USA	333.3	27.5	5.10	8.251

Source: own study.

In general, in the qualitative analysis, China has the highest return on investment in solar energy because the coefficient of economic and technological impact on solar energy development is 9.89. For the USA, this indicator is twice as low. For Europe, it is 0.03. This distribution indicates that solar energy is a priority for China and is marked by a scale manifested in implementing a unified national policy. For EU countries, implementing such a policy is complicated because each country has the right to implement the concept of solar energy development independently within the framework of a single European strategy. In addition, in financial terms, the allocation of funds for EU members for solar energy is uneven.

The analysis enables a more in-depth clarification of the trends in the development of modern solar energy in leading economically developed regions of the world. The indicators differ significantly, but they allow us to evaluate the political and economic factors of implementing a global approach to developing alternative energy by using solar energy.

4. Discussion

Solar-powered green generation has recently gained prominence as a possible means of meeting global energy demands. An essential field of research is evaluating the potential of this technology for advancing renewable energy sources. Research has demonstrated that solar energy can produce a sizable amount of electricity while cutting greenhouse gas emissions. Solar energy is becoming increasingly feasible and affordable for many nations due to technological advancements and falling solar panel costs. To create a sustainable energy future, analyzing the possibilities of a solar-driven green generation is imperative.

The calculations in this study provide a broader understanding of the trends in solar energy development. Generally, the accepted views and expert statements (Peidong et al. 2009; Wen et al. 2021; Zhou et al. 2022; Maka and Alabid 2022) that China is the world leader in the implementation of solar energy have not been confirmed by our calculations. According to some criteria (investment volume), China exceeds the EU and the USA indicators. This calculation shows that each specified region is a leader in a separate direction.

The EU has the most significant return on investment, the USA has the largest share of solar electricity use, and China has the most significant coefficient of economic and technological impact on solar energy development.

It should be noted that the analysis of the solar energy development model has certain limitations. In particular, there was a failure to consider the actual area of solar plants placement. In addition, this limitation also applies to the solar radiation index, which is taken as the average annual value. In economic terms, the volumes of solar energy investments are taken as a general indicator and do not determine the level of their allocation to the innovative and technological aspects of improving solar energy and financing the implementation of specific projects.

Further research should focus on developing specific initiatives and strategies for each region with consideration to their unique characteristics and potential. This will help develop effective and adapted solutions to specific conditions for solar energy development, contributing to creating a stable and ecologically balanced energy system.

Conclusions

This study is specific because it allowed the characterization of solar energy development in a regional context in the developed regions of the world. The assessment was performed at the expense of economic and technological modelling based on economic factors in the form of investment and the resource potential of solar radiation. The USA, China, and the EU were chosen as regions with sufficient solar radiation and significant economic potential, which in political terms, clearly implement the concept of sustainable development in the field of energy and ecology.

The approximation method was used to solve the mathematical model, which made it possible to use two indicators: the coefficient of economic and technological influence on the development of solar energy, and the share of households that use solar energy. Such modelling made it possible to analyze the indicated world regions and identify their specific features in the development of solar energy. Such features were the return on investment due to the capacity of solar energy and the share of its use by the population. It is the most powerful use of solar energy in China, with a figure of 19.6%, while the US has only 4.04% and the EU has almost 9%. According to the criterion of economic and technological influence on solar energy development, China occupies a leading position (9.89%), whereas the EU has only 0.03%. Thus, solar energy is currently not an attractive area for business and needs to prioritize the development of the EU economy, which is confirmed by insignificant investment flows compared to China and the USA.

The further conceptual development of solar energy is possible due to the transition to the next stage, which is characterized by the so-called innovative and technological breakthrough and will allow the maximum amount of solar radiation to be used.

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Analiza globalnego potencjału gospodarczego i technologicznego generacji fotowoltaicznej w rozwoju energetyki odnawialnej

Streszczenie

Rozwój energetyki słonecznej jest integralną częścią oceny odnawialnej „zielonej" energii w rozumieniu koncepcji zrównoważonego rozwoju. W opracowaniu skupiono się na specyfice wdrażania energetyki słonecznej na przykładzie USA, UE i Chin, ujętej przedmiotowo w powiązaniu ze specyfiką sytuacji geograficzno-terytorialnej i klimatyczno-przyrodniczej. Oryginalność badań polega na podejściu do modelowania realizacji energetyki słonecznej z uwzględnieniem głównych czynników ekonomicznych, technologicznych i zasobowych. Celem niniejszego opracowania jest ocena trendów w rozwoju i wdrażaniu regionalnej energetyki słonecznej, której rozwój odbywa się wyłącznie kosztem inwestycji prywatnych, a wsparcie państwa jest minimalne. Zatem moc zainstalowanych elektrowni słonecznych w stosunku do wielkości inwestycji wykazuje wysoką korelację. Z punktu widzenia działalności gospodarczej energia słoneczna w analizowanych regionach jest wykorzystywana przez gospodarstwa domowe w niewielkich ilościach. Największe wykorzystanie energii słonecznej przez gospodarstwa domowe występuje w USA, gdzie wskaźnik ten wynosi 8,3%, a najniższe w Chinach (0,13%). Z analizy wynika, że w chwili obecnej energetyka słoneczna nie jest priorytetem w rozwoju energetyki, a jedynie uzupełnieniem. Dalszy rozwój energetyki słonecznej możliwy jest dzięki innowacjom technologicznym, które zwiększą efektywność wykorzystania promieniowania słonecznego. W publikacji wykazano, że największe wykorzystanie energii słonecznej występuje w Chinach (19,6%), podczas gdy w USA tylko 4,04%, a w UE prawie 9%. Według kryterium wpływu ekonomiczno-technologicznego na rozwój energetyki słonecznej, Chiny zajmują czołową pozycję (9,89%), podczas gdy UE ma zaledwie 0,03%. Tym samym energetyka słoneczna nie jest obecnie atrakcyjnym obszarem dla biznesu i wymaga priorytetowego traktowania w gospodarce UE, co potwierdzają niewielkie napływy inwestycji w porównaniu do Chin i USA.

Słowa kluczowe: energia słoneczna, zrównoważony rozwój, model ekonomiczno-technologiczny wytwarzania energii słonecznej, promieniowanie słoneczne, instalacja fotowoltaiczna