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CHALLENGES IN EFFECTIVELY MANAGING THE DEVELOPMENT OF SOLAR ENERGY IN THE EXAMPLE OF THE UNITED STATES

The study focuses on the specifics of the implementation of solar energy in the regions of the world economic leader. The USA was taken as the object of the study in connection with the specifics of its geographic-territorial and climatic-natural position. The conducted research was based on the approach of modelling the implementation of solar power generation, taking into account economic, technological and resource factors. The purpose of the study purpose of the article is to examine trends in the development and use of solar energy in the United States, taking into account management methods and efficiency improvements. It has been proven that the development of solar energy is carried out exclusively at the expense of private investment, the state support is minimal. Therefore, the power of installed solar power plants in relation to the volume of investments shows a high correlation. From the point of view of economic activity, solar energy is used by households in small amounts, on average in the USA at the level of 3.6%. Regionally, it is quite uneven from 24% to 0.2%. The greatest development of solar energy is provided in Hawaii and California. The conducted analysis allows us to indicate that at the moment solar energy does not determine priorities for business and is not a key branch of the US economy. Further development of solar energy is possible due to technological innovations that will contribute to increasing the efficiency of using solar radiation.

Keywords: solar energy; solar radiation; investments in solar energy; national solar energy management.

Formulation of the problem. The implementation and management of renewable energy sources have become crucial aspects of the modern energy sector, as global leaders continuously seek ways to enhance efficiency and sustainability in energy production. One of the most promising directions is solar energy, which plays a significant role in minimizing environmental impact and ensuring sustainable development. Managing the implementation of solar generation requires a comprehensive approach aimed at maximizing production and consumption efficiency, ensuring system stability, and fostering balanced sectoral development.

Furthermore, the rapid expansion of solar energy infrastructure presents challenges in terms of grid integration, storage capabilities, and regulatory frameworks. Managing the intermittency of solar power generation, optimizing the deployment of solar panels, and ensuring equitable access to solar energy resources are additional complexities that must be addressed. The transition to solar energy requires significant investment in research and development, as well as in workforce training and education. Balancing these various factors while maximizing the benefits of solar energy adoption poses a complex management challenge for policymakers, energy companies, and other stakeholders. Therefore, a comprehensive examination of the trends and challenges in solar energy implementation in a leading economy like the United States is essential for informing effective management strategies and fostering sustainable energy systems.

In this context, it is important to explore the trends in solar energy development using the example of advanced economies such as the United States, in order to identify optimal management strategies and achieve maximum efficiency in solar energy utilization.

Analysis of recent research and publications. Over the past decades, solar energy has garnered significant interest as a vital source of renewable energy. Examining the example of the United States of America (USA), one of the world's largest economies and a leader in various technological spheres, allows us to understand the essence of challenges in effectively managing the development of solar energy.

Contemporary researchers have extensively explored the efficiency of solar energy [1–3]. They delve into various aspects, including technological advancements, policy frameworks, economic feasibility, environmental impact, and societal acceptance. Studies often highlight the importance of technological innovation in improving the efficiency of solar panels, storage systems, and distribution networks. Additionally, scholars analyze the effectiveness of government incentives, regulatory frameworks, and subsidies in promoting the adoption of solar energy solutions [4–5]. Discussions also encompass the integration of solar power into existing energy grids, the scalability of solar projects, and the potential for decentralized energy generation. Overall, contemporary literature underscores the multifaceted nature of enhancing the efficiency of solar energy and emphasizes the need for interdisciplinary approaches to address these challenges [6].

However, technological advancements and policy incentives alone may not be sufficient to ensure the widespread adoption and effective management of solar energy. Other factors such as public awareness, social acceptance, market dynamics, and infrastructure development play crucial roles in shaping the success of solar initiatives. Moreover, challenges such as intermittency, energy storage limitations, land use conflicts, and grid integration complexities need to be addressed to fully harness the potential of solar energy. Therefore, a comprehensive approach that considers not only technological and policy aspects but also a social, economic, and environmental dimension is essential for overcoming these barriers and promoting the effective management of solar energy.

Formulating the article goals. The purpose of the article is to examine trends in the development and use of solar energy in the United States, taking into account management methods and efficiency improvements. According to the purpose, the following tasks are proposed:

– analyze the current state and potential of solar energy development in the United States, considering its economic development and investment volumes in the sector.

– investigate the impact of different climate zones across the continental territory of the USA on the effectiveness of solar energy utilization and identify the potential for solar technology development in each region.

– evaluate the key economic, technological, environmental, and political factors influencing solar energy development in the USA to formulate an effective model for the industry's growth.

Outline of the main research material. The object of research is solar energy in the United States. The choice of country for analysis is influenced by several factors:

– The highest level of economic development in the country, indicated by the volumes of investment in the solar energy sector.

– The numerous states across the continental territory, which are situated in five climate zones of the continent: polar, subpolar, temperate, subtropical, and tropical. This allows for an assessment of the impact of solar radiation on the autonomous sphere of renewable energy.

– Solar radiation serves as the fundamental source of solar electricity generation, thereby enabling significant potential and capacity for solar energy systems with minimal capital investment. Additionally, concerning the consumption of such electricity, it is possible to fully replace traditional energy sources by households.

The economic-technological model of solar power plants formulated by Koval et. al. [7] was employed in the research. The solution of the model will be carried out through the determination of the relevant economic and technological indicators, which will be calculated from the initial data (Table 1).

Table 1

Characteristics of the state of US solar energy in 2023 by state

State	Population, mln	Solar installation, MW	Number of Residences Powered by Solar, mln	Money Invested in Solar, mln dol.	Tax Incentive	Solar Radiation (kWh / m^2 / day)
Alaska	0,733583	15	0,001496	32	no	3,65
Texas	30,02957	13947	1,082407	11200	no	5,21
California	39,02934	35950	8,054837	73700	no	5,75
Montana	1,122867	125	0,016699	160	yes	4,91
New Mexico	2,113344	1289	0,287628	2300	yes	6,49
Arizona	7,359197	5743	0,810751	13900	yes	6,68
Nevada	3,177772	4967	0,067207	7800	no	6,29
Colorado	5,839926	2236	0,034072	4300	no	5,85
Oregon	4,240137	1293	0,144197	1800	no	4,31
Wyoming	581,381	143	0,010586	153	no	5,53
Michigan	10,03411	927	0,083045	714	no	4,38
Minnesota	5,717184	1700	0,215771	2400	no	4,56
Utah	3,3808	2616	0,442889	3500	yes	5,51
Idaho	1,939033	608	0,079587	817	yes	5,48
Kansas	2,93715	97	0,012559	134	no	5,06
Nebraska	1,967923	73	0,07931	91	no	5,01
South Dakota	0,909824	2	0,000213	4	no	5
Washington	7,785786	314	0,025938	707	no	4,87
North Dakota	0,779261	1	0,000113	2	no	4,65
Oklahoma	4,0198	93	0,009557	131	no	5,41
Missouri	6,177957	358	0,033187	774	no	4,93
Florida	22,24482	9012	0,842897	9600	no	5,35
Wisconsin	5,892539	855	0,071572	644	no	4,47
Georgia	10,91288	4299	0,00035916	3700	no	5,26
Illinois	12,58203	1465	0,089781	1400	no	4,74
Iowa	3,200517	510	0,054792	568	yes	4,72
New York	19,67715	3,992	0,000817	14800	no	4,62
North Carolina	10,69897	7935	0,859707	10100	no	5,14
Arkansas	3,045637	579	0,004355	486	no	4,97
Alabama	5,074296	578	0,030531	341	no	5,2

Continuation of the table 1

Louisiana	4,590241	208	0,018248	465	no	5,14
Mississippi	2,940057	320	0,034294	354	no	5,1
Pennsylvania	12,97201	936	0,096859	2900	no	4,62
Ohio	11,75606	890	0,063137	1300	no	4,48
Virginia	8,683619	3790	0,280993	2800	no	4,97
Tennessee	7,051339	608	0,035968	877	no	4,81
Kentucky	4,51231	74	0,006241	116	no	4,68
Indiana	6,833037	1366	0,111763	1200	no	4,6
Maine	1,38534	486	0,044523	349	no	4,48
South Carolina	5,282634	1936	0,222247	2300	yes	5,19
West Virginia	1,775156	20	0,001134	33	no	4,5
Maryland	6,16466	1459	0,153463	3900	no	5,5
Hawaii	1,440196	1477	0,356477	4500	yes	5,14
Massachusetts	6,981974	3927	0,545258	9100	yes	4,57
Vermont	0,647064	401	0,069026	729	no	4,28
New Hampshire	1,395231	175	0,021763	351	no	4,52
New Jersey	9,261699	3992	0,586709	14800	no	4,67
Connecticut	3,626205	1131	0,130963	2400	no	4,53
Delaware	1,018396	171	0,018101	504	no	4,81
Rhode Island	1,093734	576	0,073698	644	no	4,59

Based on the results of the initial data, several indicators were calculated:

- indicator of the capacity of solar power plants per one invested dollar;
- indicator of power per unit of solar radiation;
- coefficient of economic and technological influence on the development of solar energy.

The calculations are carried out in tabular form, and ranking of the states according to this indicator is performed (Table 2).

Table 2

Assessment of the dependence of the development of solar energy in the US states on economic and natural factors in 2023

State	Indicator of the capacity of solar power plants per one invested dollar	Indicator of power per unit of solar radiation	Coefficient of economic and technological influence on the development of solar energy	Groups of states by potential development of solar energy
California	6252,17	0,49	12817,39	A
New York	0,86	0,00	3203,46	AA
New Jersey	854,82	0,27	3169,16	
Texas	2676,97	1,25	2149,71	AAA
Arizona	859,73	0,41	2080,84	
Massachusetts	859,30	0,43	1991,25	
North Carolina	1543,77	0,79	1964,98	
Florida	1684,49	0,94	1794,39	
Nevada	789,67	0,64	1240,06	

Continuation of the table 2

Hawaii	287,35	0,33	875,49	B
Colorado	382,22	0,52	735,04	
Maryland	265,27	0,37	709,09	
Georgia	817,30	1,16	703,42	
Utah	474,77	0,75	635,21	
Pennsylvania	202,60	0,32	627,71	
Virginia	762,58	1,35	563,38	
Connecticut	249,67	0,47	529,80	
Minnesota	372,81	0,71	526,32	
South Carolina	373,03	0,84	443,16	
Oregon	300,00	0,72	417,63	
New Mexico	198,61	0,56	354,39	BB
Illinois	309,07	1,05	295,36	
Ohio	198,66	0,68	290,18	
Indiana	296,96	1,14	260,87	
Tennessee	126,40	0,69	182,33	
Vermont	93,69	0,55	170,33	
Michigan	211,64	1,30	163,01	
Missouri	72,62	0,46	157,00	
Idaho	110,95	0,74	149,09	
Washington	64,48	0,44	145,17	
Wisconsin	191,28	1,33	144,07	
Rhode Island	125,49	0,89	140,31	
Iowa	108,05	0,90	120,34	
Delaware	35,55	0,34	104,78	
Arkansas	116,50	1,19	97,79	
Louisiana	40,47	0,45	90,47	
Maine	108,48	1,39	77,90	C
New Hampshire	38,72	0,50	77,65	
Mississippi	62,75	0,90	69,41	
Alabama	111,15	1,70	65,58	
Montana	25,46	0,78	32,59	D
Wyoming	25,86	0,93	27,67	
Kansas	19,17	0,72	26,48	
Kentucky	15,81	0,64	24,79	
Oklahoma	17,19	0,71	24,21	
Nebraska	14,57	0,80	18,16	
Alaska	4,11	0,47	8,77	E
West Virginia	4,44	0,61	7,33	
South Dakota	0,40	0,50	0,80	F
North Dakota	0,22	0,50	0,43	

According to this calculation, the states are divided into the corresponding groups according to the potential development of solar energy from "A" to "F". In general, this calculation notes that the higher the level of investments in energy, the higher the position of the state in this rating, which is led by California with investments of 73.7 billion dollars. A fairly clear dependence of the rating on solar radiation is not observed. The sunniest states are Arizona, Nevada, and New Mexico, which have a solar radiation index of more than 6 kW/m^2, but these states are placed quite far apart in the ranking. So, Arizona occupies the fifth position with investments in solar energy of 13.9 billion dollars. The sunniest state of New Mexico, with a solar radiation index of 6.49 kW/m^2, was included in the BB group, while the amount of investment compared to Nevada is three times smaller.

The greatest solar activity ensures that, with relatively small investments, the states are in the leading positions in terms of the coefficient of economic and technological influence on the development of solar energy. The states that have a significant natural potential of solar radiation are in groups with a rather low coefficient of economic and technological influence on the development of solar energy. This is due to the fact that the volume of investments is small. In addition, a rather strange situation exists with Alaska and the two Dakota states. The Dakota states, which have significant solar potential, occupy the last positions of the rating. Investments are extremely small, from 18 to 73 thousand dollars. This is due to the specifics of these states, which historically became reservation zones for the continent's indigenous Indian population. The state of Alaska, due to significant investments, with the lowest solar radiation rate, ranks fourth from the bottom.

Thus, the solar activity of the territory is not the root cause of the development of solar energy, but remains an important factor. The largest share of providing the territory of America with solar electricity belongs to the state of Hawaii, 24.75% (Table 3). This pattern is explained by the Pacific geographical location and tropical climatic zone of the island state.

Table 3

Share of solar energy use by households in US states in 2023

State	Population, mln	Number of Residences Powered by solar, mln	Coefficient of economic and technological influence on the development of solar energy	Share of households using solar energy, %
Alaska	0,733583	0,001496	8,77	0,20
Texas	30,029572	1,082407	2149,71	3,60
California	39,029342	8,054837	12817,39	20,64
Montana	1,122867	0,016699	32,59	1,49
New Mexico	2,113344	0,287628	354,39	13,61
Arizona	7,359197	0,810751	2080,84	11,02
Nevada	3,177772	0,067207	1240,06	2,11
Colorado	5,839926	0,034072	735,04	0,58
Oregon	4,240137	0,144197	417,63	3,40
Wyoming	581,381	0,010586	27,67	0,002
Michigan	10,034113	0,083045	163,01	0,83
Minnesota	5,717184	0,215771	526,32	3,77
Utah	3,3808	0,442889	635,21	13,10

Continuation of the table 3

Idaho	1,939033	0,079587	149,09	4,10
Kansas	2,93715	0,012559	26,48	0,43
Nebraska	1,967923	0,07931	18,16	4,03
South Dakota	0,909824	0,000213	0,80	0,02
Washington	7,785786	0,025938	145,17	0,33
North Dakota	0,779261	0,000113	0,43	0,01
Oklahoma	4,0198	0,009557	24,21	0,24
Missouri	6,177957	0,033187	157,00	0,54
Florida	22,244823	0,842897	1794,39	3,79
Wisconsin	5,892539	0,071572	144,07	1,21
Georgia	10,912876	0,00035916	703,42	0,002
Illinois	12,582032	0,089781	295,36	0,71
Iowa	3,200517	0,054792	120,34	1,71
New York	19,677151	0,000817	3203,46	0,004
North Carolina	10,698973	0,859707	1964,98	8,04
Arkansas	3,045637	0,004355	97,79	0,14
Alabama	5,074296	0,030531	65,58	0,60
Louisiana	4,590241	0,018248	90,47	0,40
Mississippi	2,940057	0,034294	69,41	1,17
Pennsylvania	12,972008	0,096859	627,71	0,75
Ohio	11,756058	0,063137	290,18	0,54
Virginia	8,683619	0,280993	563,38	3,24
Tennessee	7,051339	0,035968	182,33	0,51
Kentucky	4,51231	0,006241	24,79	0,14
Indiana	6,833037	0,111763	260,87	1,64
Maine	1,38534	0,044523	77,90	3,21
South Carolina	5,282634	0,222247	443,16	4,21
West Virginia	1,775156	0,001134	7,33	0,06
Maryland	6,16466	0,153463	709,09	2,49
Hawaii	1,440196	0,356477	875,49	24,75
Massachusetts	6,981974	0,545258	1991,25	7,81
Vermont	0,647064	0,069026	170,33	10,67
New Hampshire	1,395231	0,021763	77,65	1,56
New Jersey	9,261699	0,586709	3169,16	6,33
Connecticut	3,626205	0,130963	529,80	3,61
Delaware	1,018396	0,018101	104,78	1,78
Rhode Island	1,093734	0,073698	140,31	6,74

Regarding the continental territory, the state of California with a share of 20.64% occupies the first position due to significant investments. In addition, it is the most populous US state. In general, the average indicator of the share of providing households with solar energy in the USA is 3.64%. The sunniest states are Arizona (6.69 Number of Residences Powered by Solar, million), New Mexico (6.49) and Nevada (6.29). Arizona and New Mexico stand out with indicators of 11.017% and 13.61%, respectively. Nevada has a rate of 2.115%. Such a low share is explained by the location of the nuclear test site and the fact that the capital of the state was characterized as a concentration of legalized gambling business. In addition, more than 80% of the state's territory belongs to the federal government. Favorable climatic conditions for the development of solar energy in Nevada are found only in the southern part of the state and are characterized by short and mild winters.

In general, solar energy in the US does not have a dominant position in the use of households and does not reach the level of 5% of the use of solar radiation. Wyoming has the lowest share of solar energy use at -0.002%. The reason for such meager use is the topography (half of the state is covered by mountains and highlands). In addition, a significant area belongs to the federal government and is used for national parks and recreation areas, fish hatcheries, and forest parks.

Thus, solar energy is developing in the USA at the expense of capital investments. Investment promotion is followed only in a few states – Montana, New-Mexico, Arizona, Utah, Idaho, Iowa, South Carolina, Massachusetts, and Hawaii. Other states do not have the corresponding benefits and development occurs at the expense of business structures.

Conclusion. This study made it possible to characterize the development of solar energy in the most advanced economy of the USA. The assessment was carried out at the expense of economic and technological modelling, which is based on the economic factor in the form of investment and the resource potential of solar radiation. The USA was chosen as a country with high solar radiation and a wide range of climatic conditions. To solve the mathematical model, the approximation method was used, 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 provided the ability to rank states and identify groups of states based on potential solar energy development. The highest development of solar energy is characteristic of California, which achieved without state incentives, the lowest – for the Dakota states. The gap reaches tens of thousands of orders of magnitude.

As for the share of solar energy use by households, its distribution is relatively insignificant. The highest figures are for Hawaii (24.7%) and California (20.6%), and the average figure for the entire territory of the US for the use of solar energy for households is 3.6%. Thus, solar energy is currently not an attractive area for business and does not determine the priority of the development of the US economy. Its further development is potentially possible due to technological innovations, which should provide a more powerful return from solar radiation.

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ПРОБЛЕМИ ЕФЕКТИВНОГО УПРАВЛІННЯ РОЗВИТКОМ СОНЯЧНОЇ ЕНЕРГЕТИКИ НА ПРИКЛАДІ США

Дослідження акцентує увагу на специфіці впровадження сонячної енергетики у розрізі регіонів світового економічного лідера. США взято за об'єкт дослідження у зв'язку з специфікою його географічно-територіального та кліматично-природного положення, що створює унікальні умови для вивчення різноманітних аспектів впровадження сонячної енергетики та її впливу на енергетичну систему країни. Проведене дослідження базується на моделюванні впровадження сонячної електрогенерації з врахуванням економічного, технологічного та ресурсного чинників. Мета статті полягає у дослідженні тенденцій у розвитку та використанні сонячної енергії у Сполучених Штатах, беручи до уваги методи управління та підвищення ефективності. Доведено, що розвиток сонячної енергії здійснюється виключно за рахунок приватного інвестування, державна підтримка є мінімальною. Тому потужність впроваджених сонячних електростанцій відносно обсягу вкладених інвестицій відзначає високий кореляційний зв'язок. З позиції господарської діяльності, сонячна енергетика використовується домашніми господарствами у незначних обсягах, в середньому по США на рівні 3,6%, у регіональному розрізі досить нерівномірно від 24% до 0,2%. Найбільший розвиток сонячної енергетики забезпечений на Гаваях та у Каліфорнії. Загалом визначено, що існують певні проблеми, які ускладнюють управління ефективним розвитком сонячної енергетики США. Зокрема, залежність від приватних інвестицій призводить до

нерівномірного розподілу ресурсів та обмежує доступ до сонячної енергії для деяких груп населення. Відсутність значної державної підтримки гальмує швидкість розвитку і впровадження сонячних технологій. Проведений аналіз дозволяє вказати, що на даний момент сонячна енергетика не визначає пріоритети для бізнесу та не є ключовою галуззю економіки США. Подальший розвиток сонячної енергетики можливий за рахунок технологічних інновацій, які сприятимуть збільшенню ефективності використання сонячного випромінювання.

Ключові слова: сонячна енергетика; сонячне випромінювання; інвестиції в сонячну енергетику; національне управління сонячною енергетикою.

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