Perspectives on Solar Energy. Technology Analysis

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***Abstract*—Recently, interest in the use of solar energy has increased significantly, as it allows to expand energy resources, save a significant amount of fuel, does not pollute the environment and acts as a reliable maneuverable reserve of large energy. Traditionally, solar energy has been considered accessible only to some regions with the largest amount of solar energy and developed economies. It is of interest to study the prospects for solar energy development in the world. Changes in the economic and political spheres of different countries have led to a change in the situation. Significant development of technologies in this field allows the use of solar energy for the production of electrical and thermal energy in different climatic belts. The latest developments are also aimed at increasing the efficiency of solar energy installations and eliminating disadvantages such as large areas for solar power plants, variation of illumination of solar panels during the day. New promising developments, on which scientists from all over the world are working, allow us to hope for an increase in the share of renewable energy sources in the energy sector**

***Keywords*—Solar energy, Solar panel, Concentrator moduleTracker, Solar collector**

I. INTRODUCTION

Increasing requirements to reduce the environmental load from the fuel and energy complex make the development of non-conventional and renewable energy sources justified. Recently, interest in the use of solar energy has increased significantly, as it allows to expand energy resources, save a significant amount of fuel, does not pollute the environment and acts as a reliable maneuverable reserve of large energy [1-3]. Obtaining electrical and thermal energy using various varieties of solar panels and collectors is becoming more and more popular in the world. Solar power plant can be used both for the needs of the state, municipal authorities, commercial enterprises, and at home. For example, it can take some of the load off other energy sources and save money on electricity. In general, diversification of energy sources increases energy security. Global renewable energy investment in 2023 is up 24% from 2021 to more than $1.7 trillion. Carbon energy investment is growing at a more modest rate of 15% from 2021 to just over $1 trillion, according to the International Energy Agency's (IEA) Energy Investment Outlook of May 25, 2023. "For every dollar invested in fossil fuels, there is now about $1.7 in clean energy. Five years ago that ratio was one to one. One shining example is investment in solar power, which for the first time has exceeded investment in oil production," said Fatih Birol, the IEA's executive director, quoted by the agency. In 2023, $380 billion will be invested in solar generation [4, 5]. In 2023, more than 360 GW of solar generation was commissioned globally (Figure 1).

Rethink Energy reports that about 92 GW of solar capacity has been installed globally in the second quarter of 2023 alone. Of that, 55%, or 51 GW is in China.

From an environmental point of view, solar power is not entirely straightforward. It does not emit greenhouse gases and other harmful substances into the atmosphere during operation. However, the production of photovoltaic panels involves the use of toxic substances such as cadmium, lead, gallium and even arsenic in addition to concrete, glass and steel, as well as expensive silicon. Thus, the production itself has a tangible carbon footprint. This challenge does not remain without a solution. Technologies in this area are constantly developing and improving.

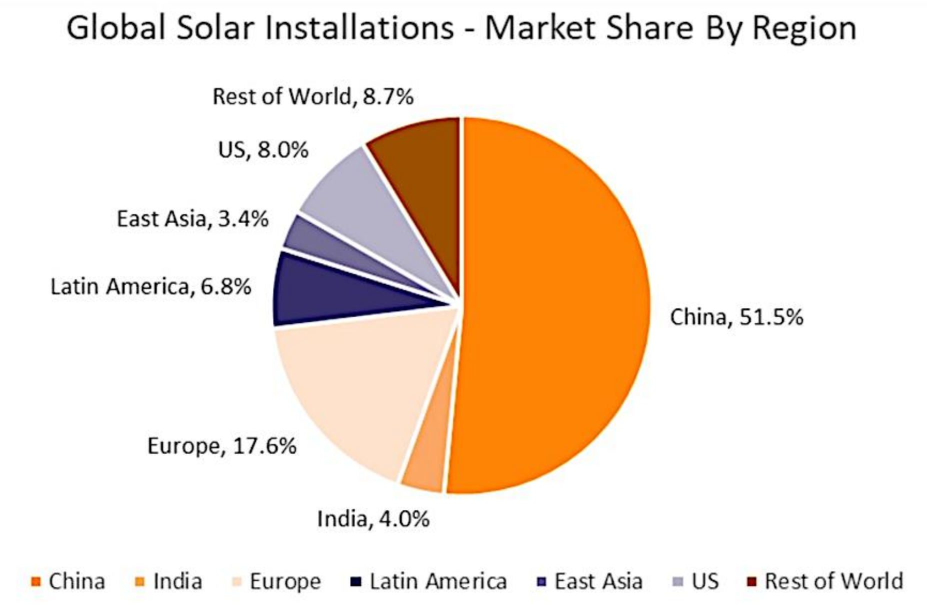

Fig. 1. Rethink Energy's 2023 solar development forecast [6]

An important factor that speaks in favor of the development of this type of energy is that the main raw material in the production of solar panels is silicon. This substance is very widespread on the planet Earth (for example, in the Earth's crust it is the second element by total mass after oxygen) and its reserves are truly great. Using it in a photovoltaic power plant can generate much more energy than, for example, when processing a similar amount of oil or gas. In this regard, some experts even call silicon "the oil of the XXI century". But there are nuances associated with its production and further processing. Production of silicon for further use as a basis for solar panels is a rather "dirty" process from the point of view of ecology, besides it is very energy-consuming. However, the final result will still be much safer for the environment, as solar panels do not pollute the environment, in contrast to energy sources based on oil and gas [7, 8].

Another peculiarity of solar energy is that it requires the use of huge areas to generate a large amount of electrical energy. For the construction of industrial solar panels it is necessary to allocate a large amount of free land. Of course, not every landscape is suitable for this purpose. That is why geographical features of a particular country influence the development of this sphere [9].

In addition, a serious problem is the utilization of photovoltaic cells at the end of their useful life (30-50 years). The International Renewable Energy Agency predicts that by 2050, 78 million metric tons of solar panels and tens of millions of tons of old turbine blades will be subject to disposal and recycling. And many companies and startups are already taking up the challenge [10, 11].

A big advantage of solar energy over traditional energy is the use of solar energy for heating and hot water supply. Two types of solar systems are used to convert solar energy into heat energy - vacuum tube and flat systems, which allow absorbing and converting up to 95% of solar radiation. The advantages of such systems are energy savings of 30 to 70 %, a long period of use of solar collector (25 years), reliability and safety of the system [12-14].

In general, the conversion of solar energy into electricity and heat has peculiarities that form the tasks of development of this direction of energy.

II. Prospects for Solar Energy

It can be argued that solar energy has great prospects. This applies both to its industrial production and to domestic production. But for this it is necessary to have suitable conditions. The use of photovoltaic stations is possible, for example, on country plots, roofs of houses, garages, etc. The price of a solar power plant will vary depending on many parameters: its size, generated and peak power and others. It can be unequivocally stated that solar panels are an excellent way to save on electricity, their payback is beyond doubt, although it will depend on certain conditions (climate, the number of sunny days per year and other factors).

Mass utilization of solar energy is limited by the high cost of solar collector and PV cells and for this reason is less competitive with other renewable and non-renewable energy sources currently available in the world. In addition, the efficiency of commercial solar modules is typically 15%, meaning that about one-sixth of the sunlight hitting the module generates electricity. Also, solar technologies are suitable for applications where direct solar radiation is high. The many types of systems being developed (including parabolic troughs, energy towers, and dish/engine systems) for different markets vary in concentration devices, energy conversion methods, storage capabilities, and other design parameters. Solar energy requires sunlight conditions specific to certain regions of the world (Fig. 2) [15].

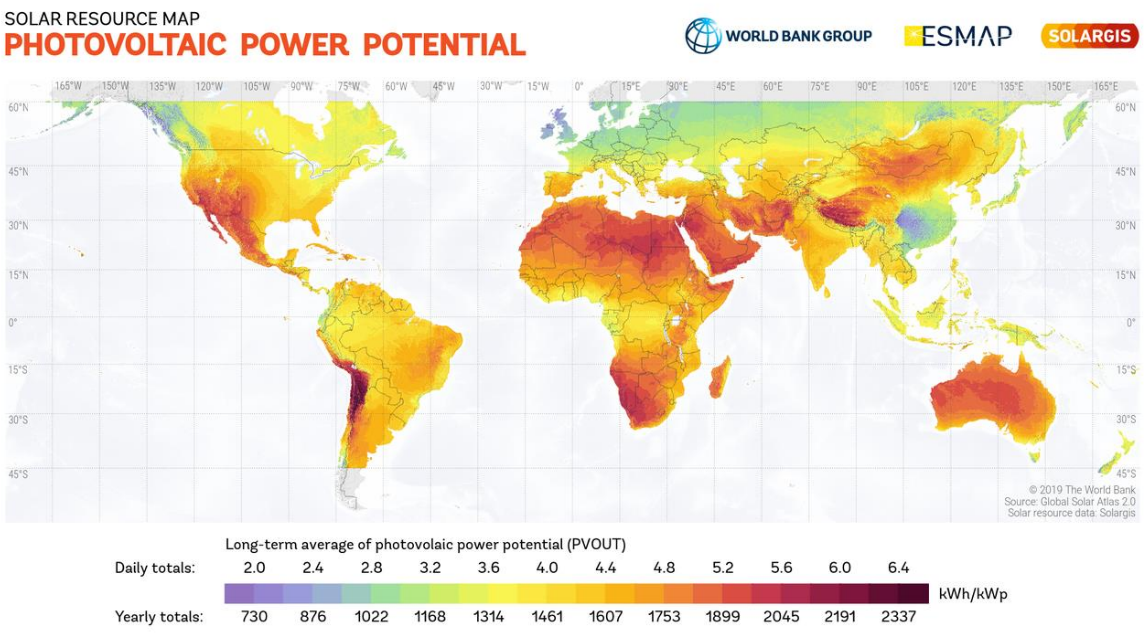

Fig. 2. Solar resource map: summary of estimated solar energy available for electricity generation and other energy applications [15]

In Europe, the best areas for solar energy development are in the Mediterranean areas covering Spain, southern France and Italy [16]. Countries with high potential tend to have low seasonality in solar PV production, meaning that the resource is relatively constant in different months of the year. A total of 86 percent of the world's population lives in 150 countries where the difference between maximum and minimum production in different seasons is less than two times and the average daily production exceeds 3.5 kWh/kWh.

In addition to solar resources, the growth potential of the solar industry is determined by electricity demand; supportive or restrictive policies; cost and payback period; weather-related risks; grid stability; predictability of solar power supply; grid interconnection providing transmission and distribution; and other technical, social, and economic factors. Consequently, solar PV can still be economically attractive in countries with relatively low solar resource potential due to the prevalence of high electricity prices or high daily peak load from industry or air conditioning [17].

Thus, the prospects for solar energy development are not only related to resource potential, but also to many other factors.

Forecasts from different authors come out a lot, and all of them prophesize a rapid growth of solar energy, but the projected rates differ. The consulting company Wood Mackenzie has published a forecast of solar energy development in the world for the current year and until 2032 (Fig. 3) [18].

Wood Mackenzie is among the "pessimists". The company's analysts estimate that in 2023 the increase in global solar power capacity will amount to "only" 270 GW (DC). This forecast is close to the IEA's estimate, which believes the world will build more than 280 GW. In 2022, 220 GW was commissioned, according to the IEA.

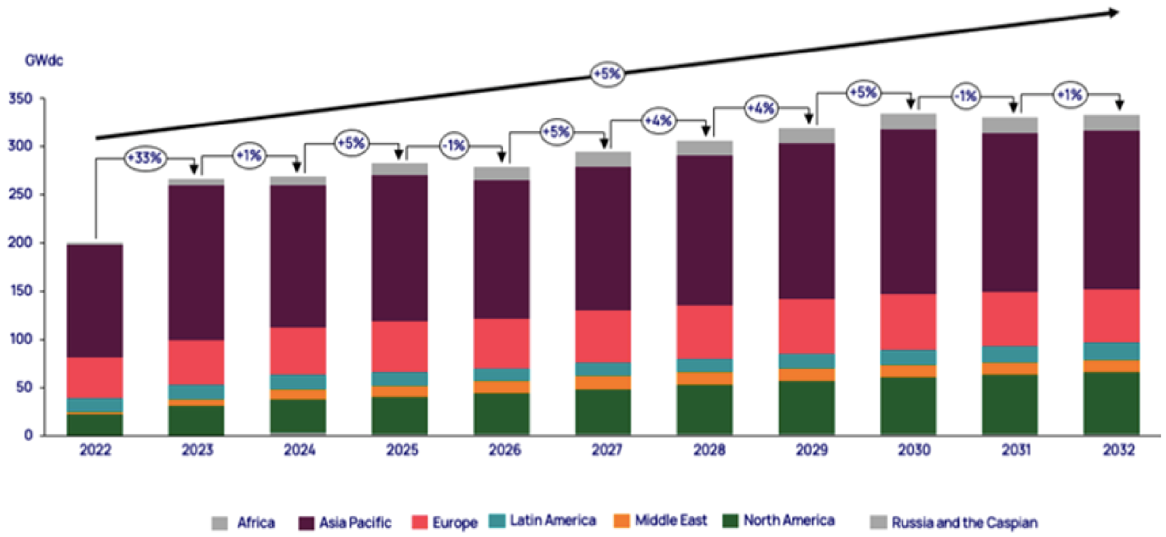

Fig. 3. Solar energy development forecast to 2032 [18]

Forecasting solar energy development by country can be complex, as it depends on many factors, including political will, economic situation, technology availability and climatic conditions. The current situation is as follows.

China is the main world leader in solar energy. The country is investing heavily in building solar farms and developing the solar industry. China is also the largest producer of solar panels in the world. The USA is actively developing solar energy in many states. Here, large solar power plant projects are underway, and tax breaks and incentives are available for installing solar panels on the roofs of private homes. India also has a strong interest in solar energy development. The country has ambitious plans to increase the share of solar energy in the overall energy system. India is actively building solar farms and incentivizing the installation of solar panels on homes and businesses. Germany is also one of the leading countries in Europe in solar energy. The development of solar energy comes from tax incentives and government programs. Japan is actively developing solar energy, especially after the Fukushima nuclear disaster in 2011. The country is building solar power plants and incentivizing the installation of solar panels on homes and buildings [19].

These are just a few examples of countries that are actively developing solar energy. However, it is worth noting that the situation may change over time, and other countries may also actively invest in solar energy development.

III. Solar energy technologies

One of the main technologies of solar energy is the installation of solar panels, which convert solar radiation into electrical energy. The composition and structure of the solar panel, its elements determine the efficiency of energy generation by the finished product. At present, silicon-based solar panels (c-Si, mc-Si and silicon thin-film batteries), cadmium telluride CdTe, copper-indium (gallium)-selenium compounds Cu(InGa)Se2, as well as concentrator batteries based on gallium arsenide (GaAs) are used to generate electrical energy.

Silicon-based solar cells account for about 85% of all solar panels produced today. Historically, this is due to the fact that silicon-based manufacturing has an extensive technology backlog and microelectronics industry infrastructure. As a result, many key microelectronics industry technologies such as silicon growth, coating, and doping have been adapted for silicon battery production with minimal change and investment. In addition, silicon is one of the most abundant elements in the Earth's crust and accounts for 27-29% by mass according to various data.

There are two main types of silicon solar cells - based on monocrystalline silicon (crystalline-Si, c-Si) and on multicrystalline (multicrystalline-Si, mc-Si) or polycrystalline silicon. In the first case, high quality (and therefore more expensive) silicon is used. The efficiency of solar cells made of monocrystalline silicon is typically 19-22%. Not so long ago, Panasonic announced the beginning of their commercial production with an efficiency of 24.5%

(which is close to the maximum theoretically possible value of ~30%) [20].

In the second case, cheaper silicon produced by the method of directed crystallization in a crucible (block-cast) is used for the production of solar cells. The resulting silicon wafers consist of many small multidirectional crystallites (typical size 1-10 mm) separated by grain boundaries. Such defects in the crystal structure lead to a decrease in efficiency - typical efficiency values of mc-Si solar cells are 14-18%. Reduced efficiency of these solar cells is compensated by their lower price, so that the price per watt of electricity produced is approximately the same for solar panels based on both c-Si and mc-Si.

However, the disadvantage of silicon is its rather low absorption coefficient, especially in the infrared wavelengths. Thus, the thickness of a silicon wafer to effectively absorb solar radiation must be a rather impressive 100-300 μm. Thicker wafers mean more material consumption, making them more expensive.

At the same time, semiconductors based on GaAs, CdTe, Cu(InGa)Se2, and even some modified forms of Si, are able to absorb the required amount of solar energy at a thickness of only a few microns. Another positive feature of solar cells based on the above semiconductors - unlike c-Si and mc-Si- is their ability not to reduce the efficiency of conversion of solar energy into electrical energy even in conditions of scattered radiation (cloudy day or in the shade).

Studies of solar cells based on solar cells began back in the 1970s due to their potential use as promising for spacecraft. And the first widespread use "on the ground" such solar cells found as power cells for pocket-sized microcalculators.

Power cells based on cadmium telluride (CdTe) are a heterostructure of thin layers of p-CdTe / n-CdS (total thickness of 2-8 microns) sputtered on a glass substrate (base). The efficiency of modern photovoltaic cells of this type is 15-17%. The main (and actually the only) manufacturer of such elements based on cadmium telluride is the American firm FirstSolar, which occupies 4-5% of the total market.

However, there are problems with both elements included in the CdTe compound. Cadmium is an environmentally harmful heavy metal that requires special handling methods and raises the difficult issue of recycling old products. In view of this, the legislation of many countries restricts the free sale of solar panels of this type to citizens (only large-scale solar power plants are built under the guarantee of recycling from the manufacturer). The second element, tellurium, is quite rare in the Earth's crust. Already at present more than half of all mined tellurium is used for manufacturing solar panels, and the prospects for increasing production are rather elusive.

Solar cells based on the copper-indium (gallium)-selenium compound Cu(InGa)Se2 (sometimes referred to as CIGS) are newcomers to the solar energy market. Despite the fact that the beginning of research on this type of cells was laid back in the mid-70s, currently commercial production is carried out only by the Japanese firm Solar Frontier KK. The efficiency of such cells can reach 20% [20].

Despite the absence of environmentally harmful elements in the composition of this compound, a significant expansion of the production of these solar modules in the future is threatened by the shortage of indium. Research is underway to replace expensive In with cheaper elements, and new products based on the compound Cu2ZnSn(S,Se)4 may soon be available.

Thin-film solar cells can also be built on the basis of silicon. One of the main advantages of such batteries is their flexibility and low weight. By using thin films of silicon, these solar cells can be fabricated as flexible materials, allowing them to be easily integrated into various surfaces such as building roofs, automobile bodies, and even clothing. Two main techniques are used:

- - Increasing the path of photons through multiple internal re-reflection;
- - using amorphous silicon (a-Si), which has a much higher absorption coefficient than conventional crystalline silicon (c-Si).

The first path was taken by the Australian firm CSG Solar Ltd, which developed solar cells with an efficiency of 10-13% with a silicon layer thickness of only 1.5 microns. On the second - Swiss Oerlikon Solar (which has now been bought by the Japanese), which created combined solar panels based on layers of amorphous and crystalline silicon a-Si / c-Si efficiency which is also 11-13%. A peculiar feature of such elements made of amorphous silicon is a decrease in the efficiency of their work when the ambient air temperature drops (all others - vice versa). Thus, the manufacturer recommends installing these modules in countries with hot climates.

The most advanced and the most expensive solar modules today have a photovoltaic conversion efficiency of up to 44%. They are multilayer structures of different semiconductors, successively grown on each other layer by layer. The most successful is a structure consisting of three layers: Ge (bottom semiconductor and substrate), GaAs and GaInP. Due to the fact that in such a combination each individual semiconductor layer absorbs most efficiently its particular range of the solar spectrum (determined by the width of the semiconductor's forbidden band), the most complete absorption of sunlight over the entire wavelength range is achieved, which is unattainable for solar cells consisting of a single type of semiconductor. Unfortunately, the manufacturing process of such multilayer semiconductor layers is technically very complex and, as a consequence, very expensive.

If solar cells are very expensive, focusing solar radiation on a smaller area of the solar cells can be applied as an effective way to reduce the financial cost. For example, by collecting sunlight from 10 cm2 using a lens and focusing it on 1 cm2 of the solar cell, the same amount of electricity can be obtained as from a 10 cm2 cell without a concentrator. In this case, the solar cell and lens must be mounted on a mechanical tracker orienting the optics in the direction of the sun. Currently, it is economically justified to use such expensive concentrator solar modules only in those countries and regions of the globe where there is plenty of direct solar radiation all year round (scattered radiation can not be focused by the lens). Thus, the French firm producing concentrator solar panels SOITEC installs them in California, South Africa, in the south of France (Provence), in Spain.

Among the latest solar energy technologies are organic solar cells and dye-sensitized modules. There is a new type of thin-film solar cells, such as dye-sensitized solar cells, which operate on a completely different principle than all the modules discussed above, on a principle more reminiscent of photosynthesis in plants. However, this technology has not yet reached commercial productionn [21].

To maximize the efficiency of a PV panel, several additional measures are required, such as sun tracking method [22], concentrating mirrors [23], and the use of panel cooling techniques, which can be classified as active and passive cooling.

The disadvantage of solar panels is that their efficiency decreases at very low and very high temperatures. This problem is also being addressed by scientists. For example, for efficient utilization of solar panels in countries with hot climates, various systems are being developed to cool the PV panels by means of air, water, their combination, phase change materials, nanofluids, etc. [24]. The active cooling system requires an external source of electrical or mechanical energy (fans, pumps). When solar panels are cooled by water, their temperature is reduced by 4 °C and their efficiency is increased by 12 %. By air cooling it is possible to achieve a temperature reduction of 15 ° C and increase efficiency up to 15%.

The combination of photovoltaic and thermal collectors allows the heat from the photovoltaic cells to be transferred to the solar collector fluid, thereby cooling the cells. In other words, combining a thermoelectric generator [25] with solar PV panels to extract energy from waste heat in solar panels [26] through the Seebeck effect allows for increased efficiency. The energy from the thermoelectric generator helps to generate additional electrical energy and at the same time reduce the temperature of the PV panels [27]. The voltage on a thermoelectric generator is produced by cooling one side of the generator while the other side is heated by solar radiation which is transmitted to the generator [28].

One way of cooling is by finning part of the PV panel to dissipate heat. Figure 4 shows the performance of V-I and P-V with and without fins [24].

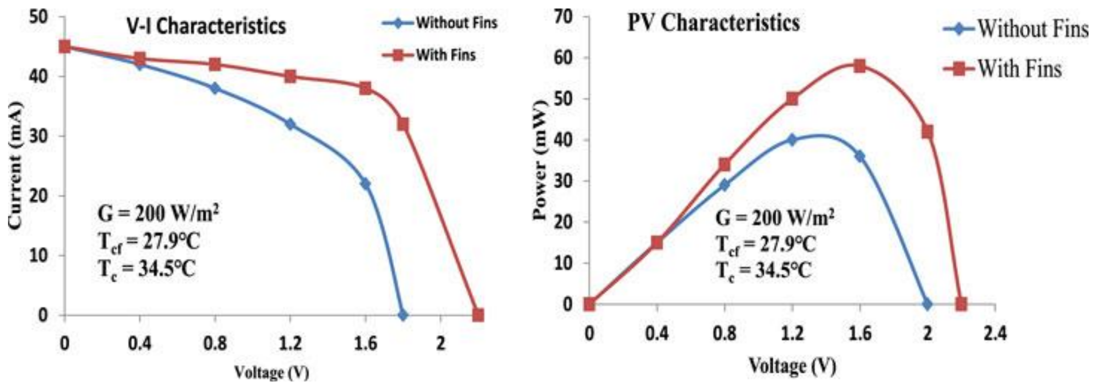

Fig. 4. V-I and P-V characteristics with and without fins [24]

Nanofluids based on nanofluids - Al2O3-water, silicon carbide (SiC)-water, etc. are also used for cooling solar panels, increasing the efficiency up to 18 %. However, the main disadvantage of nanofluids is their instability.

To improve the efficiency of solar panel operation, the irradiance incident on the solar panel during the day should be maximized, which optimizes the angle at which the panel receives solar radiation [29]. Depending on the axis direction, tracking systems are single-axis and dual-axis. A single axis tracker moves the panel along one axis of motion, on the other hand, a dual axis tracker rotates the panel along two axes of motion. The dual-axis tracker provides higher efficiency as compared to the single axis tracker. In the work of Dhanabal et al. [30] determined that the efficiency of the dual-axis tracker was 81.68%, while the efficiency of the single-axis tracker was only 32.17% higher than the fixed panel. The average daily intensity per unit area increased by 13.8 and 22.5% with the single-axis and dual-axis trackers, respectively, compared to the fixed mount. Fig. 5 shows the dependence of the integral power generation of the concentrator module on the solar tracking accuracy of the dual-axis tracker [31].

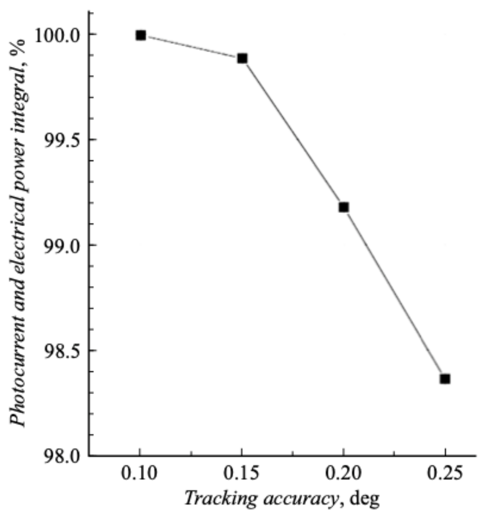

Fig. 5. Dependence of the integral power generation of the concentrator module on the accuracy of solar tracking [31]

Solar energy has proven its efficiency in solar collectors, and even in harsh cold climates. The use of solar collectors can reduce heating costs by up to 30% per year, and DHW costs by up to 66%.

The efficiency of solar collectors depends on losses - thermal and optical. Thermal losses - conduction losses, convection losses and radiation losses - depend on the temperature difference between the collector and the ambient air. Optical losses are related to the properties of the absorbing surface. Also the efficiency of solar collectors is influenced by geographical features, time of year, time of day, weather conditions, angle with respect to solar radiation, etc. Depending on the design of the solar panels, it is possible to utilize approximately 30-60% of the energy falling on the collector. The heat carrier of solar collectors can be water, air or oil.

There are the following types of solar collectors: flat, vacuum, air collectors, collectors-concentrators. The efficiencies of collectors are given in Figure 4 [20].

The design of "classic" solar air collectors, which are installed on the exterior walls of buildings, includes transparent glass covers, solar absorber panels, insulation layers and metal cladding. Solar absorbers are the main components that convert light energy into heat energy and then utilize the air medium to transfer the heat to the room.

Among the latest developments in this direction is the work of a team of scientists from Russia and China [32]. The air collector developed by them surpasses the world analogs in terms of heat accumulation efficiency, thermal conductivity, heat transfer, and cost-effectiveness. The new solar air collector is able to stably heat the premises not only during the day, but also at night. The solar collector is designed on the basis of a composite heat accumulator, which is made by fusing phase transition material and copper foam. This allowed the thermal conductivity to more than double, and the heat storage capacity of the device improved. This allowed it to release more heat energy at night, i.e. the efficiency of heat dissipation increased.

There are many areas with low population density and dispersed residential buildings, to which the central heating system is not applicable. Traditional methods of heating homes are inefficient and cause serious environmental pollution. According to UN forecasts, by 2030 carbon dioxide emissions from such buildings will reach about 30% of global emissions. Accordingly, the development of solar collectors that utilize clean energy is extremely important.

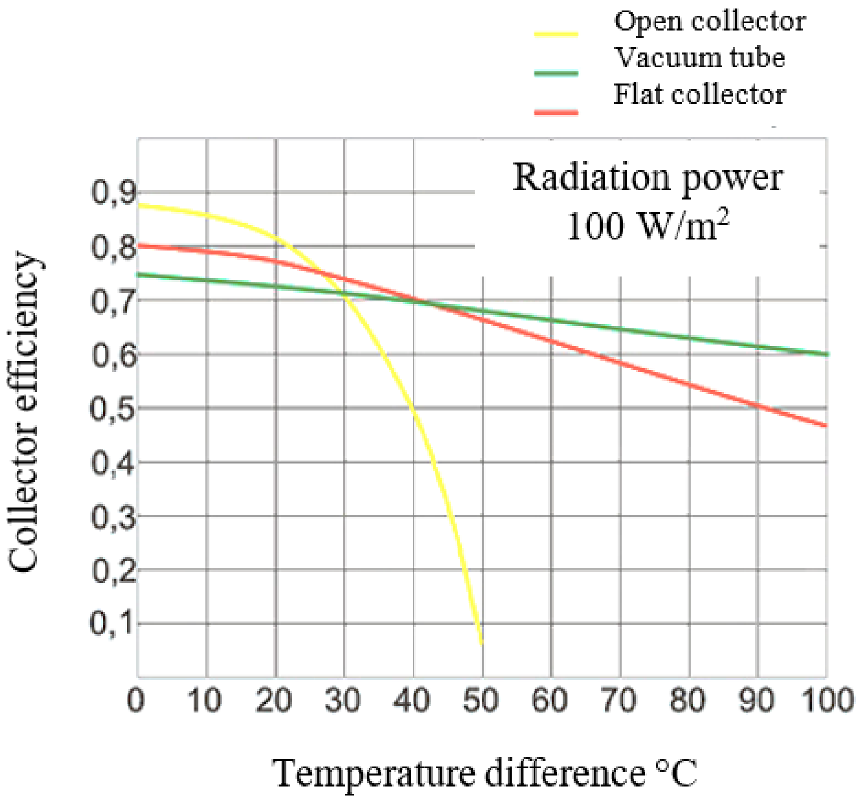

Fig. 6. Collector efficiency [20]

IV. Conclusions

The analysis of solar energy development has shown a significant growth in the capacity of solar generation installations, depending not only on the climatic and geographical features of the country, but also on economic and political ones. Photovoltaic cell production technologies based on various semiconductors allow efficient operation of solar installations in both hot and cold harsh climates. Thin-film solar cells, concentrator solar modules, organic solar cells and dye-sensitized modules are modern technologies that increase the efficiency of solar generation installations. Analyzing the shortcomings in the operation of such installations leads scientists to develop ways to improve their efficiency. For example, various methods of cooling solar panels in hot climates are very relevant with the increasing frequency of abnormally high temperatures that reduce the efficiency of solar cells. The use of concentrator solar modules can significantly reduce the space required. The use of two-coordinate tracker allows to increase the performance of solar cells up to 40%.

The development of solar energy also concerns solar collectors for heating and hot water supply. In this area, scientists have managed to achieve high coefficient of efficiency through the use of materials with high thermal conductivity, high storage capacity, which allows to obtain thermal energy at night, a combination of photovoltaic and thermal collectors.

New promising developments, on which scientists around the world are working, allow us to hope for an increase in the share of renewable energy sources in the energy sector.

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