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Influence of Climatic Parameters on the Photovoltaic Conversion Efficiency of a Polycrystalline Solar Panel

The efficiency of electricity generation by solar panels depends on many factors, one of which is the temperature of the semiconductor layer. An increase in this parameter leads to a decrease in the efficiency of the module, since the speed of electron movement increases, therefore, the resistance increases. Conversely, the lower the temperature of the silicon cells, the lower the resistance and the higher the efficiency. However, the temperature of the silicon cells depends on a number of parameters: wind speeds, insolation, and ambient temperatures. Therefore, depending on the region and time of year, the same solar module will have different performance. Based on this, an urgent issue when planning the use of solar panels is the possibility of determining how much the efficiency of photovoltaic conversion in a particular area will decrease. Therefore, to study the variability of efficiency indicators, a simulation of the temperature change of the semiconductor layer of the polycrystalline solar panel KZPV 220 M60 was carried out, taking into account climatic parameters in winter and summer days for three cities of Kazakhstan — Petropavlovsk, Karaganda and Shymkent. As a result of modeling, it was found that on July 12, solar cells reach their maximum temperature of 64.4 °C in Shymkent, 49.8 °C in Karaganda and 52.1 °C in Petropavlovsk, while efficiency decreases by 2.7 %, 1.7 % and 1.8 %, respectively, relative to the efficiency of the solar module under standard conditions (insolation 1000 W/m^2, temperature 25 °C, spectrum $AM = 1.5$). At the same time, on December 12, $T_{\max}$: in Shymkent 11.5 °C, in Karaganda — 15.8 °C, in Petropavlovsk — 16.7 °C, and efficiency increases by 0.9 %, 2.7 %, 2.8 %, respectively.

Keywords: solar panel, photocells, temperature, wind speed, insolation, efficiency, atmospheric mass, zenith angle

Introduction

Solar energy has many disadvantages, such as: high cost, dependence on the location of photovoltaic panels, toxic components of solar cells, dependence of the production of photovoltaic panels on the time of day, time of year, the presence of rain and cloudy weather, a decrease in the efficiency of the panel with an increase in its temperature. However, despite all these disadvantages, solar energy is a promising source of electric energy due to the fact that the technology and composition of solar cells and their efficiency are constantly being improved [1].

The performance of solar panels is not constant. Also photovoltaic conversion efficiency is influenced by various factors: reflectance, thermodynamic efficiency, and charge carrier separation efficiency, charge carrier collection efficiency, quality of materials, surface contamination and climatic conditions.

Theoretically, the limit of thermodynamic efficiency, equal to the absolute maximum possible efficiency of converting sunlight into electricity, is about 86 %. This value is an approximation (i.e. the Chambadal-Novikov efficiency) associated with the Carnot limit and is based on the temperature of the photons emitted from the surface of the Sun. In contrast, the actual thermodynamic efficiency limit is significantly lower and is about 33 % in the case of single-compound technology. This means conversion efficiency is no more than 12–21 % for commercial PV panels or up to 24.5 % for high-efficiency single junction cells [2].

Moreover, it is widely known that photovoltaic conversion efficiency is strictly related to the operating temperature of the cells [3].

For example, in [4] it was found that efficiency decreases by 0.38–0.42 % (i.e., in relative percentage), and in [5] that electrical power decreases by 0.4–0.5 % for every 1 degree of temperature increase in silicon cells. The usual simplification is to consider a linear decrease in panel efficiency by 1 % (i.e., in absolute percentage) every 10 degrees [6]. The temperature of the photovoltaic module (PVM) increases due to the absorption of solar radiation in the semiconductor layer, and the efficiency of the solar photovoltaic system

(PVS) decreases when the module is poorly cooled [7]. Thus, the insolation level, air temperature and wind speed significantly impact the solar panel's efficiency.

Basically, crystalline silicon FEPs were in the greatest demand on the market. Over time, other designs have been developed, for example, thin-film, multilayer, transient, cascade, etc. The designs of thin-film SE worked more efficiently at high temperature, but the efficiency in comparison with crystalline ones turned out to be almost two times lower (6–8 %) [8].

During hot summer periods, solar panels heat up to an average of 75 °C, and in equatorial regions to 80–90 °C. Overheating of the solar panel not only reduces its efficiency, but also shortens its service life. Even in modern solar panels, the problem of overheating has not been solved, for example, gallium arsenide modules with an efficiency of 46 % at 25 °C lose 20 % of their output at 70 °C, and as much as 30 % at 90 °C [9].

Due to its geographical location, the change of seasons is noticeably pronounced in the territory of Kazakhstan, and there are also differences in climatic conditions in different regions of the country. Therefore, when designing a photovoltaic system, it is essential to consider the influence of climatic factors characteristic of the area. For example, in winter and summer, solar modules produce different amounts of electricity due to differences in the length of daylight hours and various degrees of heating of photocells due to differences in air temperature and wind speed.

Methods and materials

To simulate the variations in operating temperature of solar cells under different conditions, the ANSYS software was utilized to create a detailed three-dimensional finite element model of the KZPV 220 M60 polycrystalline solar panel (Fig. 1):

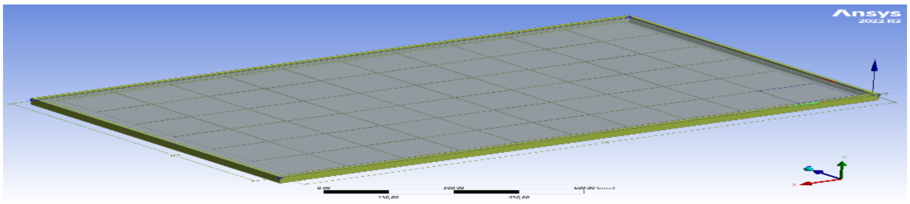

Figure 1. 3D model of a polycrystalline solar panel KZPV 220 M60 in ANSYS software

Main characteristics of the solar module under standard conditions:
– Rated maximum power — 220 W;
– Voltage at maximum power — 29.40 V;
– Current strength at maximum power — 7.5 A;
– Photocells — 60 polycrystalline cells;
– Cell size — 156×156 mm;
– Dimensions — 1.649×992×40 mm.

The climatic parameters of Petropavlovsk, Karaganda and Shymkent were chosen as boundary conditions at noon on one of the hottest days of summer — July 12, 2023, and at noon on one of the coldest days of winter — December 12, 2023 (Table):

Table

Basic parameters for setting boundary conditions

City	Petropavlovsk		Karaganda		Shymkent	
Date	12.07.23	12.12.23	12.07.23	12.12.23	12.07.23	12.12.23
Air temperature, °C	36	–33	35	–28	39	–18
Wind speed, m/s	4	2	5	5	2	1
Insolation, W/m^2	907,86	625	924,2	759	922,7	833

Although Karaganda is more distant from the equator than Shymkent, the table shows that the insolation level of 12.07.23 in the first city is 1.5 W/m^2 higher than in the second. This difference can be explained by the difference in altitude above sea level — Karaganda is 553 m, Shymkent is 506 m — since the higher the object is located, the more solar radiation reaches its surface.

Air temperature and wind speed are taken from the source [10].

The insolation value is calculated based on atmospheric mass. Atmospheric mass is the length of the path light takes through the atmosphere relative to the shortest possible path (when the Sun is at its zenith). The formula for calculating atmospheric mass taking into account the curvature and sphericity of the Earth [11]:

$$AM = \frac{1}{\cos\theta + 0.50572\left(96.07995 - \theta\right)^{-1.6364}}, \tag{1}$$

where θ is the angle measured from the vertical (zenith angle).

The value of the zenith angle can be calculated from the equation:

$$\cos\theta = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta, \tag{2}$$

where φ is the geographic latitude of the area, ω is the hour angle (at noon is 0), δ is the declination of the Sun, which can be found from the approximate Cooper equation:

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right), \tag{3}$$

where n is the serial number of the day of the year, counted from January 1.

The daily intensity of the direct component of sunlight can be determined as a function of atmospheric mass:

$$I_D = 1353 \cdot 0.7^{\left(AM^{0.678}\right)}, \tag{4}$$

where I_D is the intensity at the site perpendicular to the Sun's rays in W/m^2, AM is the atmospheric mass, 1353 W/m^2 is the solar constant, and 0.7 takes into account the fact that about 70 % of solar radiation arriving at the boundary of the atmosphere reaches the ground. The indicator 0.678 is an empirical coefficient that considers atmospheric layers' heterogeneity.

Diffuse radiation is about 10 % of direct radiation even in a clear sky. Therefore, on a clear day, the total intensity of radiation incident on the module is equal to:

$$I_G = 1.1 \cdot I_D. \tag{5}$$

The efficiency of a solar battery under standard conditions (insolation 1000 W/m^2, temperature 25 °C, spectrum $AM = 1.5$) can be determined by the formula [12]:

$$\eta = P_{STC} \div 1000\ \text{W/m}^2 \div S, \tag{6}$$

where P_{STC} is power under standard conditions, S is area.

Thus, equation (6) states that the efficiency of the KZPV 220 M60 polycrystalline solar panel is 15 %.

However, since it is known that the efficiency of photoelectric conversion decreases with increasing temperature of the solar module, the efficiency factor taking into account the heating of photocells is calculated by the formula [13]:

$$\eta_{pi} = \eta_0(1 - 0.0045(T_{pi} - 25)), \tag{7}$$

where η_{pi} is the panel efficiency, %; η_0 — solar panel efficiency at a temperature of 25 °C, %; T_{pi} — solar panel surface temperature, °C.

Results and discussions

Modelling of temperature changes and distribution as a result of heating a layer of photocells was carried out for each case separately, considering the boundary conditions corresponding to the climatic factors characteristic of the regions.

As a result, the values of the maximum temperature reached by the silicon layer when heated on December 12 and July 12 were obtained (Fig. 2).

Several conclusions can be drawn from the data in Figure 2.

Firstly, the most intense heating of the solar module in summer is observed in the climatic conditions of Shymkent — 64.4 °C, while in Karaganda and Petropavlovsk — 49.8 °C and 52.1 °C, respectively. The maximum temperature of the silicon layer in Shymkent is higher than the maximum temperatures in Karaganda and Petropavlovsk — by 14.6 °C and 12.3 °C, respectively. This difference is due to differences in climatic conditions, namely:

– Ambient temperature: Shymkent (39 °C) > Petropavlovsk (36 °C) > Karaganda (35 °C);

– Wind speed: Karaganda (5 m/s) > Petropavlovsk (4 m/s) > Shymkent (2 m/s);

– Insolation: Karaganda (924.2 W/m^2) > Shymkent (510.46 W/m^2) > Petropavlovsk (907.86 W/m^2).

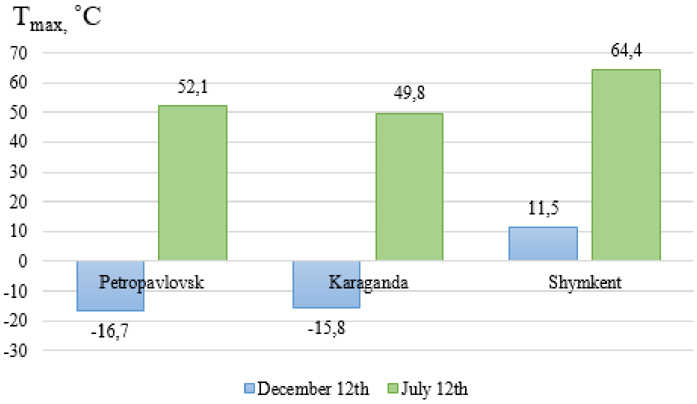

Figure 2. Maximum temperature reached by photocells

Thus, the reason for more intense heating of solar cells in Shymkent than in the other two cities is high air temperatures and insolation levels, which contribute to an increase in the temperature in the silicon layer, as well as the lowest wind speed, which provides insufficient cooling due to convection.

It can also be noted that the panel heated up more (by 2.3 °C) in Petropavlovsk than in Karaganda, even though Petropavlovsk is located north of Karaganda and has a lower insolation level. However, this result is because the module's cooling intensity in the first city is less than in the second since the air temperature in Petropavlovsk is 1 °C higher, and the wind speed, on the contrary, is 1 m/s less than in Karaganda.

Secondly, similar dynamics can be observed in winter: the panel in Shymkent heated up more than in the other two cities (up to 11.5 °C), but the difference between the temperature values is much more significant than in summer. In this case, the maximum temperature of solar cells in Shymkent is higher than the maximum temperatures in Karaganda and Petropavlovsk — by 27.3 °C and 28.2 °C, respectively. The results obtained are associated with more significant differences in the climatic conditions of cities than in the summer period:

– Ambient temperature: Shymkent (–18 °C) > Karaganda (–28 °C) > Petropavlovsk (–33 °C);

– Wind speed: Karaganda (5 m/s) > Petropavlovsk (2 m/s) > Shymkent (1 m/s);

– Insolation: Shymkent (833 W/m^2) > Karaganda (759 W/m^2) > Petropavlovsk (625 W/m^2).

The difference in insolation and air temperature for Shymkent and Karaganda is 74 W/m^2 and 10 °C and for Shymkent and Petropavlovsk — 208 W/m^2 and 15 °C.

Thus, the reason for the higher temperature of solar cells in Shymkent than in the other two cities, as in the first case, is the high values of air temperature and insolation level and the lowest wind speed.

It can also be noted that, in contrast to the first case, in Karaganda, the panel heated up more (by 0.9 °C) than in Petropavlovsk; in other words, in Petropavlovsk, the solar module has the lowest degree of heating due to the lowest ambient temperatures and insolation.

Let's consider how changing solar cell operating temperature affects photovoltaic conversion efficiency in both cases. The solar module's efficiency under standard conditions is 15 %; Figure 3 shows the efficiency values at maximum solar cell temperatures (T_{max}) on December 12 and July 12, 2023.

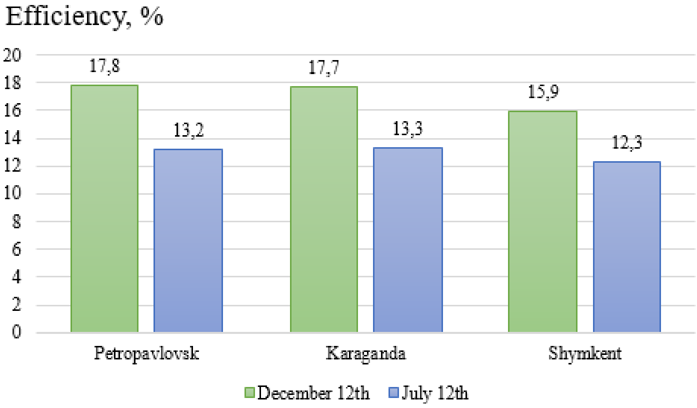

Figure 3. Efficiency values at maximum temperature of photocells

As shown in Figure 3, the efficiency of solar panels on December 12 is higher for all cities compared to July 12 because, during the winter period, the modules heat up significantly less than in the summer period, meaning thermal losses in energy production are less pronounced.

As a result, on July 12, when the layer of solar cells reaches the maximum temperature, the efficiency decreases by 1.8 % in Petropavlovsk, 1.7 % — in Karaganda and 2.7 % — in Shymkent, that is, the lowest efficiency corresponds to the city with the highest maximum temperature — Shymkent.

However, on December 12, the efficiency in all cities on the contrary, increased due to the lower temperature of the solar cells. However, in Shymkent, the efficiency of the module still remains the lowest, as in the first case — 15.9 %, while in Karaganda and Petropavlovsk — 17.7 % and 17.8 %, respectively.

It can be noted that on December 12, the efficiency of solar panels exceeded the value under standard conditions and was, on average, 4.3 % higher than on July 12. This is because the efficiency of solar panels in sunny winter weather is higher than in summer, as, at lower temperatures, electrons in the semiconductor layer move more slowly, which leads to reduced resistance and, consequently, increased efficiency.

Conclusion

As a result of the simulation, it was found that on July 12, solar cells reached their maximum temperatures of 64.4 °C in Shymkent, 49.8 °C — in Karaganda and 52.1 °C — in Petropavlovsk, while on December 12, the values were much lower: in Shymkent — 11.5 °C, in Karaganda — –15.8 °C, in Petropavlovsk — –16.7 °C.

Based on the obtained temperatures, the efficiency values were calculated: on July 12, when the layer of photocells reaches its maximum temperature, the efficiency decreases by 1.8 % in Petropavlovsk, 1.7 % — in Karaganda and 2.7 % — in Shymkent, but on December 12, on the contrary, it increases by 2.8 % in Petropavlovsk, 2.7 % — in Karaganda and only 0.9 % — in Shymkent. The difference in efficiency between the two dates averages 4.3 %.

Thus, the loss of efficiency in Shymkent due to increasing the temperature of solar cells is greater than in Karaganda and Petropavlovsk, which is caused by a hotter climate and a higher level of insolation.

The closer to the north and further from the equator, the solar module is located, the less intensely the solar cells heat up. This happens because as you move away from the equator, the amount of solar radiation reaching the Earth decreases, that is, the level of insolation, and the climate becomes colder; therefore, the air temperature decreases. Then, less solar energy reaches the surface of the solar panel, which means less of this energy is converted into heat due to absorption by silicon cells, and due to the lower ambient temperature, more efficient cooling occurs due to radiation and convection. At the same time, the lower the operating temperature of photocells, the greater their efficiency.

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Климаттық параметрлердің поликристалды күн панелінің фотоэлектрлік түрлендіру тиімділігіне әсері

Күн батареяларының электр энергиясын өндірудің тиімділігі көптеген факторларға, яғни олардың бірі жартылай өткізгіш қабаттың температурасына байланысты. Бұл параметрдің жоғарылауы модульдің тиімділігінің төмендеуіне әкеледі, өйткені электрондардың қозғалыс жылдамдығы өседі, сондықтан қарсылық артады. Керісінше, шақпақ тас жасушаларының температурасы неғұрлым төмен болса, соғұрлым қарсылық аз болады және тиімділігі жоғары болады. Алайда, шақпақ тас жасушаларының температурасы бірқатар параметрлерге байланысты: желдің жылдамдығы, инсоляция және қоршаған орта температурасы. Демек, аймақ пен жыл мезгіліне байланысты бір күн модулі әртүрлі өнімділікке ие болады. Осыған сүйене отырып, күн батареяларын пайдалануды жоспарлаудағы өзекті мәселе белгілі бір аймақтағы фотоэлектрлік түрлендірудің тиімділігі қанша төмендейтінін анықтау мүмкіндігі. Сондықтан тиімділік көрсеткіштерінің вариативтілігін зерттеу үшін Қазақстанның үш қаласы — Петропавл, Қарағанды және Шымкент үшін қысқы және жазғы күндердегі климаттық параметрлерді ескере отырып, KZPV 220 M60 поликристалды күн панелінің жартылай өткізгіш қабатының температурасының өзгеруін модельдеу жүргізілді. Модельдеу нәтижесінде 12 шілдеде күн жасушалары Шымкентте 64,4 °C-қа, Қарағандыда 49,8 °C-қа және Петропавлда 52,1 °C-қа тең ең жоғары температураға жететіні анықталды, бұл ретте тиісінше ПӘК 2,7 %-ға, 1,7 %-ға және 1,8 %-ға төмендейді. Сонымен қатар, 12 желтоқсанда $T_{\max}$: Шымкентте –11,5 °C, Қарағандыда –15,8 °C, Петропавлда –16,7 °C, ал тиісінше ПӘК 0,9 %, 2,7 %, 2,8 %-ға артады.

Кілт сөздер: күн панелі, фотоэлементтер, температура, желдің жылдамдығы, инсоляция, тиімділік, атмосфералық масса, зенит бұрышы.

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Влияние климатических параметров на эффективность фотоэлектрического преобразования поликристаллической солнечной панели

Эффективность выработки электроэнергии солнечными батареями зависит от множества факторов, одним из которых является температура полупроводникового слоя. Увеличение данного параметра приводит к снижению КПД модуля, так как возрастает скорость движения электронов, следовательно, повышается сопротивление. И наоборот, чем меньше температура кремневых ячеек, тем меньше сопротивление и больше КПД. В свою очередь температура кремниевых ячеек зависит от других параметров: скорости ветра, инсоляции и температуры окружающей среды. Следовательно, в зависимости от региона и времени года один и тот же солнечный модуль будет иметь разную производительность. Исходя из этого, актуальным вопросом при планировании использования солнечных батарей является возможность определения снижения эффективности фотоэлектрического преобразования в той или иной местности. Поэтому для исследования вариативности показателей КПД было проведено моделирование изменения температуры полупроводникового слоя поликристаллической солнечной панели KZPV 220 M60 с учётом климатических параметров в зимний и летний период для трёх городов Казахстана — Петропавловска, Караганды и Шымкента. В результате моделирования было установлено, что 12 июля солнечные ячейки достигали своей максимальной температуры, равной 64,4 °С в Шымкенте, 49,8 °С в Караганде и 52,1 °С в Петропавловске, при этом КПД снизилось на 2,7 %, 1,7 % и 1,8 % относительно стандартной температуры 25 °С. В то же время 12 декабря $T_{\max}$ в Шымкенте — 11,5 °С, в Караганде — минус 15,8 °С, в Петропавловске — минус 16,7 °С, а КПД повысилось на 0,9 %, 2,7 %, 2,8 %.

Ключевые слова: солнечная панель, фотоэлементы, температура, скорость ветра, инсоляция, КПД, атмосферная масса, зенитный угол.

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