Effects of Temperature on the Efficiency of Photovoltaic Modules

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Abstract: This article presents calculations of the efficiency and power of modules of various technologies using mathematical expressions and equations. In the calculations, we used experimentally measured values of solar radiation, module temperature and passport values of some parameters obtained by module manufacturers under Standard Testing Conditions (STC). The results of analytical calculations and comparisons are presented in graphical and tabular forms. The object of the study, were the following types of photovoltaic modules: silicon monocrystalline (mc-Si), silicon polycrystalline (pc-Si), thin-film based on copper, indium, gallium and selenide (CIGS), thin-film based on cadmium telluride (CdTe). In this work is determined the influence of the temperature factor, external parameters on the energy performance and efficiency of photovoltaic modules. At the maximum module temperature of 85°C, the power losses from nominal power value of the modules, respectively, had the following percentages: pc-Si, mc-Si - 33%, CdTe – 20%, CIGS–29%. According to the calculations the decrease in the efficiency of modules under the influence of heating temperature was 2-2.4% in silicon modules, 0.6-0.7% in thin-film modules.

1 INTRODUCTION

At present, renewable energy is more widely implemented in the energy supply system of consumers. In particular, to compensate for the energy deficit in the energy system during peak hours of energy consumption, to provide a backup power supply system, to provide individual consumers located far from the centralized power supply system and for a number of other consumers. One of the promising technologies of renewable energy, in particular solar energy, is photovoltaic modules (PVM) for converting solar energy into electrical energy. The performance and efficiency of the PVM is directly related to environmental factors, the movement of the sun, the geographical latitude of the area, the angle of inclination and orientation of the modules, the design parameters and manufacturing technology of the modules and other factors [1], [2].

During the operation of the PVM, in the order of 80-85% of solar radiation is absorbed by the module, of which only 10-15% of solar energy at the point of maximum power is converted into electrical energy, the rest is converted into heat [3]. In hot operating conditions, the modules are heated above the normal operating temperature under the influence of solar radiation. As a result of overheating, the efficiency of the modules decreases [4]. A decrease in efficiency leads to an increase in the average price of energy production. In commercial use, photovoltaic modules based on crystalline silicon are mainly used, the cost of production of which is high. In recent years have been developed, modules based on thin-film technology, such as amorphous silicon, cadmium telluride, copper-indium-gallium-selenide and a number of others. Due to the lower consumption of materials, thin-film modules are cheaper than modules based on crystalline silicon [5]. The influence of environmental parameters on the parameters of the modules was investigated in many researches [6], [7], [8], [9], [10]. And the influence of the heating temperature on the characteristics of the modules has been studied by follow works [11], [12], [13], [14]. In these works are determined, the correlations of the energy and electrical parameters of the modules with the heating temperature and external parameters.

In the geographical conditions of Tashkent of the Republic of Uzbekistan, we have studied the PVM of various manufacturing technologies in the summer season. In this paper, the following goals were set for the studied types of PVM, depending on the temperature factor:

- calculation of efficiency and power values by mathematical expressions and equations;
- calculation of power losses and efficiency;
- presentation of the results of these calculations in graphical forms;
- comparison of calculation results in tabular forms.

For achieve these goals, we used the passport values of some parameters of PVM measured by manufacturers under STC testing conditions.

2 PVM TESTING CONDITIONS

As a rule, PVM manufacturers in the module passport give the characteristics of the modules obtained by testing in laboratory conditions, according to the relevant testing standards. The regulations for testing PVM in various climatic and geographical conditions were published by the International Electrotechnical Commission in the IEC 61853 standard "Photovoltaic Module. Power Rating", which provides HTC, LIC, HTC, NOCT and STC tests. There is also the PV-USA Test Condition (PTC) standard, which is not included in the IEC standard. Table 1 shows the types and parameters of testing conducted by PVM manufacturers [15].

Table 1: Types and parameters of testing of modules.

Para-meter	STC	NOCT	PTC	HTC	LIC	LTC
Illumi-nation W/m^2	1000	800	1000	1000	200	500
The tempe-rature of the solar cell,ºC	25	43-50	-	75	25	15
Ambi-ent tempe-rature, ºC	-	20	20	-	-	-
Wind speed, m/s	-	1	1	0	0	0
Height above groud level,m	-	-	10	-	-	-
AM	1.5					

As can be seen from Table 1, environmental parameters have different values in all PVM testing conditions. But, in real operating conditions of the PVM, the values of these parameters vary depending on the seasons of the year.

3 MATERIALS AND METHODS

In this paper, in order to achieve these goals, we used a method for calculating the efficiency and energy parameters of the studied types of PVM using mathematical expressions and equations. For the calculations were used measured values of solar radiation and PVM temperature in accordance with the experimental studies previously conducted by us. Experimental studies of PVM were conducted in the conditions of the summer season on the heliopolygon of the Department of "AES" of the Tashkent STU named after I.Karimov. To carry out measurements of parameters, these types of PVM were installed at an angle of inclination of 45° to the horizon (Figure 1).

Figure 1: Photos of various types of PVM.

For the study was used the following types of the photovoltaic modules:

- Monocrystalline silicon PVM (mc-Si), Sky(AR) 290W;
- Polycrystalline silicon PVM (pc-Si), ODA50-18-P 50W;
- Thin-film PVM based on copper, indium, gallium and selenide (CIGS), SC-50MDF 48W;
- Thin-film PVM based on cadmium telluride (CdTe), ASP-S1-90.

In the passport data of the studied types of photovoltaic modules, according to Table 2, are given the parameter values obtained by the module manufacturers according to Standard Test Conditions (STC), at a solar radiation flux density of 1000 W/m2, ambient temperature T = 25°C, AM 1.5).

Table 2: Passport data of photovoltaic modules.

PVM Characteris-tics	Types of PVM			
	CdTe	pc-Si	mc-Si	CIGS
Module sizes, mm	1200x 600	670x 530	960x 1620	1075x 610
Area of modules, S_m, m^2	0.72	0.35	1.56	0.65
Electrical characteristics				
Nominal power, P_n, W	90	50	290	48
Open-circuit voltage, U_{oc},V	122	22,14	39,8	24,5
Short-circuit current, I_{sc}, A	1.06	2.89	9.6	2.7
Voltage at max power, U_{max}, V	96	18.5	32.2	19.8
Current at max power, I_{max}, A	0.94	2.7	9.1	2.52
Temperature coefficients:				
I_{sc}, α, %/^{0}C	0.060	0.065	0.033	0.008
U_{oc}, β, %/^{0}C	-0.321	-0.380	-0.360	-0.280
P_n, γ, %/^{0}C	-0.214	-0.450	-0.440	-0.380

4 RESULTS AND DISCUSSIONS

Experimental measurements were previously carried out by us in the month of July of the summer season of 2021. In work [16], were compared only the values of environmental parameters, temperature, short-circuit current and open circuit voltage of various types of PVM measured in July and August of the summer season. The difference between this work and the previous study in the new work is the carrying out of computational calculations of the values of efficiency, power, their reduction and loss of values under the influence of the temperature factor for the studied types of PVM. These calculations were carried out using mathematical expressions and equations depending on the temperature and the amount of solar radiation. To calculate the set of efficiency and power values, we used the measured values of solar radiation and module temperature from the experiments conducted in July. And also, in this work, during the hours of the maximum arrival of solar radiation, we compare the low, high and maximum values of the surface temperature of the modules. A comparison of the measured values is given in Table 3.

Table 3: Comparison of temperature values of different types of PVM.

Parameters		Measurement time 13-00			
		Types of PVM			
		pcSi	CdTe	mcSi	CIGS
W, w/m^2	Solar radiation	916	940	940	915
T_h°C	The high value of tempera-ture on the surface of the module	70,3	71,0	67,6	77,9
T_{hts}°C	Tempera-ture at module hotspots	77,8	76,6	79,6	81,1
T_l°C	The low value of tempera-ture of the module	64,1	71,1	65	69,1
Ta°C	Air tempera-ture	44,8	44,8	44,8	44,8
T_{hs}/Ta, times	Specific tempera-ture rise of the module	1,74	1,71	1,78	1,81

From the comparisons, it can be seen that the temperature increase of the module relative to the air temperature at 13-00 o'clock in the afternoon is 71-81%, and the average daily temperature increase is 50-70%.

The dynamics of the heating temperature of the modules of four types according to the measured values during the day is shown as a graph in Figure 2.

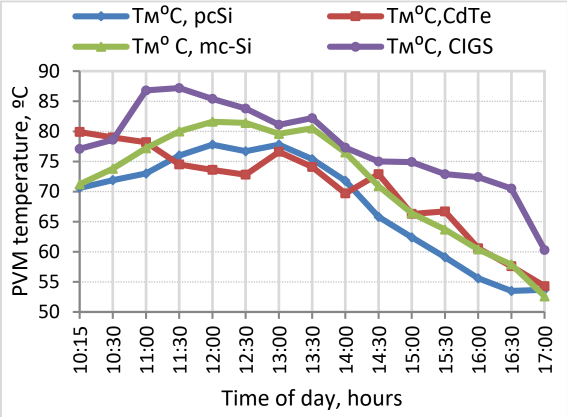

Figure 2: Dynamics of module heating temperature during the day.

As you can see from the graph, the modules have different temperatures. This is due to the different properties of the module materials and their convective heat exchange with the environment.
The efficiency of PVM, as given in [17], may be calculated using (1)

$$\eta_{stc} = \frac{P_n}{W_{stc} \cdot S_m}, \tag{1}$$

where, P_n-nominal power of PVM, W_{stc}-solar radiation in STC, S_m-area of PVM. By using (1) will calculate the efficiency of the modules according to the values of parameters as Table 2.

$$\text{CdTe}, \ \eta_{stc} = \frac{90}{1000 \cdot 0.72} \cdot 100\% = 12{,}5\%$$

$$\text{pc-Si}, \ \eta_{stc} = \frac{50}{1000 \cdot 0.35} \cdot 100\% = 14{,}1\%$$

$$\text{mc-Si}, \ \eta_{stc} = \frac{290}{1000 \cdot 1.56} \cdot 100\% = 18{,}6\%$$

$$\text{CIGS}, \ \eta_{stc} = \frac{48}{1000 \cdot 0.65} \cdot 100\% = 7{,}4\%,$$

As mentioned above, the efficiency of the module depends on the temperature and temperature coefficient of the module. The efficiency of the module depending on the temperature factor as given in [18] may be calculated using (2),

$$\eta_{\text{м}} = \eta_{stc} \cdot [1 - \gamma(\text{T}_{\text{м}} - \text{T}_{stc})] + \varphi \cdot Log_{10}W \tag{2}$$

here, φ is the coefficient of solar radiation. In most sources, the radiation coefficient is assumed to be zero. Then (2) takes a simplified form,

$$\eta_{\text{м}} = \eta_{stc} \cdot [1 - \gamma(\text{T}_{\text{м}} - \text{T}_{stc})] \ , \tag{3}$$

where, η_{stc} is the nominal efficiency (efficiency) of the module according to STC; T_M at the temperature of the module 25 °C and at W of solar radiation equal to 1000 W/m^2; γ - is the temperature coefficient of the module according to power, T_{stc} is the temperature of the module according to STC.

The values of the listed parameters for calculations are taken from Table 2. T_M is the temperature of the module, ^{0}C, experimentally measured data were used in the calculations. According to the (3), the values of the η_M efficiency of modules of various types tested in environmental conditions were calculated according to the experimentally measured values of the T_M temperature of the modules during the daytime from 10-15 to 17-00 hours. Experimental measurements were carried out on July 26, 2021. When calculating the value of η_M according to the (3), γ is the temperature coefficient for power, while it was assumed that during the day the value of this coefficient remains unchanged, which was taken according to the manufacturer's passport of each module according to Table 2. The values of η_M were calculated according to the (3), in depending on the heating temperature of the modules. In Figure 3 and Figure 4 constructed efficiency graphs.

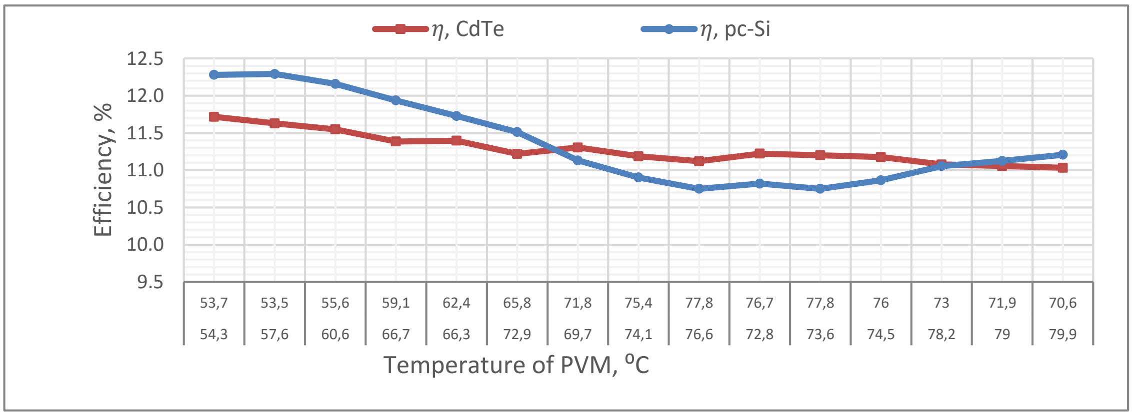

Figure 3: Graph of the dependence of the efficiency of CdTe and pc-Si types of PVM on its heating temperature.

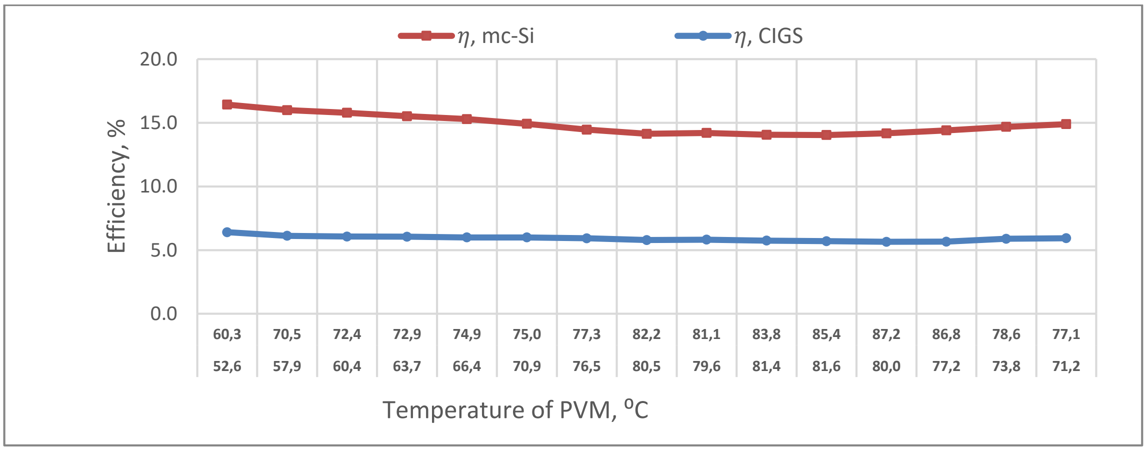

Figure 4: Graph of the dependence of the efficiency of mc-Si and CIGS types of PVM on its heating temperature.

As can be seen from Figure 3 and Figure 4, with an increase in the temperature of the module, the efficiency decreases. The analysis of graphical values shows that the decrease in the efficiency of modules during the daytime of measurement is the following indicators.

pc-Si–13 %, CdTe–6 %, mc-Si –14 %, CIGS –11 %,

The relatively low reduction turned out to be for a CdTe type photovoltaic module and was almost half as much as the other modules. A comparison of the change in efficiency with an increase in temperature is given in Table 4.

Calculations of efficiency indicators and temperature changes based on experimental measurements show that in a hot climate, the efficiency loss or temperature coefficient of efficiency in silicon crystal modules such as pc-Si, mc-Si is on average 36.5% higher relative to thin-film technology modules such as CdTe, CIGS. According to the analytical data, the effect of increasing the temperature of the module was relatively stable in the PVM of thin-film technology of the CdTe type.

The power P_m of the module, as given in [17], [18] may be calculate using (4),

$$P_m = \eta_m \cdot W \cdot S_m \quad (4)$$

or substituting (3) instead of η_m in (4) get the following dependence,

$$P_M = \eta_{stc} \cdot [1 - \gamma(T_M - T_{stc})] \cdot W \cdot S_M \, . \quad (5)$$

Here, η_m is the efficiency of the module calculated by (3). W is the solar radiation flux density, w/m^2; S_m is the module area, m^2, the values according to Table 2 were taken for calculation. To calculate the power of the modules according to the (5), the values of solar radiation measured in July were used. A graph of the change in the value of solar radiation falling on the surface of various types of PVM during the day from 10-15 to 17-00 is shown in Figure 5.

Table 4: Comparison of the effect of temperature on the efficiency of PVM.

Parameters	Types of PVM			
	pc-Si	CdTe	mc-Si	CIGS
Min temperature of PVM, T_{min}, ^{0}C	53,7	54,3	52,6	60,3
Max temperature of PVM, T_{Max}, ^{0}C	77,8	79,9	81,6	87,2
Increasing of temperature of PVM, ΔT_0,%	24,1	25,6	29	26,9
Changing pf temperature of PVM relative to T_{stc}, 25^{0}C,(T_m-T_{stc})	52,8	54,9	56,6	62,2
Decreasing of efficiency,$\Delta\eta_m$,%	-2,0	-0,6	-2,4	-0,7
Decreasing of efficiency relative to η_{stc}	-3,4	-1,4	-4,6	-1,7
$\Delta\eta_m/\Delta T_{stc}$, temperature coefficient relative to T_{stc}, %/^{0}C	-0,064	-0,026	-0,081	-0,027

According to the (5), we calculated the power values for the four tested module types. The changes in the power values are given in the form of graphs in Figure 6 and Figure 7. The graph of the power changes during the daytime of the measurements change according to the polynomial law and in proportion to the density of the solar radiation flux.

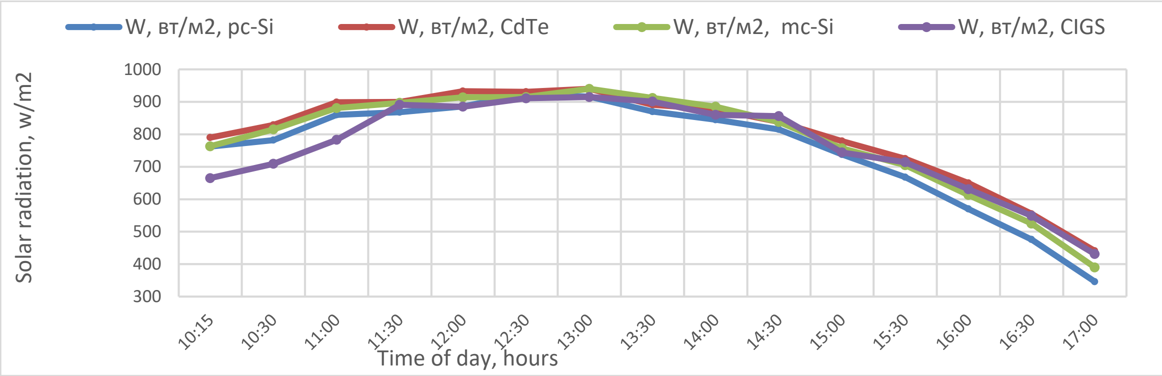

Figure 5: Graph of changes in solar radiation falling on various types of PVM during the day.

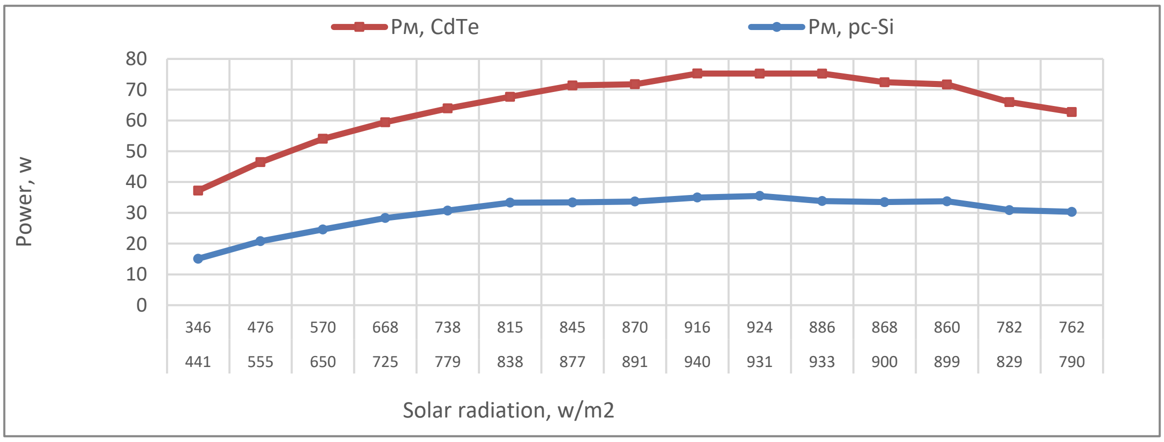

Figure 6: Graph of the dependence of CdTe and pc-Si types PVM power on solar radiation measured during the day.

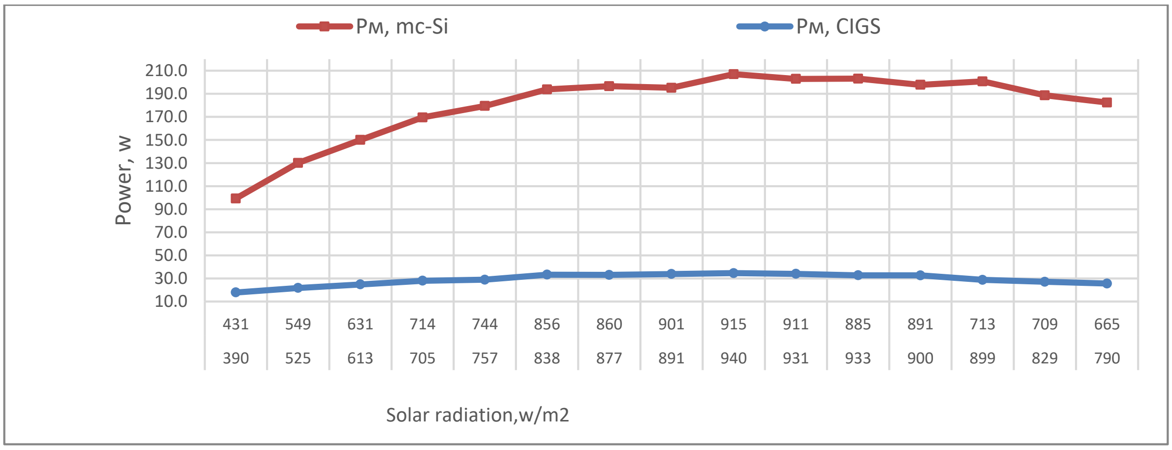

Figure 7: Graph of the dependence of the power of the mc-Si and CIGS type PVM on solar radiation measured during the day.

From the analysis of the graphs of power changes depending on the density of the solar radiation flux, the following values can be calculated.

The increase in the *W* - density of the solar radiation flux on the frontal surface of each module from 10-15 hours to 13-00 hours was, respectively, the following values, pc-Si – 1.7 times, CdTe – 2.1 times mc-Si – 2.4 times, CIGS – 2.1 times.

Accordingly, the increase in power proportional to solar radiation by modules is the following values, pc-Si – 2.2 times, CdTe – 2.1 times, mc-Si – 2.1 times, CIGS – 1.9 times.

The data show small deviations between the modules in the reception of solar radiation to the frontal surface and a corresponding increase in their power.

The effect of temperature increase on the output power of photovoltaic modules for various materials and manufacturing technology was given in [19]. Based on the results of experimental study of various types of PVM, it is possible to construct graphs of power loss depending on the temperature of the module (Figure 8). In this case, the power values were calculated by (4), depending on the heating temperature of the modules.

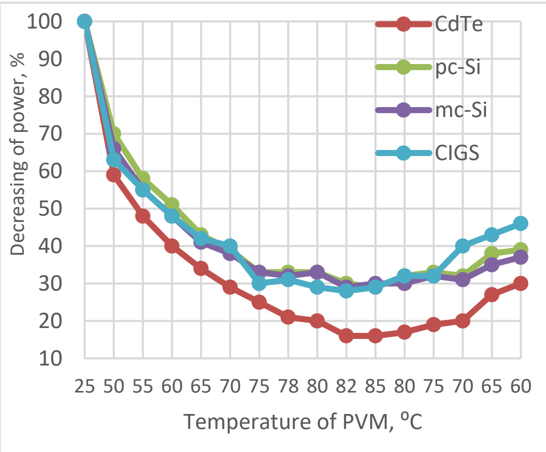

Figure 8: Graph of the dependence of the power of various types of PVM on their heating temperature.

Graphs of changes in power losses depending on the temperature of the modules vary according to the polynomial law. From the analysis of the data in Figure 8, based on the measured temperature values and calculations, the power losses of the PVM relative to the nominal power value of the module amounted to the following values.

At the maximum temperature of the module 85^{0}C, power loss, respectively made up of the following values, pc-Si-33%, mc-Si - 33%, CdTe – 20%, CIGS – 29%. These data show that the relatively low power sensitivity to temperature rise was for a CdTe type module. This can be explained with the optimal design and good convective heat exchange of this thin-film module.

5 CONCLUSIONS

In accordance with the goals of this work, the values of efficiency and power of various types of PVM were calculated using mathematical expressions and equations. Analysis of the calculated values, presented graphs and tabular comparisons of parameters shows that the influence of the temperature factor on the values of changes in efficiency, power, as well as the loss of these parameters of photovoltaic modules of various types in natural environmental conditions is significant. In hot climates, photovoltaic modules based on thin-film technologies have relative stability to heating compared to crystalline silicon modules. The magnitude of the decrease in the performance of photovoltaic modules primarily depends on the geographical conditions of the area. In our research of various types of modules in the environment conditions of Tashkent, photovoltaic modules based on thin-film technologies had relative stability to heating compared to crystalline silicon modules. When studying these types of modules in the environment of other geographical areas, the efficiency and energy indicators may change in a different ratio in contrast to those presented in this study.

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