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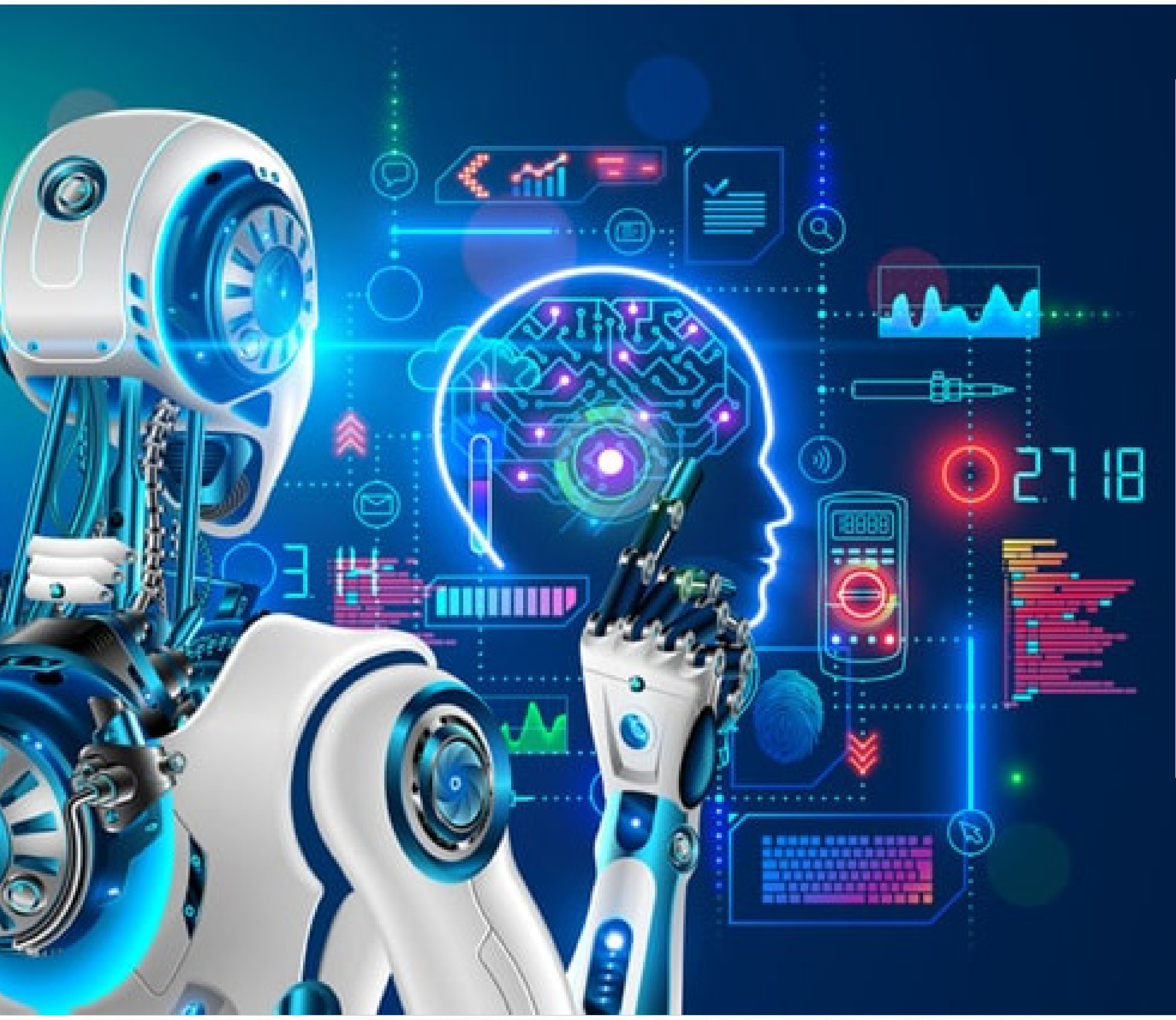

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THE IMPACT OF DEGRADATION ON THE OPERATIONAL CHARACTERISTICS OF PHOTOVOLTAIC MODULES UNDER SHARPLY CONTINENTAL CLIMATIC CONDITIONS

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Abstract: In this paper, the degradation process of a crystalline silicon photovoltaic module SL100TU-18P (100 W), operated for 14 years under harsh continental climate conditions, is experimentally evaluated. The passport parameters of the module (Uoc, Isc, Umpp, Impp, and Pmax) are compared with the values measured under real operating conditions. The results show that high-intensity solar irradiance, sharp temperature fluctuations, high humidity, and increased dust concentration have a significant impact on the electrical characteristics of the module. In particular, a pronounced degradation is observed in the maximum power and current parameters. The experimental studies were conducted at the Heliopolygon of Tashkent State Technical University, and it was determined that the annual degradation rate of the module is significantly higher than the passport values specified under ideal conditions.

Key words: photovoltaic module, degradation, harsh continental climate, SL100TU-18P, I–U characteristics, maximum power (Pmax), short-circuit current (Isc), open-circuit voltage (Uoc), efficiency, temperature effect, solar radiation flux density, experimental measurements.

Annotatsiya: Ushbu maqolada keskin kontinental iqlim sharoitida 14 yil davomida ekspluatatsiya qilingan SL100TU-18P (100 Vt) kristalli kremniy fotoelektr modulining degradatsiya jarayoni eksperimental usulda baholandi. Modulning pasport parametrlari (Uoc, Isc, Umpp, Impp, Pmax) real ekspluatatsiya sharoitida o'lchangan qiymatlar bilan solishtirildi. Olingan natijalar shuni ko'rsatdiki, yuqori intensivlikdagi quyosh nurlanishi, issiq va sovuq haroratlarning keskin almashinuvi, namlik hamda changning yuqori darajasi modulning elektr parametrlariga sezilarli ta'sir ko'rsatadi. Ayniqsa maksimal quvvat (Pmax) va tok ko'rsatkichlarida yaqqol degradatsiya holatlari kuzatildi. Tajribalar Toshkent davlat texnika universiteti Geliopoligonida olib borildi hamda modulning yillik degradatsiya koeffitsiyenti ideal pasport qiymatlariga nisbatan ancha yuqori ekani aniqlandi.

Kalit so'zlar: fotoelektr modul, degradatsiya, keskin kontinental iqlim, SL100TU-18P, I–U xarakteristika, maksimal quvvat (Pmax), qisqa tutashuv toki (Isc), salt yurish kuchlanishi (Uoc), samaradorlik, harorat ta'siri, quyosh nurlanishi oqim zichligi, eksperimental o'lchov.

Аннотация: В данной статье экспериментально оценен процесс деградации кристаллического кремниевого фотоэлектрического модуля SL100TU-18P (100 Вт), эксплуатируемого в течение 14 лет в условиях резко континентального климата. Паспортные параметры модуля (Uoc, Isc, Umpp, Impp, Pmax) были сопоставлены с измеренными значениями в реальных условиях эксплуатации. Результаты показали, что высокая интенсивность солнечного излучения, резкие температурные колебания, повышенная влажность и высокая концентрация пыли оказывают существенное влияние на электрические параметры модуля. Наиболее выраженная деградация наблюдается по показателям максимальной мощности и тока. Экспериментальные исследования проводились на Гелиополигоне Ташкентского государственного технического университета, при этом установлено, что годовой коэффициент деградации модуля значительно превышает паспортные значения, полученные в идеальных условиях.

Ключевые слова: фотоэлектрический модуль, деградация, резко континентальный климат, SL100TU-18P, вольтамперная характеристика (I–U), максимальная мощность (Pmax), ток короткого замыкания (Isc), напряжение холостого хода (Uoc), эффективность, влияние температуры, плотность потока солнечного излучения, экспериментальные измерения.

INTRODUCTION

At present, among renewable energy sources, the share of photovoltaic (PV) technologies is increasing rapidly. In particular, in regions with a sharply continental climate, the use of solar energy plays a significant role in ensuring energy security, reducing the cost of electricity generation, and minimizing negative environmental impacts. However, in such areas, high ambient temperatures observed throughout the year, intense solar irradiance, wind, dust storms, and ultraviolet radiation have a considerable influence on the physicochemical condition of photovoltaic modules [1].

During long-term operation, degradation of photovoltaic modules inevitably occurs. Degradation refers to the gradual decline of a module's electrical parameters over time and is characterized by a reduction in key indicators such as short-circuit current (I_{sc}), open-circuit voltage (U_{oc}), maximum power (P_{max}), and overall efficiency (η). Under sharply continental climatic conditions, the rate of this process may be higher than in temperate climates. For example, elevated temperatures activate thermally induced defects within silicon cells caused by the combined effects of heat, solar radiation, and time, while leading to the yellowing of the encapsulant (EVA) layer [16]. In addition, dust storms contribute to increased optical losses [1–2–4].

Recent studies indicate that the annual degradation rate of photovoltaic modules is directly dependent on the type of technology—monocrystalline, polycrystalline, or thin-film—as well as on module design features and the climatic parameters of the installation area [1–5–11]. Scientific research confirms that factors such as high temperature cycling, low annual humidity, limited cloud cover, strong solar radiation, and increased UV radiation density in sharply continental climate zones can accelerate module aging and shorten their actual operational lifetime [5–6–15].

REVIEW OF LITERATURE ON THE SUBJECT

Photovoltaic (PV) module degradation has been extensively studied over the past decades, as it directly affects long-term energy yield, system reliability, and economic feasibility of solar power plants. One of the most comprehensive analytical overviews of PV degradation mechanisms and rates is provided by Jordan and Kurtz (2013), who synthesized global field data and demonstrated that degradation is a cumulative process influenced by climate, technology type, and operational conditions. Their findings established degradation rate analysis as a standard tool for assessing PV system performance over time.

Field-based experimental studies have significantly contributed to understanding real-world degradation behavior. Skoczek, Sample, and Dunlop (2009) investigated field-aged crystalline silicon modules and reported that current-related parameters, particularly short-circuit current and maximum power, exhibit more pronounced degradation compared to voltage parameters. This observation has been repeatedly confirmed in later studies and is considered characteristic of crystalline silicon technologies.

Climatic stress factors play a decisive role in accelerating degradation processes. Ndiaye et al. (2013) analyzed PV module performance in desert environments and identified high temperatures, dust deposition, and intense solar radiation as dominant degradation drivers. Similar conclusions were drawn by Bouaichi et al. (2019) in Morocco, where harsh climatic conditions caused early-stage degradation across different PV technologies, with crystalline silicon modules showing notable power losses. These findings are especially relevant for sharply continental climate zones, where thermal cycling and solar irradiance levels are high.

Temperature variability has been identified as a critical degradation factor in continental regions. Liang et al. (2021) demonstrated that frequent temperature fluctuations intensify thermomechanical stress in PV modules, leading to microcrack formation, encapsulant aging, and increased internal resistance. Long-term exposure studies further support this conclusion. Han et al. (2018) examined crystalline silicon modules exposed for over

30 years and confirmed that prolonged thermal and ultraviolet stress significantly reduces power output, even when voltage parameters remain relatively stable.

Encapsulant degradation, particularly EVA discoloration and loss of optical transmittance, is another key mechanism affecting PV performance. This aspect is highlighted in the works of Dyskin et al. (2025), who analyzed the temporal degradation of EVA transmittance and demonstrated its direct impact on photogeneration efficiency. Increased optical losses due to encapsulant aging have also been linked to reduced current generation in multiple field studies.

Regional investigations conducted in Uzbekistan provide valuable insights into PV module behavior under sharply continental climatic conditions. Yuldashev et al. (2025) performed a comparative analysis of polycrystalline PV modules and reported substantial reductions in current and power parameters after long-term operation. These results align with broader regional climate assessments provided by the World Meteorological Organization, which characterize Central Asia by high solar irradiance, low humidity, and significant temperature extremes—conditions known to exacerbate PV module degradation.

Comparative international studies from tropical and hot climates further reinforce these findings. Limmanee et al. (2016) and Aboagye et al. (2021) documented degradation trends in Southeast Asia and West Africa, respectively, emphasizing that current and power losses dominate long-term performance decline. Ndiaye et al. (2014, 2013) also proposed novel diagnostic approaches for identifying degradation mechanisms, highlighting the importance of in-situ measurements for accurate performance evaluation.

Finally, Sharma and Chandel (2013) provided a comprehensive review of performance degradation mechanisms and emphasized that long-term reliability of PV systems depends on effective mitigation strategies, including improved materials, thermal management, and protective coatings. From a broader energy systems perspective, Strebkov (2012) underscored the strategic importance of accounting for degradation effects in future solar energy development, particularly in regions with challenging climatic conditions.

Overall, the reviewed literature consistently demonstrates that sharply continental climatic conditions—characterized by high solar irradiance, temperature extremes, low humidity, and strong ultraviolet radiation—significantly accelerate degradation processes in photovoltaic modules. Current-related parameters and maximum power output are most affected, while voltage parameters remain comparatively stable. These findings provide a strong theoretical and empirical foundation for analyzing the degradation-induced changes in the operational characteristics of photovoltaic modules under sharply continental climate conditions.

RESEARCH METHODOLOGY

This study is based on experimental field measurements of a crystalline silicon photovoltaic module operated under sharply continental climatic conditions. Primary data were obtained through in-situ monitoring of electrical parameters and environmental variables and compared with datasheet values. The analysis employed descriptive statistics and comparative evaluation to identify degradation levels and assess climatic impacts on module performance.

ANALYSIS AND RESULTS

To evaluate the operational parameters of a 100 W SL100TU-18P photovoltaic module after 14 years of operation, field measurements were conducted on November 12 of the current year. During the measurements, solar irradiance, ambient temperature, open-circuit voltage (U_{oc}), short-circuit current (I_{sc}), voltage (U_{mpp}) and current (I_{mpp}) at the maximum power point, as well as maximum power output (P_{max}), were determined [7,8] (Figure 1; Table 1).

Figure 1. General view of the photovoltaic module (PV module)[1]

1 Source: Author's compilation.

Table 1. The main electrical parameters of the photovoltaic module (PVM) specified in the datasheet[2]

Short-circuit current (I_{sc})	Open-circuit voltage (U_{oc})	Current at the maximum power point (I_{mpp})	Voltage at the maximum power point (U_{mpp})	Maximum efficiency of the PVM
5,6 A	22,68 V	5.23 A	19,12 V	14,9%

According to the experimental results, the Uoc value during the day ranged between 19.6 and 19.8 V, indicating that voltage degradation of the module is minimal. This behavior is consistent with crystalline silicon modules, in which voltage tends to remain relatively stable over long periods of operation (Table 2).

Table 2. Experimental results[3]

No.	Time (min)	Solar irradiance (W/m²)	Ambient temperature (°C)	U_{oc} (V)	I_{sc} (A)	U_{mpp} (V)	I_{mpp} (A)	P_{mpp} (W)
1	11:00	685	14	19.8	3.28	13.5	2.43	33
2	11:10	701	14	19.8	3.28	13.2	2.56	34
3	11:20	714	14	19.7	3.18	13.1	2.45	32
4	11:30	701	14	19.6	2.95	13.1	2.40	31
5	11:40	693	15	19.6	2.72	14.2	2.00	28
6	11:50	686	15	19.6	2.70	14.4	1.97	28
7	12:00	691	15	19.6	2.87	14.4	2.00	29
8	12:10	680	16	19.6	2.78	14.2	1.96	28
9	12:20	683	17	19.6	2.86	14.4	2.00	29
10	12:30	682	17	19.6	3.03	13.1	2.37	31

However, the I_{sc} values exhibited significant variation within the range of 2.73–3.28 A. These changes are directly associated with fluctuations in solar irradiance between 680 and 714 W/m². Since short-circuit current is the most sensitive parameter to irradiance, even variations of 20–30 W/m² resulted in noticeable changes in current. After 14 years of operation, the reduction in Isc confirms a decline in photogeneration within the light-sensitive layer of the module and indicates probable thermally induced degradation processes.

During the experiment, P_{max} was recorded in the range of 28–34 W. Considering that the module is rated at 100 W according to its datasheet, this indicates a sharp reduction in power output under real operating conditions. This decline may be attributed to the following factors:

1. natural degradation of the photovoltaic layer,
2. yellowing of the EVA and protective layers,
3. elevated module temperature (although ambient temperature was around 14–17 °C, solar irradiance density was high),
4. aging of metallic contacts.

The I_{mpp} values ranged between 1.97–2.56 A and varied in direct correlation with $P_{max.}$ As solar irradiance density increased, I_{mpp} also rose; however, due to increased internal resistance of the module, the maximum power did not recover significantly. This behavior indicates long-term degradation accumulated within the internal components of the module (series contacts, shunt losses).

The experimental results obtained for the SL100TU-18P module reveal the following degradation characteristics: a reduction in maximum power exceeding 60–70%, which represents a very high level of degradation for such modules. Significant losses in current parameters, particularly decreases in I_{sc} and $I_{mpp,}$ indicate a reduced light absorption efficiency of the module. Voltage parameters remain relatively stable, which is typical for crystalline silicon modules. Increased sensitivity to solar irradiance density can be explained by thermal and ultraviolet aging effects.

Overall, these results confirm a substantial deterioration of the real operating parameters of PV modules that have been in long-term service under sharply continental climatic conditions.

2 Source: Author's compilation.
3 Source: Author's compilation.

CONCLUSIONS AND SUGGESTIONS

In the course of this study, experimental measurements of the operating parameters of a crystalline silicon photovoltaic module enabled a comprehensive assessment of the technical condition, degradation level, and the impact of sharply continental climatic conditions by comparing the actual performance parameters of the SL100TU-18P photovoltaic module after 14 years of operation with its datasheet specifications. According to the manufacturer's data, the module's short-circuit current should be I_{sc} = 5.6 A, open-circuit voltage U_{oc} = 22.68 V, current at the maximum power point I_{mpp} = 5.23 A, voltage at the maximum power point U_{mpp} = 19.12 V, and maximum power output 100 W, corresponding to an efficiency of 14.9%. However, the experimentally obtained results under real operating conditions revealed a significant reduction in these parameters. Specifically, during the measurements, I_{sc} ranged from 2.7 to 3.28 A, U_{oc} from 19.6 to 19.8 V, I_{mpp} from 1.97 to 2.56 A, U_{mpp} from 13.2 to 14.4 V, and P_{max} from 28 to 34 W.

These values indicate pronounced degradation in the most sensitive parameters of the module—namely I_{sc}, I_{mpp}, and P_{max}. The reduction in current-related parameters by approximately 40–55% can be attributed to long-term deterioration in light absorption, electron–hole pair generation, and increasing internal resistances within the module. The decline in maximum power by up to 60–70% reflects degradation processes in the photovoltaic layer induced by prolonged exposure to heat and ultraviolet radiation, yellowing of the EVA encapsulant, and intensified shunt-related losses.

Although voltage parameters (U_{oc} and U_{mpp}) remained relatively more stable, a decrease of about 10–15% nevertheless confirms the overall aging of the module. Climatic factors characteristic of sharply continental regions—such as high solar irradiance, elevated temperatures, low cloud cover, and low humidity—impose significant thermomechanical stress on the structural layers of the module during long-term operation, substantially weakening its operational performance.

Overall, the conducted experiment demonstrates that after 14 years of service, the SL100TU-18P module has experienced significant degradation in efficiency, current, and power parameters, resulting in a sharp reduction in actual energy generation capacity compared with the rated specifications. These findings underscore the necessity of implementing additional thermal management solutions, improved protective coatings, and structural reinforcement measures to maintain stable performance of photovoltaic modules operating under sharply continental climatic conditions throughout their service life.

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