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Degradation Analysis of 8.65-Year-Old Multicrystalline Silicon PV Modules under the Weather Conditions of Sana'a – Yemen

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Abstract

In 2016, an off-grid PV system (14.64 KW) of (48) multicrystalline silicon (mc-Si) modules were installed on the roof of the Yemen Standardization, Metrology and Quality Control Organization (YSMO) in Sana'a – Yemen. In this work, thirty-eight modules from this system were selected for studying the performance degradation after 8.65 years of operation. Degradation analysis of the selected modules was done using visual inspection and current–voltage (I-V) characterization techniques. Results show that the degradation rates in P_{max} of the modules under study, over the outdoor exposure period (8.65 years), were found to be between 2.44% and 7.99% with mean of 5.42% and median of 5.24%. By comparing the annual degradation rates with the industry linear warranty based on nominal power of this module, out of the 38 PV modules studied, only 2 modules have been degraded more than 0.7%/year, which implies that these two modules are likely to fail before 25 years in operation under outdoor conditions of Sana'a, Yemen. The remaining 36 PV modules degraded less than 0.7%/year, which are likely to operate reliably for 25 years under outdoor conditions of Sana'a, Yemen. The analysis of electrical performance indicated that the P_{max} reduction of the studied modules are mainly related to the losses in the I_{SC} and I_{mp}. Losses in I_{mp} can be ascribed to the decreases of the shunt resistance (R_{sh}). On the other hand, the reduction in I_{SC} of the modules under study can be correlated to the encapsulation discoloration. The most noticeable visual defect in the studied modules was a discoloring of EVA encapsulant. The encapsulant discoloration reduced the incident photons that reach the solar cells and thus, decreased the I_{SC} and output power (P_{max}) of the modules. Corrosion of the metallisation was also observed in some modules. This defect can lead to reducing the FF of the modules.

Article Info

Keywords:
Multicrystalline silicon modules, Degradation rate, Standard test conditions (STC), Visual inspection

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1. INTRODUCTION

Amongst the different renewable energy resources, solar energy is the most prevalent renewable source in most regions of the world due to its installation simplicity and cost-effective application [1]. Electricity generated from solar PV systems is one of the sources the world is currently focusing on to mitigate the negative environmental impacts of generation and use of energy from fossil fuel and combat climate change [2]. Thus, the globally annual installed capacity of photovoltaic modules has increased from 31 GW in 2011 to more than 240 GW in 2022 [3]. The main component of a solar PV system is the PV module [2]. Usually, photovoltaic (PV) modules are expected to produce at least 90% and 80% of their rated power after 10 years and 25 years of operation, respectively [4, 5]. However, PV modules are exposed to various environmental stresses and climatic conditions during the outdoor operation that degrade the module materials and reduce their performance and long-term reliability [6]. Suleske et al. [7] reported that 10.7 years old (p-Si) modules in a hot and desert climate showed degradation rate of 1.68 %/year. Kazem et al. [8] evaluated the degradation of 7 year's old (p-Si) modules under the hot and desert climate of Sohar – Oman and reported degradation rate of 0.84 %/year. On the other hand, Bayandelger et al. and Bansal et al. [9, 10] analyzed the performance degradation of (p-Si) modules operated under cold and desert climate for 9.33 and 7 years, respectively; and reported degradation rates of 1.28 %/year and (2 – 2.5) %/year respectively. In this study, 38 multicrystalline PV modules were tested to evaluate the outdoor degradation of their performance after 8.65 years of operation under the weather conditions of Sana'a – Yemen. Section 2 presents the experimental procedures as related to materials (PV modules) description, climate conditions description, a short description of the characterization techniques considered in this work and degradation rate calculations. PV modules performance, degradation rates, and the results of the visual inspection, are presented and discussed in the third section of this paper. The conclusions are outlined in the fourth and final section of this paper.

2. EXPERIMENTAL PROCEDURES

2.1. Climate conditions of Sana'a

Sana'a City (15.35° N, 44.21° E) is situated in the western part of Yemen, at an altitude of 2,200 m above the red sea level. Sana'a features the very rare mild version of a desert climate (or "BWk" by Köppen classification) [11]. The low latitude of Sana'a city and its high elevation above sea level has strengthen the effect of UV on the performance of PV modules. The statistics of the irradiance and temperature data can be found in [12]. The average annual of the direct normal (DIN) and global horizontal (GHI) irradiations are approximately 2305 kWh/m^2 per year and 2341.7 kWh/m^2 per year respectively [13]. Fig. 1 shows the monthly climatology of minimum, mean, and maximum temperatures, and precipitation in Sana'a for the period 1991-2020 [14].

2.2. PV Modules characteristics

In April 2016, an off-grid PV system (14.64 kW) was installed on the roof of the Yemen Standardization, Metrology and Quality Control Organization (YSMO) in Sana'a–Yemen. The system capacity is 14.64 kW and builds from forty-eight multicrystalline silicon technology 305 Wp module (SUNTECH, STP305-24/Vem) rating as shown in Fig. 2. This system remained in work as off-grid until June 2022. After that, it was reconnected to the grid as a part of an on-grid PV system project. Thirty-eight modules (SUNTECH, STP305-24/Vem) were selected for degradation analysis in this study.

Table 1 summarizes the STC electrical, temperature and mechanical characteristics of the modules under study as delivered by the manufacturer [15].

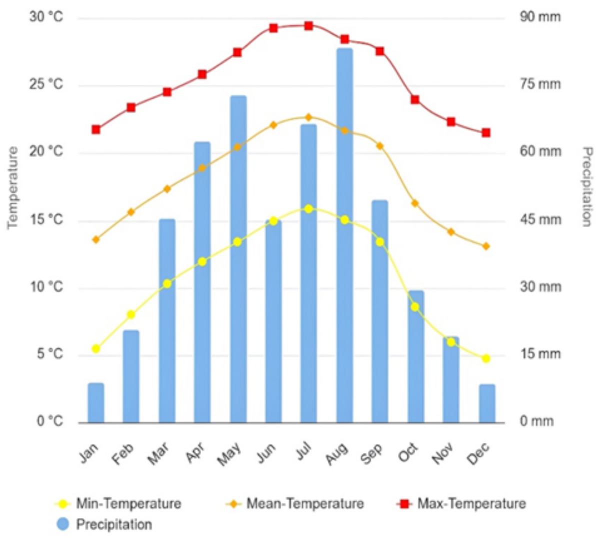

Figure 1. Monthly climatology of minimum, mean, and maximum temperatures, and precipitation in Sana'a for the period 1991-2020 [14].

Figure 2. A section of the (P-Si) PV modules that are installed on the roof of the Yemen Standardization, Metrology and Quality Control Organization (YSMO) in Sana'a – Yemen.

Table 1. Electrical, temperature and mechanical characteristics of the Suntech, STP305 24/Vem modules as delivered by the manufacturer [15].

Parameters	Specifications
P_{max}	305 Wp
V_{mp}	36.2 V
I_{mp}	8.43 A
V_{OC}	44.7 V
I_{SC}	8.89 A
Module Efficiency	15.7 %
NOCT	45 ± 2°C
TC of P_{max}	-0.42 %/°C
TC of V_{OC}	-0.33 %/°C
TC of I_{SC}	0.067 %/°C
Solar Cell Type	Multicrystalline silicon 156 × 156 mm
Number of Cells	72 (6 × 12)
Dimensions	(1956 × 992 × 40) mm
Front Glass	4.0 mm tempered glass
Junction Box	IP68 rated (3 bypass diodes)

2.3. Characterization techniques

The I-V characteristics of all PV modules under study was acquired using a handheld I-V Tracer (SEAWARD PV 210). A Solar Survey 200R solar irradiance meter was correctly affixed to the plane of the PV module to measure irradiance. The technical specifications of the I-V tracer and irradiance meter can be found in [16, 17]. A suction mount PV module temperature sensor was connected to the Solar Survey 200R solar irradiance meter and attached to the back side of the module to measure the module temperature. In this work, the I-V curve characterizations of PV modules were measured under outdoor conditions (under clear sky). Corrections of the measured I-V curve characteristics to standard test conditions (STC) (G =1000 W/m^2 and T_m =25 °C) were performed using the method of IEC 60891 [18]. The I-V curve measurements of each module under investigation were performed in Jan 2022, June 2023 and November 2024. We identify the selected modules by (YSMO 01 to YSMO 38) ID codes. Visual inspections of the modules were carried out to identify and document any visible defects on the modules such as front glass breaking, encapsulation discoloring, cracked cells, back sheets defects, junction box failures, and internal circuitry corrosion. The visual inspection was performed according to checklist and guidelines recommended by IEA and NRLE [4, 19]. Photographs of modules with visual defects were also taken during the visual inspection.

2.4. Degradation rate calculations

The degradation rates of the P_{max}, I_{SC}, V_{OC}, I_{mp}, V_{mp}, and FF were calculated by comparing the measured values (that corrected to STC) of these parameters and the nameplate rating of the PV modules as listed in Table 1. The accumulated (R_d) and annual (R_{da}) degradation rates of each PV module parameters were estimated analytically using the methodology and equations described in [20].

3. RESULTS AND DISCUSSION

3.1. Modules performance and degradation rates

Considering the initial measurement (in Jan 2022), the degradation rates of the P_{max}, I_{SC}, V_{OC}, and FF were found to be in the ranges of (5.35% to 8.19%) with median of 6.82%; (0.89% to 5.43%) with median value of 2.35%; (1.44% to 3.18%) with median value of 2.26%; and (0.9% to 3.26%) with median value of 2.17%, respectively. In the second measurement (in June 2023), the degradation rates of the P_{max}, I_{SC}, V_{OC}, and FF were found to be in the ranges of (4.45% to 8.94%) with median of 5.96%; (3.28% to 6.13%) with median value of 5.10%; (-1.79% to 1.73%) with median value of - 0.70%; and (-0.35% to 3.45%) with median value of 1.94%, respectively. Table 2 lists the measured parameters of the I-V characteristics under STC of the PV modules under investigation, taken in November 2024. The corresponding degradation rates of these photovoltaic modules are displayed in Fig. 3.

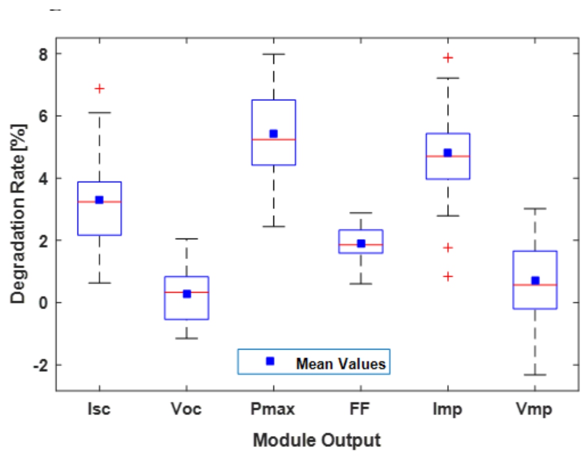

Figure 3. Box plot of the degradation rates of ISC, VOC, Pmax, FF, Imp, and Vmp for the modules under study.

Two important aspects may have impacted the reported degradation rates in this study. First, the tolerance of nameplate power, which is 0/+5%. Second, the degradation rates in this study were calculated by using the nameplate rating as a reference. Lopez-Garcia and Sample [21] reported that, in the period 2010 – 2014,

the mean value of the difference between the P_{max} measured and the P_{max} from the label was +0.01% with standard deviation of 3%. Consequently, using the nameplate rating as a reference may not have impacted the degradation rates in this study.

As shown in Fig.3, the degradation rates in P_{max} of the modules under study were found to be between 2.44% and 7.99% with mean of 5.42% and median of 5.24%. The annual degradation rates in P_{max}, over the outdoor exposure period (8.65 years), were found to be between 0.28%/year and 0.92%/year with mean of 0.63%/year and median of 0.61%/year. According to the datasheet of the STP305-24/Vem module [15], the industry linear warranty based on nominal power of this module is described as that 97.5% in the first year, thereafter, for years two (2) through twenty-five (25), 0.7% maximum decrease from the module's nominal power output per year, ending with the 80.7% in the 25th year after the defined warranty starting date. Accordingly, out of the 38 PV modules studied, only 2 modules have been degraded more than 0.7%/year, which implies that these two modules are likely to fail before 25 years in operation under outdoor conditions in Sana'a, Yemen. The remaining 36 PV modules degraded less than 0.7%/year, which are likely to operate reliably for 25 years under outdoor

Table 2. The measured parameters of the I-V characteristics under STC of the PV modules under investigation, taken in November 2024.

ID code	I_{SC} (A)	V_{OC} (V)	P_{max} (Wp)	FF (%)	I_{mp} (A)	V_{mp} (V)
YSOM 01	8.52	44.48	284.85	75.13	8.03	35.47
YSOM 02	8.83	44.94	297.56	74.95	8.36	35.60
YSMO 03	8.52	44.60	283.61	74.67	8.00	35.44
YSMO 04	8.68	44.11	288.63	75.41	8.17	35.31
YSMO 05	8.45	44.69	284.60	75.34	7.87	36.14
YSMO 06	8.60	43.78	281.13	74.69	8.01	35.11
YSMO 07	8.59	44.42	286.70	75.13	7.97	35.96
YSMO 08	8.58	44.97	290.21	75.20	8.04	36.08
YSMO 09	8.57	44.31	285.49	75.21	8.02	35.62
YSMO 10	8.56	44.51	285.73	74.97	7.96	35.88
YSMO 11	8.43	44.36	282.51	75.53	7.90	35.77
YSMO 12	8.43	44.37	281.74	75.28	7.82	36.02
YSMO 13	8.28	45.21	284.40	75.98	7.77	36.62
YSMO 14	8.35	45.16	287.61	76.29	7.77	37.04
YSMO 15	8.72	44.33	290.36	75.11	8.09	35.88
YSMO 16	8.66	44.61	291.13	75.33	8.06	36.12
YSMO 17	8.61	44.29	288.28	75.58	7.98	36.13
YSMO 18	8.54	44.51	288.70	75.90	8.03	35.97
YSMO 19	8.61	44.68	290.27	75.47	7.98	36.39
YSMO 20	8.65	44.57	292.72	75.91	8.08	36.22
YSMO 21	8.66	44.54	291.78	75.64	8.04	36.30
YSMO 22	8.59	45.10	293.44	75.74	8.04	36.52
YSMO 23	8.55	44.96	290.29	75.56	8.00	36.30
YSMO 24	8.59	44.97	291.51	75.47	8.02	36.33
YSMO 25	8.55	44.83	289.49	75.53	7.94	36.46
YSMO 26	8.66	44.41	290.15	75.46	8.10	35.84
YSMO 27	8.73	43.80	285.15	74.55	8.12	35.13
YSMO 28	8.72	44.27	289.31	74.95	8.04	35.98
YSMO 29	8.71	44.65	293.28	75.44	8.14	36.01
YSMO 30	8.46	44.19	280.63	75.03	7.91	35.47
YSMO 31	8.71	44.04	288.21	75.13	8.10	35.59
YSMO 32	8.76	44.02	287.30	74.54	8.12	35.40
YSMO 33	8.73	44.71	291.73	74.77	8.28	35.23
YSMO 34	8.64	45.06	291.58	74.93	8.04	36.27
YSMO 35	8.71	44.63	290.21	74.68	8.10	35.81
YSMO 36	8.70	45.03	295.08	75.35	8.20	36.01
YSMO 37	8.63	45.10	294.08	75.57	8.04	36.56
YSMO 38	8.43	44.44	281.99	75.32	7.83	36.02
Mean	**8.60**	**44.57**	**288.46**	**75.28**	**8.03**	**35.95**
Median	**8.60**	**44.55**	**289.00**	**75.33**	**8.03**	**35.99**

conditions in Sana'a, Yemen. Fig. 4 shows the degradation of P_{max} correlated to the degradation of I_{SC}, V_{OC}, I_{mp}, and V_{mp} for the modules under study. Degradation

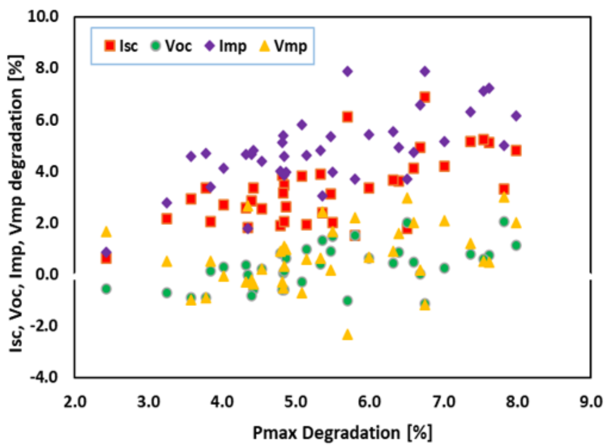

Figure 4. Degradation of P_{max} correlated to the degradation of I_{SC}, V_{OC}, I_{mp}, and V_{mp} for the modules under study

rates shown in Fig. 4 indicate that the P_{max} reductions of modules under investigation are mainly correlated to the losses in the I_{SC} and I_{mp}. Losses in I_{mp} can be ascribed to the decreases of the shunt resistance (R_{sh}). With exception of two modules (YSMO 02, YSMO 33), I_{mp} loss (shunting defect) impacted all modules under study. On the other hand, the reduction in I_{SC} of the modules under study can be correlated to the encapsulation discoloration. According to climate conditions of Sana'a (refer to Section 2.1), encapsulation discoloration is expected to have a significant effect on the degradation of the I_{SC} of modules under study because of these modules being exposed to ultraviolet (UV) light. All modules (except YSMO 02) were affected by this degradation mode. Table 3 summarize the P_{max} degradation rates of multicrystalline silicon modules from different countries with different operational times.

Table 3. Pmax degradation rates of multicrystalline silicon modules from different countries with different operational times.

Country	Climate condition	Operation time (Year)	P_{max} deg. (%/year)	Reference
Yemen	mild	8.65	0.63	This study
Algeria	semi-arid	10	1.7	[22]
Oman	hot and desert	7	0.84	[8]
Mongolia	cold and desert	9.33	1.28	[9]
Ghana	warm and humid	5-9	0.79–1.67	[2]

3.1.1. Visual defects in the modules

The reduction in I_{SC} is one key factor in the evolution of the performance degradation of the studied modules (see Section 3.1). The most noticeable visual defect in the studied modules was a discoloring of EVA encapsulant. Encapsulant discoloration was found on 37 modules with different extent. The encapsulant discoloration reduced the incident photons that reach the solar cells and thus, decreased the I_{SC} and output power (P_{max}) of the modules. Fig. 5 up) shows the module (YSMO 13) with EVA discoloring effect, and Fig. 5 down) shows the I-V curve of this module compared with the datasheet I-V curve of this module. In this module, the I_{SC}, I_{mp}, and FF reductions were 6.88%, 7.87%, and 1.01%, respectively. These reductions lead to a decrease in the P_{max} of 6.76%. This module showed improvements in V_{OC} and V_{mp}. Encapsulation discoloration appears through photo-degradation while being exposed to UV light [23]. Due to the weather conditions of Sana'a, encapsulation discoloration is expected to occur on the modules under study. Minor discoloration of metallisation was found on

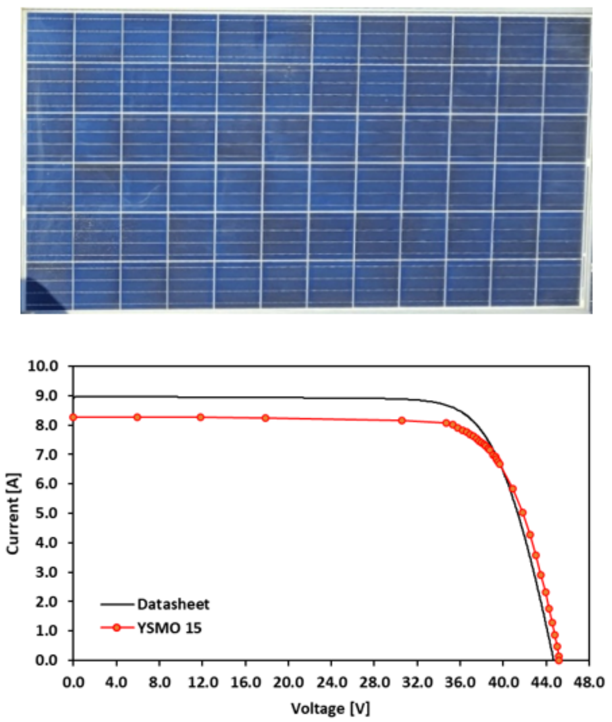

Figure 5. Encapsulant discoloration on the module (YSMO 13), ***down***) I-V curve of this module compared with the datasheet I-V curve.

8 modules. The metallisation of the module consists of busbars and fingers. The discoloration of the metallisation of a module is a type of corrosion of the metallisation. The discoloration of metallisation increased the series resistance (R_S) and led to a reduction in fill factor and output power of the module. Fig.6 up) shows the module (YSMO 06) with discoloration of the metallisation, and Fig. 6 down) shows the I-V curve of this module compared with the datasheet I-V curve of this module. The less steep slope in the vertical leg of the I-V curve is a manifestation of both series and shunt resistance due to resistive interconnections caused by the discoloration of metallisation of the module. In this module, the I_{SC}, V_{OC}, and FF reductions were 3.30%, 2.05%, and 2.69%, respectively. These reductions lead to a decrease in the P_{max} of 7.83%. The discoloration of the metallisation likely occurred because of the presence of moisture and acidity in the encapsulant [24, 25].

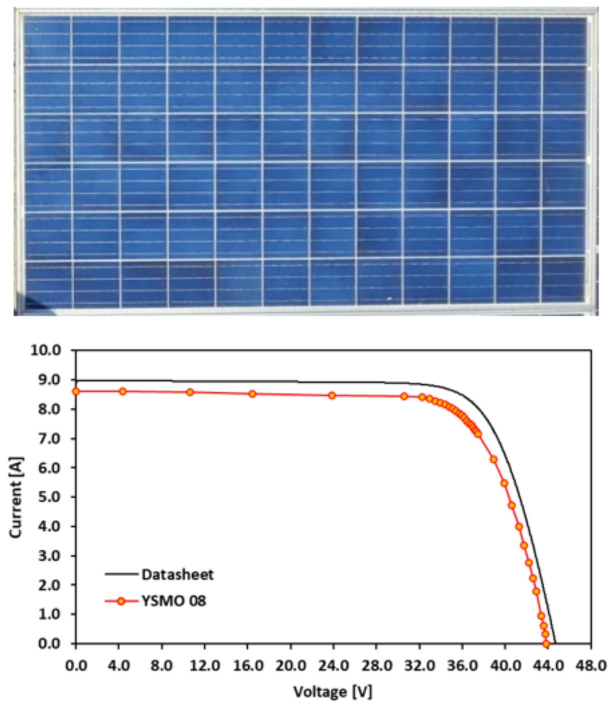

Figure 6. Discoloration of the metallisation on the module (YSMO 06), ***down***) I-V curve of this module compared with the datasheet I-V curve.

4. CONCLUSION AND FUTURE WORK

This study aimed to evaluate the degradation of 38 multicrystalline silicon PV modules that have been exposed to the climatic conditions of Sana'a - Yemen for 8.65 years, to predict the long-term performance of these modules. This analysis was performed based on the results of the visual inspection and I-V curve measurement characterization techniques. The annual degradation rates in P_{max}, over the outdoor exposure period (8.65 years), were found to be between 0.28%/year and 0.92%/year with mean of 0.63%/year and median of 0.61%/year. Based on the industry linear warranty based on nominal power of this module, only 2 modules are likely to fail before 25 years in operation under outdoor conditions in Sana'a, Yemen. The remaining 36 modules are likely to operate reliably for 25 years. The analysis of electrical performance indicated that the P_{max} reductions of the modules under investigation are mainly related to the losses in the I_{SC}

and I_{mp}. Reductions in the I_{SC} and I_{mp} are likely caused by encapsulation discoloration and shunting defects. Some visual defects on the modules under study have been identified. Encapsulant discoloration was found on 37 modules with different extent. Also, minor discoloration of metallisation was found on 8 modules. The impact of the visual defects, like the encapsulation discoloration and discoloration of the metallisation, on the I-V curve of some modules was discussed. Usually, the degradation of the electrical performance parameters of the modules could not be solely attributed to the observed visual defects. So, in the future work, using further characterization techniques such as electroluminescence (EL) and infrared (IR) imaging will be useful to accurately identify the degradation modes affecting these modules. In addition, a quantitative analysis of degradation mechanisms at the cell level using the dark I-V measurement is planned to be carried out as soon as possible.

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