EVALUATION OF PHOTOVOLTAIC MODULES AT DIFFERENT INSTALLATION ANGLES AND TIMES OF THE DAY

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ABSTRACT

Several electricity-consuming components for cooling and heating, illumination, ventilation, and irrigation are used to maintain proper environments of protected crop cultivation facilities. Photovoltaic system is considered as one of the most promising alternative power source for protected cultivation. Effects of environment, type of solar cell, method of installation and operation on power generation performance should be investigated for design and application of photovoltaic system suitable for specific crop, season, and location. In this study, three types of photovoltaic modules were evaluated at different installation angles and times of the day. Units used were single-crystalline, poly-crystalline, and amorphous modules. Installation angle of the modules was varied from 0° (vertical) to 90° (horizontal) on a 15° interval, and measurement times were after sunrise, noon, and before sunset. Solar radiation (total and spectrum) and generated electricity were obtained for 270 seconds for each installation angle and photovoltaic module, and optimum installation angles providing the greatest ratio of tilt to horizontal radiations. The values were 2.77 at 60° and sun-set, 2.39 at 75° and sun-rise, and 1.40 at 45° and noon, respectively, for all of the modules. Power generation was in the order of noon, sun-set, and sun-rise. Generated power of the amorphous module was about 43% of those of single- and poly-crystalline silicon modules. Results of the study would be useful for selection of installation method suitable for different crops and regions.

Keywords: Protected cultivation, Alternative energy, Photovoltaic module, Installation angle

INTRODUCTION

Area of protected crop production has been increasing in many countries in the world as well as in Korea. In Korea, area of protected crop production increased from 44,613 ha in the 1990s to 91,487 ha in 2010, about 26% of the total crop production, and among them leaf vegetable was 55.8% (KAMICO and KSAM, 2010). Farming household of protected crop production increased from 3,416 in 2002 to 4,075 in 2007 in USA (USDA, 2009). Protected crop production has advantages of year-round production and controllable environments for higher yield and quality, but requires greater energy (e.g., electricity) to maintain optimum environmental conditions proper for crop growth than field production. Hatirili et al. (2006) classified energy for protected crop production into five categories as cooling and heating fuel, nutrients, chemicals, human power, and electricity, and stated that electricity took about 16% of the total required energy.

Among alternative energy sources, solar energy is considered as a promising energy source for protected crop production facilities. Research on application of alternative energy, especially using photovoltaic (PV) modules, to protected crop production facilities has been reported. Yano et al. (2007) developed a PV-based system for window opening motors. With 3.2-W amorphous-silicon modules, cumulative energy production of the system was 2.84 MJ during the two-month experimental period. And he extended the PV system to cover greenhouse roof with arch-shaped 5 modules (Yano et al., 2009).

Performance of a PV system is influenced by various factors including type and operation method, installation angle, temperature, humidity, cloud cover, solar radiation and spectral wavelength bands. In study on comparison of solar-tracking and fixed PV systems, Huang et al. (2011) reported that the efficiency of the solar-tracking system ranged from 18.5 to 28% (mean: 23.6%) of solar radiation, which was greater than that of the fixed system by 34.6%. Carr et al. (2004) compared performance of 7 PV modules, and reported that amorphous silicon and CIS (copper indium diselenide) modules generated 8~15% and 9~13% greater than crystalline silicon modules.

Among factors affecting power generation of PV systems, installation angle is important, especially for fixed PV systems. Kacira et al. (2004) analyzed cumulative radiation levels onto PV modules at different installation angles. Cumulative solar radiation was the greatest at a 10° installation angle and the lowest at 50° installation angle in June in Sanliurfa, Turkey. Kim et al. (2009) analyzed distribution of solar radiation at 22 locations in Korea and reported that optimum installation angles for spring, summer, fall, and winter were 35°, 5°, 45°, and 60°, respectively. Ibraham et al. (1995) compared monthly solar radiation using Cyprus National Weather Service of Northern Ireland (latitude 35 ° 11'N) and suggested that optimum installation angles 48° and 14°, for summer and winter seasons, respectively.

Beringer et al. (2001) analyzed relationships between installation angle and generated electricity. When the angles were varied from 0 to 70° on a 10° interval in Hannover, Germany, optimum angles were in ranges of 0 ~ 30° during the summer and 50 ~ 70° during the winter seasons. Mohd et al. (2001) analyzed total solar radiation data by the National Weather Service in Brunei, Darussalam, using mathematical modeling, and determined condition of the maximum radiation, or optimum installation angle. Optimum angles obtained using five 2-hour interval data sets from 8 to 16 were monthly averaged, and an annual optimal angle Brunei, Darussalam was calculated as 3.3°. Hussein et al. (2004) studied on estimation of power generation of a fixed type single-crystalline PV system by installation angle, and found that the optimum annual installation angles for Cairo, Egypt, were 20~30° when the module was facing to the South. Generated electricity when the PV module was horizontally (0°) and vertically (90°) installed were 95% and 41% of that of the optimum installation, respectively.

Efficiency of PV modules may not be constant due to different solar radiation spectrum. Objective of the study was to evaluate PV modules at different installation angles and times of the day.

MATERIALS AND METHODS

Experimental system and data acquisition

Three 200-W level PV modules were used in the study; single- and poly-crystalline modules (Hyundai Heavy Industries Co. Ltd., Ulsan, Republic of Korea) and amorphous module (Getwatt Co. Ltd., Jeungpyeong, Republic of Korea). The crystalline and amorphous modules used 400~1,100 nm and 400~700 nm of the solar radiation spectrum, respectively, as shown in Table 1. Experiments were conducted on a clear day (cloud level is less than 2 out of 10 ratings) at Chungnam National University (latitude: 36°.52'N, longitude: 127°.21', altitude: 63 m), Daejeon, Korea. Installation angle of the modules was varied from 0° (vertical) to 90° (horizontal) on a 15° interval, and measurement times were after sunrise, noon, and before sunset. Experimental duration at each time was less than 2 hours including the angle adjustment and 270 seconds data acquisition at each angle. Criteria of the "clear day" and experimental times were based on the announcement by the National Weather Service, Korea.

Table 1. Characteristics of the PV modules used in the study.

		Single-crystalline	Poly-crystalline	Amorphous
Model	-	HIS-S200SF	HIS-M200SF	S100E
Output tolerance	%	±3	±3	±5
Module efficiency	%	13.8	13.8	-
Wavelength range	nm	400~1000	400~1000	400-700

Along with the power generated from the modules, several auxiliary data were also collected for analyses. Two solar radiation sensors (Model: SP-110, Apogee Instrument Inc., Logan, Utah, USA) were used: one on the plane of the inclined photovoltaic module and the other on the horizontal plane. Module temperature (Model: PT-100; Shinsegi Sensor Co., Seoul, Republic of Korea) measured on the back side of each module, and ambient (Model: DY-HQ-7-N-N, Daeyeon control & Instrument Co., Seoul, Republic of Korea) were collected. Solar radiation spectrum was also collected on the inclined module using a spectrometer (Model: PS-300, Apogee Instrument Inc., Logan, Utah, USA). Figure 1 shows experimental setup and data acquisition equipment.

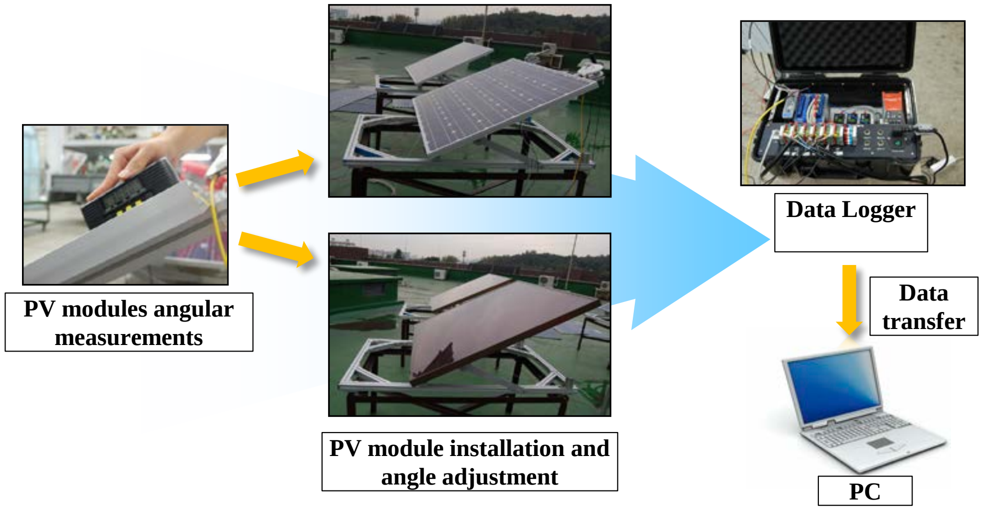

Figure 1. Fixed installation of PV systems.

Theoretical optimal angle

Theoretical optimum angle of fixed PV modules at a certain time is calculated as shown in Figure 4. Solar declination (δ) is expressed as a function of the ordinal date (d) as in equation (1) (Messenger, 2010).

$$\delta = 23.46^{\circ} \left[\sin \frac{360(d-80)}{365}\right] \quad (1)$$

Where, d is the ordinal date (1 at January 1st, and 365 at December 31st).

Declination value varies from 23.45˚ to -23.45˚ as the earth rotates around the sun (Figure 2). Zenith angle varies according to the declination angle, and determines the optimal angle of fixed PV modules. Figure 3 shows relationship among declination (δ), latitude ($\emptyset$), and zenith angle (θ_z) in winter and summer at noon. For the northern hemisphere, the hour angle (ω) can be calculated following equation (2).

$$\omega = \frac{12-T}{24} \times 360^{\circ} = 16(12-T)^{\circ} \quad (2)$$

Where, T is the time of a day.

Altitude of the sun is calculated using the solar declination, hour angle, and latitude values, as in equation (3).

$$\sin\alpha = \sin\delta \sin\emptyset + \cos\delta \cos\emptyset \cos\omega \quad (3)$$

Sun azimuth is calculated using equation (4). In this experiment, the solar module was faced to the South $(\varphi = 0°)$ (Tawanda, 2000).

$$\cos\varphi = \frac{\sin\alpha \sin\emptyset - \sin\delta}{\cos\alpha \cos\emptyset} \quad (4)$$

Finally, optimum installation angle of PV modules (β), facing perpendicular to the direction of solar radiation is calculated as in equation (5) (Kacira et al., 2004).

$$\beta = 90° - \alpha \quad (5)$$

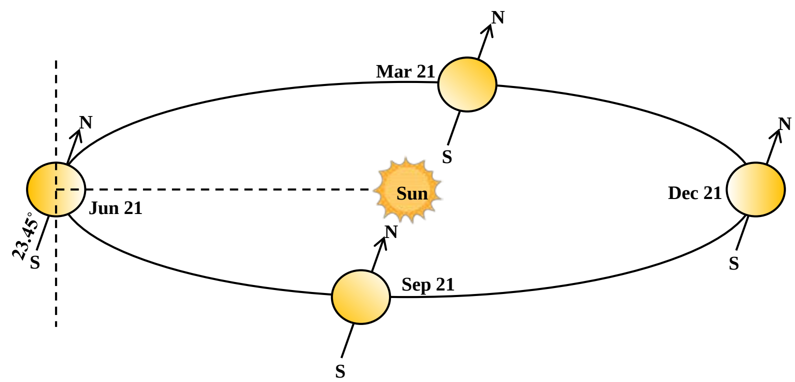

Figure 2. The orbit of the earth and the declination at different times of the year.

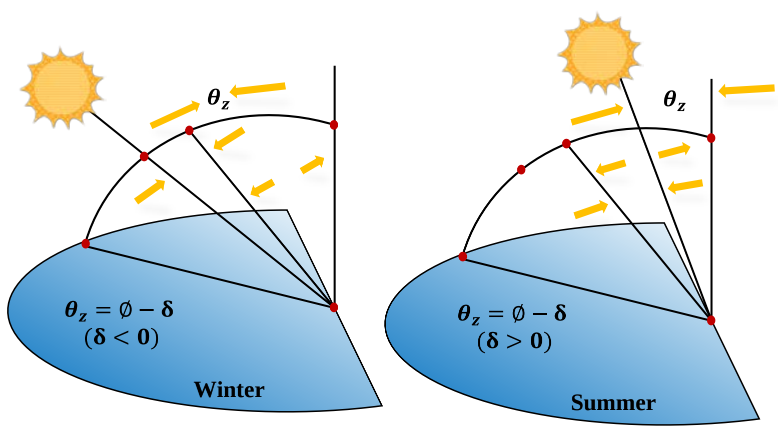

Figure 3. Relationships among zenith angle, latitude and declination at solar noon in winter and summer.

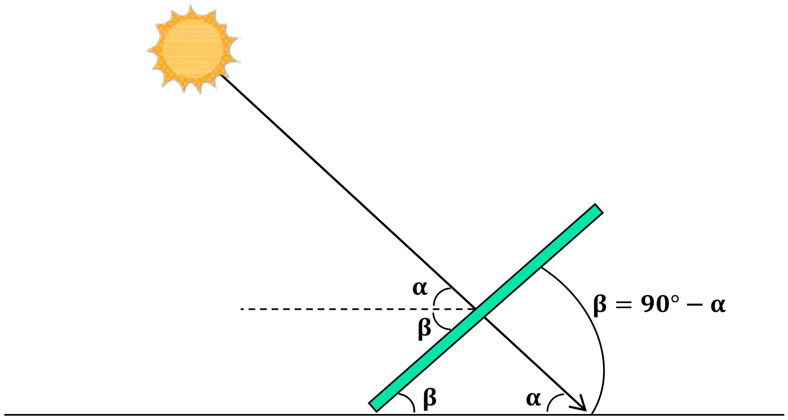

Figure 4. Optimum installation angle of fixed PV modules.

RESULTS AND DISCUSSION

Figure 5 shows example plots of generated power, and module and ambient temperature levels during the experiments at noon. The module temperature showed only a slight change (maximum 43°), therefore efficiency change of the PV modules was not considered for later analyses.

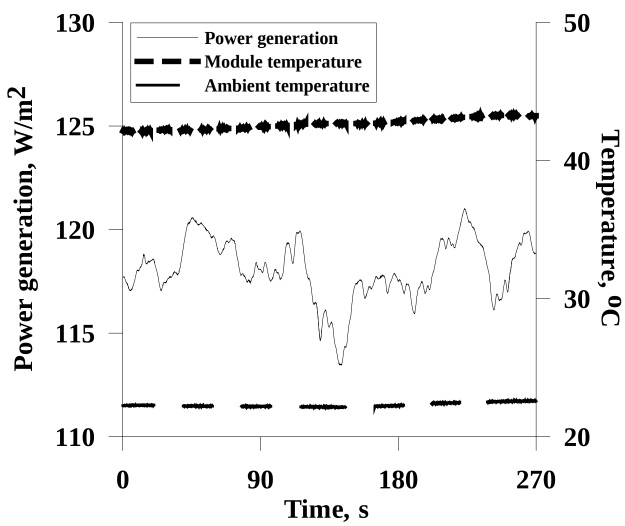

Figure 5. Example plots of generated power and temperature values.

Figure 6 shows ratio of tilt to horizontal solar radiation values (left) and radiation spectrum (right) for the sun-rise (top), noon (medium), and sun-set (bottom) periods. Ratio of tilt to horizontal solar radiation (RTH) was used as a criterion for optimum installation angle receiving maximum solar radiation (Figure 6 and Table 2). Amount of solar radiation energy and RTH changed with time due to change in relative radiation direction. During the "after sun-rise" period, RTH values were in the order of 75 (2.39), 60 (2.28), 45 (2.07), 90 (1.89), 30 (1.67), 15 (1.34), and 0° (1.0) installation angles, indicating the 75° was the optimum angle during the “after sun-rise” period. Radiation values were less than 2 W/m^2 for all wavelengths.

Although solar radiation at noon was greater than that at “after sun-rise”, especially at visible wavelength bands, RTH values were less. The maximum RTH (1.40) was obtained for a 45°-installation angle. Similar to the case of “after sun-rise”, solar radiation decreased and RTH values increased, compared to “noon”. Optimum installation angle was 60°, and corresponding RTH was 2.77. As summarized in Table 2, experimental optimum installation angles were similar with the theoretical optimum installation angles.

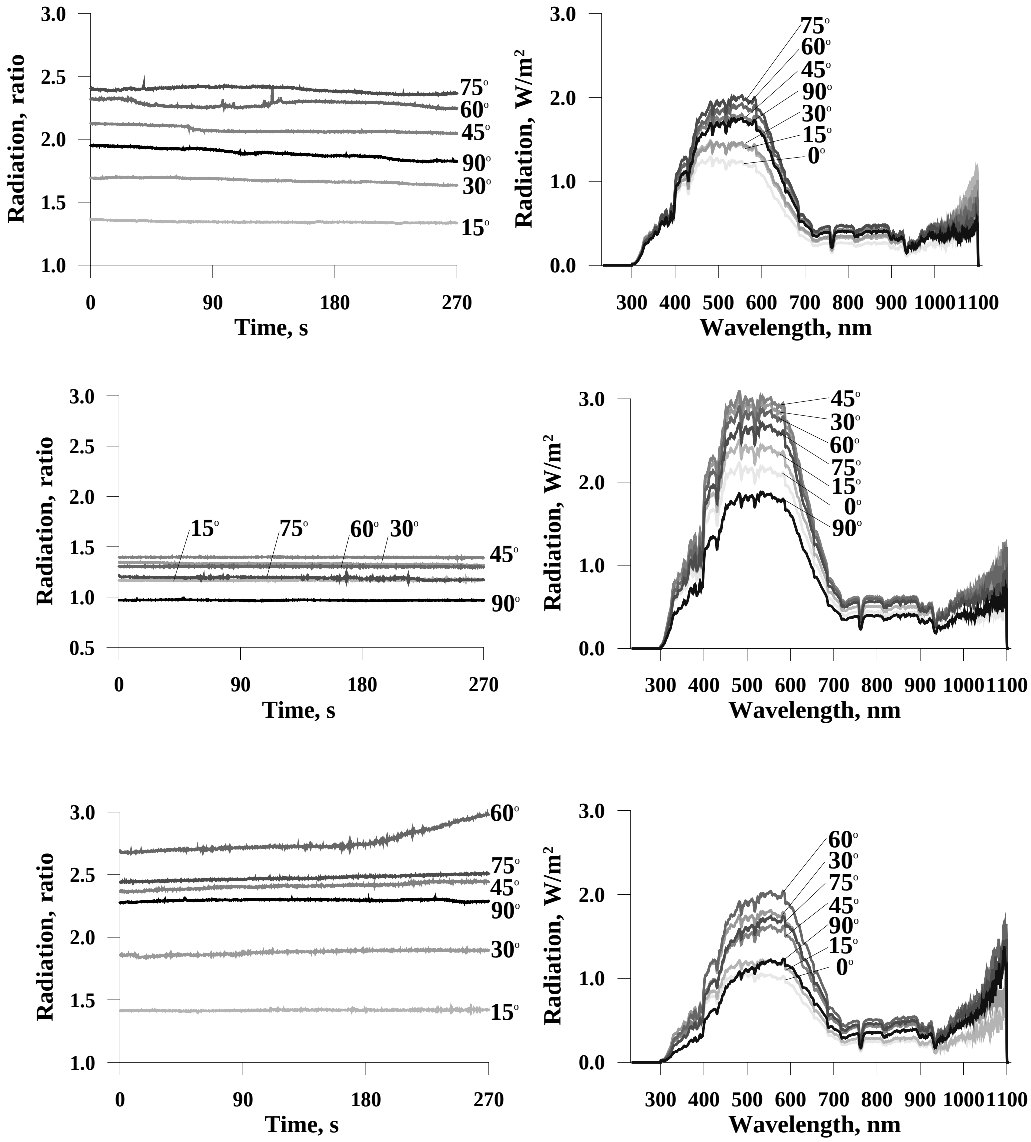

Figure 6. Ratio of tilt to horizontal radiation (left) and tilt radiation spectrum (right) for "after sun-rise" (top), noon (medium) and "before sun-set" (bottom) by installation angle.

Table 2. Experimental RTH values by installation angle and time of the day.

Installation angle	Ratio of tilt to horizontal radiation		
	After sun-rise	Noon	Before sun-set
15°	1.34	1.17	1.42
30°	1.67	1.33	1.88
45°	2.07	**1.40**	2.41

60°	2.28	1.30	**2.77**
75°	**2.39**	1.19	2.48
90°	1.89	0.97	2.29

Different PV modules use different wavelength band ranges of solar radiation. The ranges for the crystalline and amorphous modules were 400~1,100 and 400~700 nm, respectively. Table 3 summarized summation of radiation within the wavelength ranges measured by the spectrometer at each experimental level, and the results confirmed maximum cumulative solar radiations at the optimum installation angles.

Table 3. Solar radiation (W/m^2) within the wavelength ranges used for the PV modules at different installation angles.

	Wavelength range (nm)	Installation angle						
		0°	15°	30°	45°	60°	75°	90°
Sun-rise	400-1100	882.4	1080.9	1068.8	1253.5	1315.2	**1342.2**	1161.3
	400-700	667.3	781.6	793.6	965.4	1021.1	**1084.9**	966.3
Noon	400-1100	1474.8	1731.8	2035.0	**2116.3**	1990.0	1833.4	1274.2
	400-700	1160.4	1313.2	1606.2	**1636.6**	1567.3	1476.8	1054.4
Sun-set	400-1100	788.1	869.0	1284.2	1219.1	**1495.0**	1281.2	939.7
	400-700	563.0	649.9	951.9	857.6	**1069.9**	921.2	676.0

Figure 7 shows plots of electricity generation during the experiments for the three optimum angles, and Table 4 summarizes quantity of the power. For "after sun-rise" period and crystalline modules, power generation levels were in the order of installation angles of 75, 60, 90, 45, 30, 15 and 0°, while solar radiation levels and RTH values were in the order of 75, 60, 45, 90, 30, 15 and 0°. For the amorphours module, the patterns were similar with a little discrepancy as the case of the crystalline modules.

Power generation levels of the two crystalline modues were similar, and that of the amorphouse module was about 42%, 38% and 34% for "after sun-rise", noon, and "before sun-set" periods, respectively.

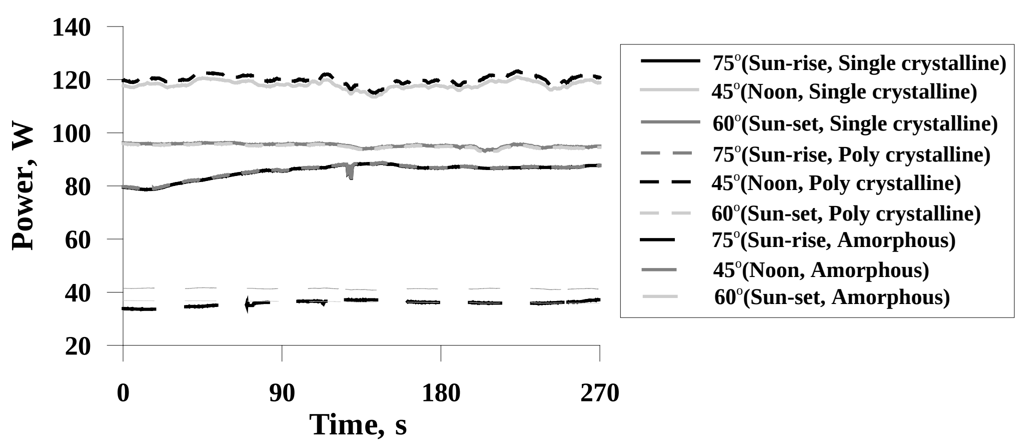

Figure 7. Power generation during the experiments.

Table 4. Summary of power generation(mean value) during the experiments.

Type	Time	Power generation based on the angle (W)						
		0°	15°	30°	45°	60°	75°	90°
Single-crystalline	Sun-rise	20.30	40.39	52.25	55.99	73.74	**85.59**	58.97
	Noon	84.50	110.09	115.46	**118.03**	113.84	90.36	73.73
	Sun-set	17.32	35.92	53.68	71.96	**95.27**	81.48	70.82
Poly-crystalline	Sun-rise	19.72	40.30	51.65	58.75	75.40	**85.76**	63.43
	Noon	85.95	112.23	118.34	**120.01**	115.77	91.71	76.70
	Sun-set	17.14	34.69	54.70	72.71	**94.90**	80.73	70.17
Amor-phous	Sun-rise	18.78	24.52	28.71	29.85	33.26	**35.91**	27.85
	Noon	38.01	**41.13**	**41.34**	**41.32**	40.59	37.24	31.73
	Sun-set	12.01	21.43	27.42	32.46	**36.35**	32.80	28.91

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