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APPLICATION OF MONITORING AND MANAGEMENT OF SOLAR PHOTOVOLTAIC SYSTEM—CASE STUDY OF SHADOW EFFECT AT NATIONAL TAIPEI UNIVERSITY OF TECHNOLOGY

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ABSTRACT: This study analyzed the influences of the solar photovoltaic system's partial shadow on the solar modules' power generation capacity. The shadow effect reduces the electricity generation capacity and may lead to the hot spot effect. The solar photovoltaic equipment of the comprehensive science building at the National Taipei University of Technology is managed by a solar power generation monitoring and management system. The important data such as solar irradiance, temperature, and power generation capacity are read by Modbus and sent back to the remote monitoring system after being converted into Ethernet by communication converter RS-485. Managers could observe the current power generation in real-time and understand the use of solar equipment after analyzing the historical data. According to the experimental findings, the recent installation of the anti-falling net resulted in the partial shadow of the solar modules. This reduced the efficiency of the solar photovoltaic system by 31.78%. It also leads to higher temperatures of the solar modules than the normal module. If this continues for a long time, the hot spot effect will occur, and the solar modules will be damaged and will be unusable.

INDEX TERMS—solar photovoltaic system, shadow effect, power generation capacity of the system, hot spot effect

1. INTRODUCTION

For industrial and economic development, traditional energy sources such as coal, oil, and natural gas, are used for power generation. These fossil fuels cause air pollution, acid rain, climate change, and global warming. These traditional energy sources are facing depletion [1]. Therefore, renewable energy development has become the research target of countries in recent years. Renewable energy includes solar energy, wind energy, hydropower, geothermal energy, and biomass energy. Among these, the sun provides permanent energy which is available everywhere [2]. Therefore, all countries are suitable to develop solar energy. Solar energy applications are increased with the rise of environmental awareness and the continuous advancement of science and technology. These applications include solar water heaters, solar power generation systems, solar cells, and solar street lamps. These applications are gradually integrated into our daily lives [3]. Silicon semiconductors are the main material in most solar modules. Silicon is cheap and easy to get. It can be divided into monocrystalline and polycrystalline silicon. Monocrystalline silicon has the highest conversion efficiency. Monocrystalline silicon has complete structure, no impurities, long crystallization time, and high manufacturing cost. Polycrystalline silicon has many impurities due to its short crystallization time and a low cost [4-5].

For energy safety and environmentally sustainable development, Taiwan's government is committed to achieving the goal of a solar photovoltaic installed capacity of 20GW by 2025. The government can increase the installed capacity in various industries by building

demonstration fields, developing incentives mechanisms, and strengthening talent training. Moreover, the solar energy symbiosis with agriculture, fishing, livestock, roof-type, and floor-type photovoltaic equipment, also increases the effective usage of space. All these methods help achieve the government's goals [6].

Before installing the solar photovoltaic system, it is necessary to consider the installation location, orientation, angle, and the shadow effect resulting from buildings and trees in the surrounding environment [7-8]. This is to protect the solar modules from the hot spot effect caused by the temperature of the solar modules at 200℃ [9]. Regular inspection and maintenance of the equipment such as regular cleaning of the solar modules, maintenance of the remote monitoring and management system, follow-up maintenance, and removal of abnormal conditions, influence the operational efficiency of the solar photovoltaic system [10].

This study compared the difference in power generation of the solar photovoltaic system installed in the middle hall of the comprehensive science building at the National Taipei University of Technology under normal operation and under the condition that some solar modules are shaded for a long time after the recent installation of the anti-falling net on the walls of the top floor to enhance campus safety. This study also explored the subsequent influences and damages.

2. RESEARCH METHOD AND PROCEDURES

A. Solar photovoltaic device

The total installed capacity of the north, middle and south halls of the comprehensive science building at National Taipei University of Technology (NTUT) is 70.38 kWp. The power generation system is grid-connected utility power. The grid-connected solar photovoltaic system supplies power to the load, and Taiwan Power Company supplies power in case of insufficient power generation. The direct current generated by the solar photovoltaic system is converted into the alternating current by the load by the converters. The data of the converter, wattmeter, pyrheliometer, and thermometer in three halls are read by Modbus. The data is then sent to the server after being converted into Ethernet by communication converter RS-485. The required data is displayed on the public solar electronic information billboard. The monitoring system architecture is shown in Fig. 1 [11].

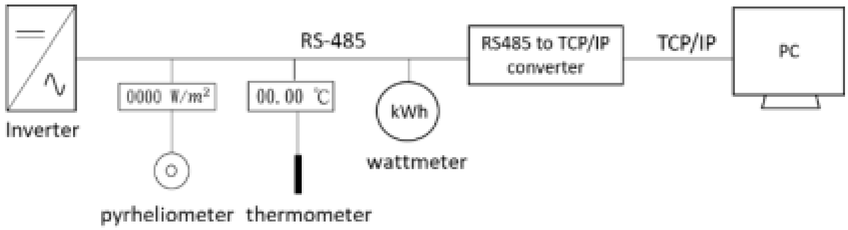

Fig. 1 Monitoring system architecture

B. Communication equipment

After the data read by Modbus are converted into Ethernet by communication converter RS-485 and then transmitted to the server host for storage, the data of all devices are shown on the remote network monitoring page. Afterward, the overall power generation is displayed on the public solar electronic information billboards via Ethernet.

(a) Modbus communication protocol

Modbus is a serial communication protocol with a master-slave scheme. It is often used in Human Machine Interface (HMI) and Supervisory Control and Data Acquisition (SCADA) systems [12]. A slave is the transmission parameter in the main Modbus protocol, and each slave has a unique address. Only one master device is responsible for starting each command and waiting for the response of other slave devices. Master devices are usually man-machine interfaces or SCADA systems, and slave devices are usually sensors or electric meters. Communication transmission modes can be divided into Modbus RTU, Modbus ASCII, and Modbus TCP. Modbus RTU transmits using a binary system while Modbus ASCII transmits ASCII code. RTU adopts hexadecimal coding, which saves half of the communication overhead compared to ASCII. In terms of check codes, RTU adopts CRC (Cyclic Redundancy Check) and cyclic correction codes, and ASCII uses Longitudinal Redundancy Check(LRC), the longitudinal correction. In contrast, CRC correction codes are rigorous. Modbus TCP is transmitted via the Ethernet, consistent with the current mode of the data transmission in the monitoring system.

(b) RS-485 communication transmission

RS-485 is a data transmission mode commonly used in industry, with a transmission distance of 1.2 km and a transmission rate of 10 Mb/s. It adopts a differential transmission mode and has a strong ability to resist common-mode interference. RS-485 is half-duplex and requires a transmission line (TxD) and a receiving line (RxD). The difference between the potentials at both ends is the voltage reference standard, and transmission can be achieved without ground wires [13]. Table I is the RS-232 & RS-485 Comparison of Communication Specification.

Table I RS-232 & RS-485Comparison of Communication Specification

Type	RS-232	RS-485
Operating mode	Single-Ended	Differential transmission
Drivers/Receivers number	1/1	32/32
Maximum transmission distance (m)	15	1,200
Maximum transmission speed (Mbit/s)	1	10

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C. Hardware

To build a solar photovoltaic system, tools such as a solar module, converter, pyrheliometer, and module temperature measurement device are required. The collected data can be sent back to the server through communication equipment for management and analysis by the background monitoring system.

(a) Pyrheliometer and thermometer

A pyrheliometer is a sensor that measures the sunlight intensity, expressed in W/m^2 [14]. The actual values are output as the voltage of 0-10 V or current of 4-20 mA to the digital electric meter for display. The solar radiation monitoring equipment is shown in Fig. 2.

(a) ***(b)***

Fig. 2 Solar radiation monitoring equipment (a)pyrheliometer (b) digital electric meter

In addition, the influence of temperature on solar modules cannot be ignored. Under the same illumination, if the module temperature rises, the open-circuit voltage decreases, the short-circuit current increases, the output power decreases, and the overall efficiency decreases. Therefore, it is necessary to monitor the temperature of the solar photovoltaic modules. In this case, a Pt100 temperature sensor is used. After the converter converts the output analog signals, their actual values are displayed on the digital electric meter, as shown in Fig. 3 solar temperature monitoring device.

(a) ***(b)***

Fig. 3 Solar temperature monitoring device (a) Pt100 thermometer (b) digital electric meter

(b) Solar module

Solar cells can be divided into silicon solar cells, compound semiconductor solar cells, and organic solar cells (also known as dye-sensitized solar cells). Silicon is commonly used in solar cells, subdivided into monocrystalline silicon, polycrystalline silicon, and amorphous silicon solar cells [15].

In this case, polycrystalline silicon solar cells are mostly used. The specifications are shown in Table II, and solar modules are shown in Fig. 4.

Table II PV module specification

Rated Power	230W
Rated Voltage	29.49V
Rated Current	7.8A
Open Voltage	37.2V
Short Current	8.39A
Efficiency	14.3%

Fig. 4 Field solar modules

(c) Inverter

The direct current generated by the solar modules is converted into alternating current by an inverter, as shown in Fig. 5.

Fig. 5 Inverter

Inverters are selected according to the number of solar modules on the field. For example, eight solar modules were connected in series in this case, each with a rated power of 230 W and a combined output power of 1,840 Wp. Therefore, 5 kW capacity inverters were used. The inverter specifications, in this case, are shown in Table III. The supplied load transmission and distribution system adopt a three-phase four-wire alternating current of 120/208V. If the DC input voltage is 70-580 V in the inverter, the automatically tracked AC output voltage will be 208 V, the frequency will be 60 HZ, and the conversion efficiency will be 98%.

Table III Inverter Specification

Type		PV-5000S-V
DC input	Start-up voltage	90V
	Maximum voltage	600V
	PV input operating voltage range	70~580V
	Maximum current	13x2A
	Maximum short circuit current	15x2A
	Maximum power point tracker	2
AC output	Rated power	5kW
	Maximum apparent power	5.5kVA
	Maximum current	23.8A
	Rated voltage	220/230

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		/240V
	Rated frequency	50/60Hz
Efficiency	Maximum efficiency	98.0%
	European efficiency	97.2%
Environment	Temperature	-25~60℃
	Humidity	0~100%
	Waterproof/dustproof grade	IP66
Communication	Communication interface	RS485

D. Remote monitoring and management system

WebAccess, the monitoring software used in this case, can be used for data value display, trend chart analysis, and equipment operation monitoring. The server collects data on all solar photoelectric devices, such as voltage, current, power, and solar irradiance. This helps the server monitor converter operation, real-time power generation information, and historical data search. It also makes it easy for managers to manage and analyze power generation efficiency and remove faults in real-time [16], as shown in Fig. 6.

Fig. 6 Real-time monitoring page

After calculation, the three halls' total solar photoelectric power generation information is transmitted to the public solar electronic information billboard on campus via the Ethernet, as shown in Fig. 7.

Fig. 7 Public solar electronic information billboard

3. RESULTS AND DISCUSSION

A. Shadow effect in the case field

In the case field, some solar modules have the shadow effect due to the anti-falling net installed around them, as shown in Fig. 8.

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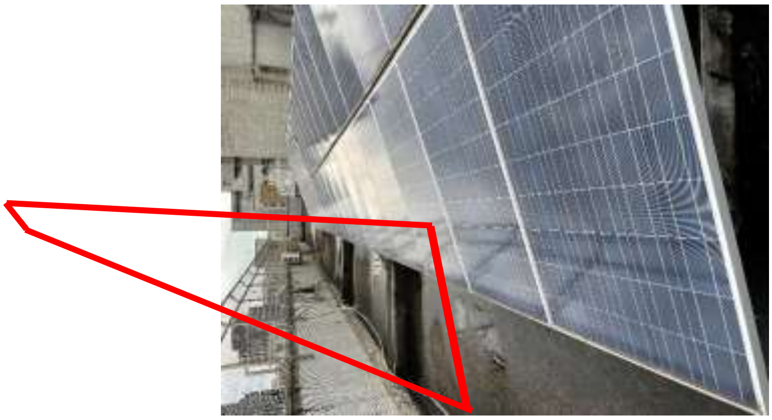


Fig. 8 In the field of shadow

To compare its influence, the data in the monitoring system are analyzed. The data of the same module at different times and the data of different modules simultaneously were collected and analyzed.

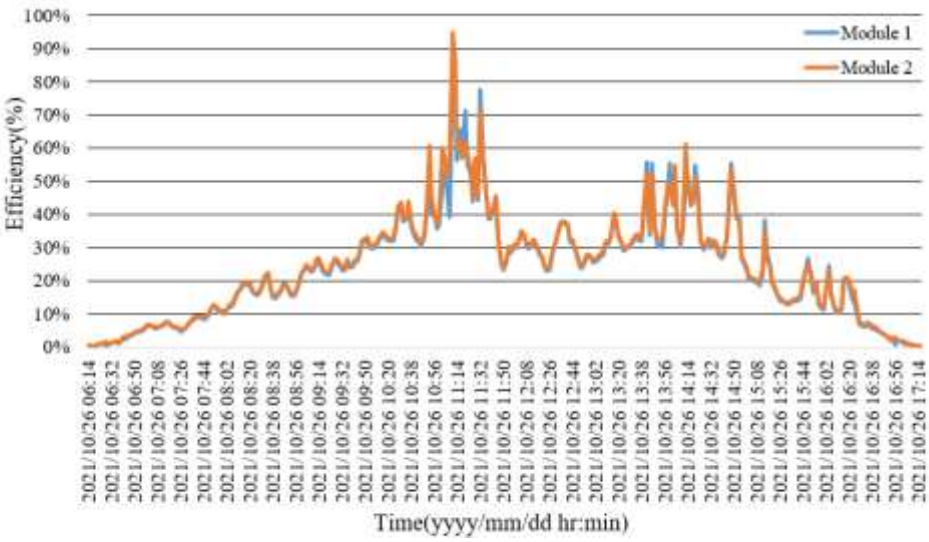
B. **Efficiency analysis based on experimental results**

According to the data collected by the remote monitoring system, at the solar irradiance of 930 W/m^2 of the same solar power generation device, the power generation efficiency without shadow is 87.54%. The power generation efficiency with the shadow is 55.76%. This indicates that the efficiency was reduced by 31.78%. A higher solar radiation intensity has a greater influence on the efficiency of solar modules, as shown in Table IV.

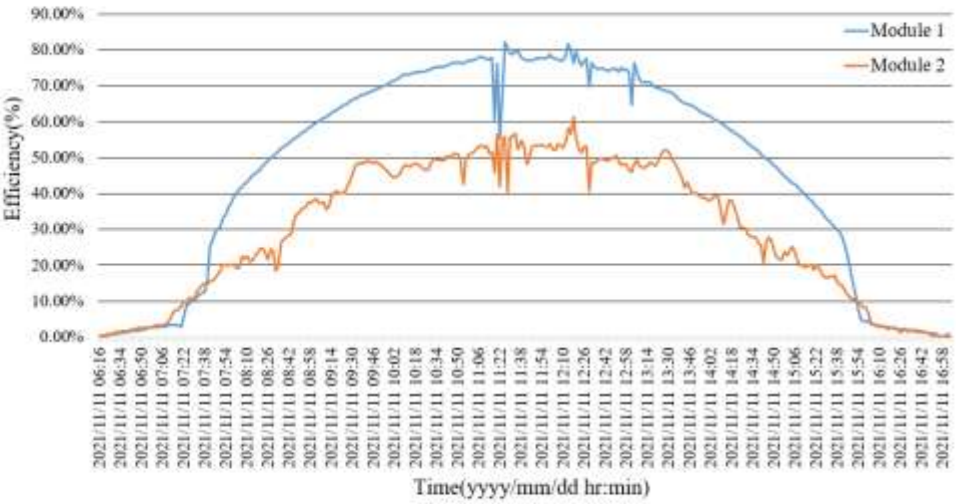
Table IV Compare efficiency with shadow and unshadow

	930 W/m^2	705 W/m^2	528 W/m^2	299 W/m^2
Before	87.54%	60.91%	45.70%	27.51%
After	55.76%	38.47%	24.69%	15.19%
Difference	31.78%	22.44%	21.01%	12.32%

By comparing two different solar power generation devices simultaneously at the same orientation and at the same tilt angle, Module 1 is the one without the shadow effect, and Module 2 is the one with the shadow effect. Without the shadow effect, the power generation efficiency of Module 1 and Module 2 was almost the same. After installing the anti-falling net, Module 2 had the shadow effect. This resulted in a significant reduction in overall power generation. There was a significant difference in efficiency compared with Module 1 without shadow effect, as shown in Fig. 9.



(a)



(b)

Fig. 9 Comparison of solar power generation efficiency (a) before the shadow effect (b) after the shadow effect

Through further data comparison, at the solar irradiance of 931W/m^2, the power generation efficiency is 77.11% without shadow effect and 48.27% with shadow effect. The difference is 28.84%. This indicates that with the shadow effect, the efficiency of solar photovoltaic equipment is significantly reduced by 20%-30%, as shown in Table V.

Table V Compare efficiency with shadow and unshadow

	931 W/m^2	859 W/m^2	617 W/m^2	433 W/m^2
Module 1	77.11%	74.11%	54.74%	38.00%
Module 2	48.27%	46.44%	28.83%	20.16%
Difference	28.84%	27.67%	25.91%	17.84%

Based on the above findings, in the case of partial shadow, the power generation of solar modules declined. This leads to a reduction in power generation efficiency and lower power generation than expected.

4. CONCLUSION

In this study, the current operation of the solar photovoltaic system was effectively observed in real-time through the solar remote monitoring and management system of the comprehensive science building at the National Taipei University of Technology. It was observed through the remote monitoring and management system that the power generation capacity at the field declined. This decline was found to be caused by the shadow effect. According to the comparison and analysis results of the data, the efficiency of the same solar module decreased by 31.78%. A higher solar irradiance negatively influences efficiency. If the shadow effect cannot be solved, there will be a severe hot spot effect over time. Moreover, the whole solar module will be damaged and will be unusable.

Installing solar photovoltaic systems has been the government's policy worldwide. After installation, the management, regular cleaning, and maintenance are important items for the long-term efficient operation of solar photovoltaic modules. This extends their service life, strengthens energy safety, and achieves environmentally sustainable development.

Consent to participate

This manuscript has no human experiments (not applicable).

Consent to publish

This manuscript has no human experiments (not applicable).

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Conflict of interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Availability of data and materials

The data used to support the findings of this study are included within the article.

Ethical Approval

Not applicable

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