（様式第１３号）

学 位 論 文 要 旨

氏名:　LI ZHI

題目: Development of a greenhouse dynamic shading system using a semi-transparent photovoltaic blind
（半透過型太陽電池ブラインドを利用した温室動的遮光システムの開発）

Reduction of the dependence on fossil fuel consumption and utilization of renewable energy have been demanded for greenhouse cultivation management. On a single land unit, semi-transparent photovoltaic (PV) modules installed on a greenhouse roof can provide electrical generation and an adequate level of shading to crops. This study assessed a prototype greenhouse venetian-blind-type shading system using bifacial semi-transparent PV modules as blind blades. This stand-alone system was operated using electrical energy generated by the PV module. Moreover, the blind orientation can be change autonomously according to solar irradiance levels. The PV blind orients itself parallel to the greenhouse roof and generates electricity with moderate shading when the solar irradiance is intense. When the irradiance is less than a threshold value, the blind orients itself as perpendicular to the roof. Priority is assigned to the solar irradiance intake in the greenhouse rather than to the electricity generation. This dissertation presents three phases of development of this electrical-energy-producing greenhouse shading system.

The semi-transparent PV module differs greatly from general PV products in terms of structure and performance. In one semi-transparent PV module with 0.1 m^2 area, 13,764 particles of mono-crystalline-silicon PV cells with 1.2-mm-diameter were embedded. The percentage of the opaque area comprising the PV cells and the conductors was 31.1% when the module was viewed from the module normal direction. Its peak output was 1.5 W. As a shading material, it can provide many benefits for greenhouse crop production. In the three phases of the study, one, two, and three semi-transparent PV modules were used, respectively, to construct the rotatable PV blind. The electrical characteristics and shading percentages of the PV modules were measured. The measured maximum power output P_{max} of the single PV module was 1.5 W. The single PV module was installed on the west-facing roof of a greenhouse without glass surface. The average module efficiency values based on the entire PV-module single-side area were 1.3%. The measured maximum P_{max} of the twin PV-modules was 2.3 W. The twin PV modules were installed underneath the east-facing roof of another greenhouse with a glass surface. The average efficiency of the twin PV-modules was 1.1%. In the triple PV module blind system test, the PV module’s electrical characteristics were measured underneath the east-facing greenhouse roof and at a field plot. The measured maximum P_{max} of the triple PV modules was 2.1 W inside the greenhouse and 3.75 W outside the greenhouse. Their respective efficiency values were 1.0% and 1.2%. The results suggest that external installation would greatly improve electricity production. Externally mounted PV blinds with lower PV cell density would compensate the electricity demands of conventional greenhouses in high-insolation regions. Moreover, the decreased cell density is expected to increase agronomic

sustainability for greenhouse crop cultivation. Waterproofing and mechanical reliability against severe weather conditions should be included in PV blind systems that are intended to be installed externally.

Irradiance in the PV cell shadows was measured using a pyranometer positioned 1 m below the PV module in the first study phase. Then, at the second and third study phase, this distance was changed to 0.2 m. The respective calculated module shading percentages in all three phases were 39%, 42%, and 38%. Because the sun altitude and azimuth during the measurements differed, the ranges of angle between direct sunlight incidence and the sky-directing PV module's normal differed. Therefore, slight differences were found in the measured results. Some reports of earlier studies suggest that the present dynamic blind control with less than 40% shading of the PV blind might be beneficial for greenhouse cultivation of moderate-light demand crops in high-insolation seasons or regions.

In the first study phase, an electronic control circuit was developed specifically to regulate the PV module inclination autonomously according to solar irradiance. Successful operations of the PV blind system demonstrated that the idea is feasible. Unfortunately, at the end of six-day and four-day experiments in the spring, the energy balances were negative. Therefore, in the next two study phases, the motor control circuit was improved to enhance the system efficiency and to make the system more precise. To increase the electricity production, one more PV module was added in each of the second and third phases of the study. A MOS FET relay was added at the drive circuit inlet to reduce the standby energy consumption of the motor drive circuit during night-time. Consequently, the energy balance became positive at the end of the two-month experiment in the spring. In the third phase of the study, the motor control circuit was improved further. The system operation was tested for nearly five months. Results show that the efficiency of the drive circuit was improved greatly. At the end of the experiment, the energy supplied to the motor control circuit E_D was even less than in the two-month experiment in the second phase of the study. Although the experiment was conducted in the winter, the system still produced considerable surplus energy. To prevent the battery from overcharging, a discharge LED-load was tentatively installed. The surplus electrical energy of the improved PV blind system was estimated for one year.

Operations of the DC motor were evaluated in each study phase. Two DC geared motors were used for the study. In the first study phase, a DC geared motor with rated torque of 1.6 N m and rotation speed of 25 rpm was used. The average measured energy consumption and operating duration of the DC motor were, respectively, 4.6 J and 0.9 s. In the last two study phases, the DC geared motor was replaced with another motor with rated torque of 2.0 N m and rotation speed of 4 rpm. The replaced motor had operating duration of 4 s and energy consumption of 10 J. The number of installed PV modules has no marked effect on the motor operation. Irrespective of the motor type, the energy demand of the motor was much less than the PV electricity generation.

In the last study phase, the PV blind system was operated continuously for five months without outage. The PV modules generated surplus electrical energy of 2125 kJ during the test period. When the daily total system efficiency η_0 was 0.6%, the estimated surplus electrical energy was 7.8 kWh m^{-2} yr^{-1}. The present PV blind system would be sufficient to compensate some small-scale greenhouse demand for microclimate control. In addition, through the estimation, electricity generation is expected to decrease as the threshold irradiance of the blind turn increases. By contrast, the greenhouse crops would receive more solar energy. Assuming that 1% of the solar energy can be converted into plant biomass, the solar-energy use ratio for plant biomass production to electricity production would be approximately 1:1 using the present PV blind system at the greenhouse under actual sky conditions. That ratio is adjustable by the set-point of the threshold irradiance for the blind rotation.