Final Report

Investigating novel glass technologies and photovoltaics in protected cropping

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Project:

Investigating novel glass technologies and photovoltaics in protected cropping (VG15038)

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Content

Summary

Climate control, pumping and other energy requirements in protected cropping represent a major cost. Thus, focus is increasingly on the use of energy efficient design and renewable energy in greenhouses. The goal of this project was to (1) survey the advanced smart glass (SG) and renewable energy technologies available worldwide, (2) evaluate their cost-effectiveness, based on the energy saving, productivity impacts, and economic viability, and (3) recommend optimal solutions for the growers who wish to use advanced energy efficient technologies in their greenhouses.

In this project, the team at Swinburne University of Technology (SUT), composed of glass and renewable energy experts and economist, in collaboration with plant biology specialists in Western Sydney University (WSU) investigated novel glass and renewable energy technologies in protected cropping.

Here, two energy solutions are considered:

i. Smart glass, defined here as glass with adjustable light transmittance and high thermal insulation, which blocks the heat from the sunlight in summer to reduce the cooling cost, and maintains the heat inside the glasshouse in winter to reduce the heating cost.

ii. Renewable energy is to generate energy from sunlight to compensate the energy consumption within greenhouses. The renewable energy solutions considered in this project include: (a) photovoltaic (PV) technology converting light energy to electricity, which can be used to power the ventilation, supplementary lighting and sensors, and compensate the energy consumption in a greenhouse. (b) Solar thermal collectors (STCs), commonly known as solar hot water modules; which are used to store the heat from the sun in water. The stored heat can be used in greenhouses for environmental heating and drying purposes.

The significant outcomes are briefly summarized below:

(1) Smart films were integrated with the state-of-the-art greenhouse in WSU. The transmission spectra show that the smart films have high transmittance in the visible region, especially in the region of photosynthesis active radiation (PAR). Meanwhile, the smart films significantly block the UV region (300 nm~380 nm) and thermal energy in the IR region.

(2) The cooling cost and water consumption of the smart film integrated greenhouse were significantly reduced by 20%. In the meantime, quality of the fruit (eggplant in this case) was maintained with a slight reduction in the yield. The smart film is expected to bring more benefits to leafy vegetables with more yields on the biomass. In addition, the installation of smart films does not require significant infrastructure changes of the greenhouses, thus reducing the installation costs. The smart films have more than 15 years lifetime, thus it represents a cost-effective energy solution.

(3) To more accurately evaluate the cost effectiveness of the renewable energy solutions and better convey the outcomes to the key stakeholders, a cost-effectiveness model was developed with the aim to establish a user friendly evaluation software for growers to use when they wish to adopt advanced energy efficient technologies in their greenhouses. The software is able to consider the real weather conditions at different locations, the sun irradiance, the structure of the greenhouse and the glazing materials, the different renewable energy strategies selected and the real installation cost to provide good estimation on the annual energy generation, energy cost saving, and payback period.

(4) Field data was collected and input into the cost-effectiveness evaluation software. The applicability of the evaluation model was experimentally verified by comparing the measured data from the field study (including Sydney, Melbourne and Alice Spring) with those predicated by the model. Good agreement was found suggesting the effectiveness of the evaluation model. In addition, it was found that by considering the temperature effect of the renewable energy products under real operation conditions, better agreement can be achieved between the measured data and the evaluation model. The model can be further improved, completed and made assessable for growers. It is expected, such software will be easy to use and provide useful insights to growers to facilitate their sound decision.

In summary, significant advancement in knowledge and understanding on developing energy efficient

greenhouses have been achieved. The outcome of the project will have broad and profound impact in protected cropping industry.

Keywords

Photovoltaic, smart glass, solar thermal heater, vegetable, protected cropping, greenhouse

Introduction

Background

Australian horticulture is the fastest growing primary production sector in Australia[1]. As one of Australia's largest horticultural industries, the vegetable sector generates around $3.8 billion for the Australian economy and exports around $248 million, or some seven per cent of the total production[2].

Protected cropping can provide a suitable interior microclimate for growing high quality crops independent of exterior environments. The climate control inside greenhouses, including light, temperature, relative humidity and carbon dioxide enrichment, accounts for a major part of the running cost. The cost varies greatly depending on crop, greenhouse design, and regional location under different climate conditions[3]. In general, the energy cost has increased significantly in recent times, resulting in a contraction in aggregate profit margins[3]. So, it is valuable to actively apply advanced technologies with energy efficient design and renewable energy in greenhouses.

Recently, the world's first greenhouse that fully relies on solar power was built in Port Augusta, South Australia[4], indicating the great potential of renewable energy in horticulture. However, the investigation into energy efficient designs with renewable energy for different types of greenhouses is lacking. It is acknowledged that challenges and needs in designing energy efficient greenhouses strongly depend on the crop, region, and farm. Introducing new technology on renewable energy can save the energy cost but it is associated with additional costs for installation and maintenance. In addition, the impact of the new technologies on vegetable productivity is unknown.

Objectives of the project

The goal of this project was to (i) survey the advanced smart glass (SG) and renewable energy technologies available worldwide, (ii) evaluate their cost-effectiveness through field trials, based on the energy and productivity requirements, and (iii) recommend optimal solutions for the growers who wish to use advanced energy efficient technologies in their greenhouses.

Based on the team's comprehensive expertise on SG and renewable energy technologies, economical modelling together with the extensive plant biology expertise in WSU, the project aimed at establishing a cost-effectiveness model to consider the real weather conditions at different locations, the sun irradiance, the structure of the greenhouse and the glazing materials, the different renewable energy strategies selected and the real installation cost to provide good recommendations on the annual energy generation, energy cost saving, and payback period for growers.

In the meantime, the project also conducted field experiments on selected strategies to determine the final cost effectiveness and input the collected data into the economic model to validate and optimise the model. We aimed to develop user-friendly and interactive software and make it accessible for growers to provide them basic sense of the renewable solution options. This software is valuable not only for growers but also for horticulture industry and will be of significant social and economical value. Based on the findings, the team has developed more innovative designs to tackle the energy related problems in greenhouses and provide optimal energy efficient solutions and recommendations to growers to maximise the benefits.

Methodology

Method 1- Cost-effectiveness modeling

There are two complementary methods in this project:

Method1 Establish a cost-effectiveness model to consider the real weather conditions at different locations, the sun irradiance, the structure of the greenhouse and the glazing materials, the different renewable energy strategies selected and the real installation cost to provide good recommendations on the annual energy generation, energy cost saving, and payback period for grower.

Method2 Collecting field experimental data to determine the final cost effectiveness and input into method 1 to validate and optimise the model and provide optimal energy efficient solutions and recommendations to growers to maximise the benefits.

With method 1, the team from SUT, including the Centre for Translational Atomaterials (CTAM), Pathways and vocational education (PAVE) and economist, has collected data from all existing SG and renewable energy technologies, including those currently on the market and those under development. Some of the technologies, which have already been used in other countries but not within Australia have been noted and analysed for Australian conditions. The most frontier laboratory validated technologies with high commercial viabilities have also been considered.

Two detailed methods have been applied to study the effects of the applications of novel technologies on greenhouse:

(1) Literature review to summarize the state-of-the-art applications of novel technologies in the world (Appendix 1); and

(2) To predict the influence of novel technologies in Australia, a numerical model based on the weather conditions in Australia was built to simulate the running cost of greenhouses.

We focused on key novel technologies of energy saving (smart glass) and renewable energy generation (photovoltaic and solar thermal collector) for greenhouses in the world. Following the brief assessment of existing greenhouse systems in terms of the role in total energy consumption, cost-effective, energy-efficient and environmentally friendly technologies were analysed in detail for potential utilization in greenhouses for notable reductions in energy consumption and emission levels.

To establish the cost-effective model, first, the Australia climatic conditions, including temperature and sun irradiation, was downloaded from the Bureau of Meteorology (BOM) website. Since the weather conditions may vary significantly every year, it will be inaccurate if only one year is taken into account. Therefore, we took a five-year data average. These were applied in the simulation of running cost of greenhouses and the energy gained from the renewable energy technologies.

The simulation comprised two independent parts: 1) simulation to obtain the running cost of greenhouses, in which conventional greenhouse models were built according to the state-of-the-art greenhouse design as the base case study. Then the glazing materials, incorporating conventional glazing materials and SG, were varied as a parameter to study the effects. 2) The energy generated from renewable energy technologies, including photovoltaic (PV) and solar thermal collector (STC), was calculated using System Advisor Model (SAM) software.

Method 2-Field data

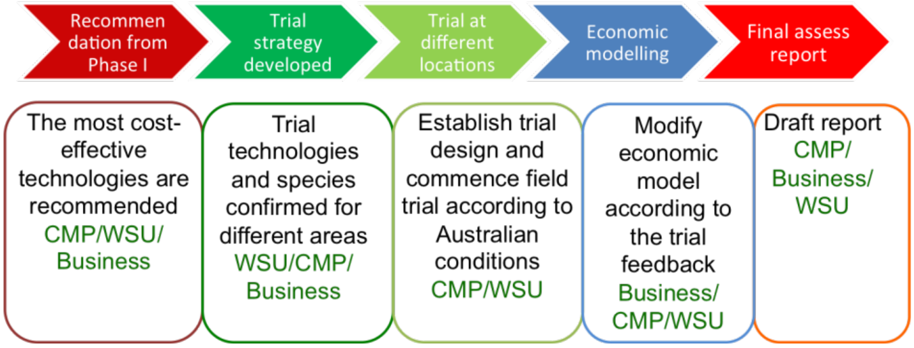


Figure 1 Schematic of the method used in field data collection and the team responsible for it.

The objective of Method2 was to empirically validate productivity and energy impact of technologies. The methodology is illustrated in Fig. 1. Based on the results of Method 1, we proposed field data collection focusing on the four technology bundle options outlined in Table 1.

Table 1 Proposed technology bundles to evaluate via field data. Concentrated photovoltaic (CPV), concentrated solar thermal collector (CSTC), flat plate photovoltaic (FPPV) and flat plate solar thermal collector (FPSTC).

Options	Greenhouse conditions	Suitable technologies	Space requirement	Potential energy cost savings
1	Greenhouse in the area with high land cost	SG + roof-top CPV + CSTC*	No extra space required	60%~70%
2	Extra space available around the greenhouse	SG + ground-mounted CPV+CSTC*	Require extra space for CPV setup	Up to 100% (Self-sustaining)
3	Large extra space available around the greenhouse	SG + ground-mounted FPPV+FPSTC*	This design requires larger extra space than Option 2	Up to 100% (Self-sustaining)
4	Greenhouse in the area with high land cost	Smart Glass + roof-top semitransparent PV	No extra space required	40%~50%

*In these designs, the STC is integrated with the PV cell, and so no extra setup for the STC is required. The potential saving is estimated based on the simulation model for a 1000 m^2 greenhouse.

In order to evaluate the actual cost effectiveness of using novel SG and renewable energy technologies in greenhouses and eventually to make meaningful recommendations to growers in terms of optimum energy efficient solutions, the trials were divided into 2 stages.

Stage 1:

(March 2017- March 2019) SUT team worked with the horticulture team from WSU to quantify the productivity and cost effectiveness of the four different options in Table 1 in their state-of-the-arts greenhouse. The resulting productivity effects and overall costs and benefits were determined for each option under optimal conditions.

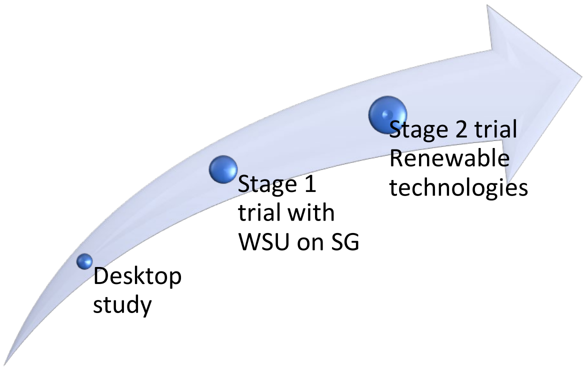


Figure 2 Schematic of the progression of the project.

The WSU greenhouse has eight replicate research bays (104 m^2 each) and there is additional space to install ground-mounted PV cells and STCs. The current greenhouse was amendable with SG. The data for the climate inside the greenhouse and energy consumption was acquired automatically in real time by sensors. Plant productivity and yield were monitored. Finally, the cost effectiveness was analysed based on the productivity and energy savings. The trials were conducted for two years continuously, in which there were several seasons of different vegetables being studied.

Stage 2:

(March 2019- March 2020) We collected field data of all different renewable energy solutions to compare the productivity and cost effectiveness. The data for the climate inside the greenhouse and energy consumption was acquired automatically in real time by sensors. The cost effectiveness was analysed based on the productivity and energy savings. In addition, a cost effectiveness evaluation model was developed and further applied to calculate the energy generation and cost-effectiveness of the renewable energy technologies at different geological areas with varied sunlight and weather conditions. The goal was to further study the suitability and accuracy of the model in different areas under different conditions. Thus, growers from different areas can apply the model to predict the cost-effectiveness of different products according to local weather conditions. More importantly, the model is able to help growers to access the most suitable solutions according to the locations and the plants. The schematic of the project progression is shown in Fig. 2.

Outputs

Design, installation, and trial of smart glass technology

The following considerations were taken into account for a fair comparison of the effects of the smart glass on the inner climate of the greenhouses

1. There were at least two compartments for fair comparison of the average effects of the smart glass.
2. The two compartments should share one wall in order to minimize the effects on the benchmark (control) compartments.
3. The smart glass should be chosen according to the local weather condition of the greenhouse.
4. The smart glass should have minimal effect on the light condition in the greenhouse.
5. The installation cost should be minimized for a better cost benefit.

The choice of the two compartments:

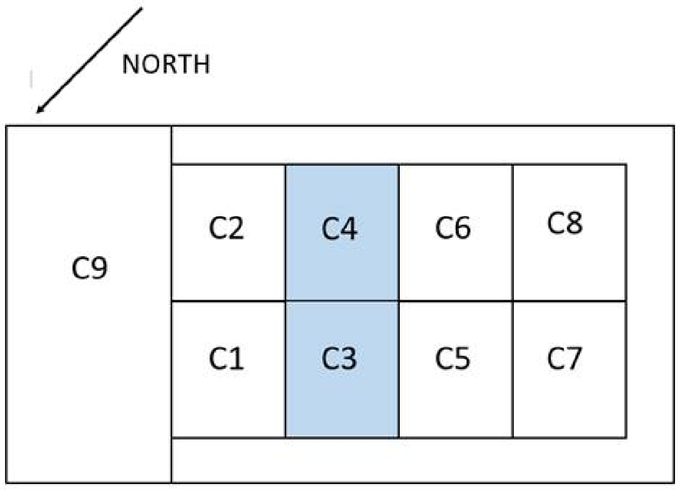


Figure 3 Schematic of the greenhouse. C3 and C4 are selected to integrate the smart film.

The schematic of the greenhouse in WSU is shown in Fig. 3. The two compartments for the experiment of the smart glass were C3 and C4. C5 and C6 were the control compartments. As one can see the compartments were in the middle area, because the sunlight of C1 and C2 was partially blocked by the demonstration bay (C9) and C7 and C8 might be affected by the equipment and pipes on the walkway of the greenhouse. Therefore, compartments C3, C4, C5 and C6 were best suitable for the experiments.

In addition, C3 and C4 shared one wall, thus minimized the walls shared with the other compartments. In this way, the effects of the smart glass on the control compartments were minimized.

The choice of the smart glass:

First, the following points were considered to minimize the cost of the installation to achieve the highest cost benefit:

1. If the existing glass in the greenhouse was completely replaced, high labour cost would be required in the removal process of existing glass.
2. In addition, the removed glass, which was expensive customized glass special for the greenhouse, cannot be directly applied to other greenhouses. Therefore, the replaced glass is most likely

wasted, leading to increased overall cost of the project.

3. The installation cost of the smart glass was high.
4. The cost of smart glass for two compartments, including removal and reinstallation, was significantly higher than the available budget.

By taking all the factors into account, we proposed to use smart films with similar specified parameters as those of smart glass to integrate on the surface of the existing glass structure. The advantages were the followings:

1. It can be directly applied on the existing greenhouse glass without requiring the removal of the existing glass, which saved the removal cost and the existing glass can still be used.
2. The cost of smart films was lower than smart glass.
3. The installation cost of smart film was much lower than smart glass making this solution fit well within the budget.
4. Smart film can be more broadly applied to other built greenhouses, without significant disruption to the existing structure, therefore rendering a great cost saving.

Secondly, we considered the smart film met the requirements of the local environment in WSU. From the data obtained from Bureau of Meteorology (BOM) Australia, the temperature distributions over a year on a 5-year average is shown in Fig. 4. Generally, the temperature in Sydney was relatively high. For the particular area, Hawkesbury, it was even higher. One can see, there were only a few days in a year with the low temperature in a day dropping below 10 °C. In addition, sunlight heated up the greenhouse quickly during the daytime. Therefore, the main consideration was to block the heat from the sunlight and allow as much visible sunlight go through the film as possible so that it produced least impact on the growth of the plants.

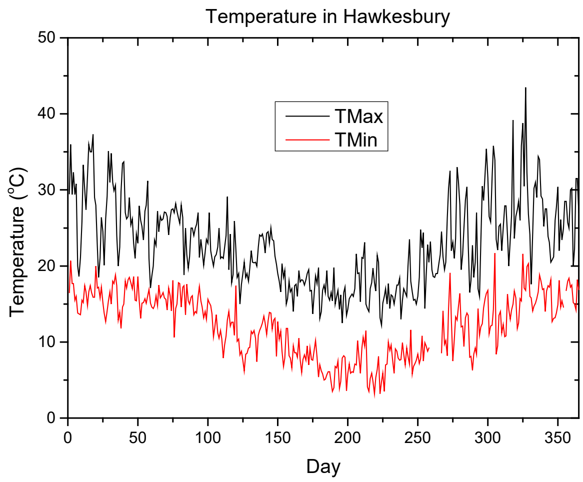


Figure 4 Temperature distributions of WSU over a year. Data from Bureau of Meteorology (BOM) Australia.

As a result, we chose the smart film with the highest transmittance (~80%) among all the smart film products. The detailed specifications of the smart film (Solar Gard® Solar Control Window Films Sentinel™ Plus SX 80 OSW) are shown in Fig. 5.

Performance results	1/8" (3mm) Single clear
Visible light	
Transmittance %	78
Reflectance exterior %	8
Reflectance interior %	8
Glare reduction %	14
Solar energy	
Transmittance %	40
Absorptance %	54
Reflectance %	6
Total solar energy rejected %	43
Infrared rejection @ 780 to 2500 nm % [1]	88
Shading coefficient	.65
Solar heat gain coefficient	.57
Light to solar heat gain ratio (VLT/SHGC)	1.36
Solar heat gain reduction %	34
Thermal energy	
Emissivity	.87
Winter U-factor (Btu hr/ft² °F)	1.05
Winter U-factor (W/m² °C)	6.0
Winter heat loss reduction %	-1
Ultraviolet light	
Blocked @ 300 to 380 nm %	>99

Figure 5 Specifications of the employed smart film (Solar Gard® Solar Control Window Films Sentinel™ Plus SX 80 OSW).

The overall transmittance of the film covered 4 mm glass is around 78%, which is the highest on the market. The comparison between the 4 mm thick clear glass with and without the smart film is shown in Fig. 6.

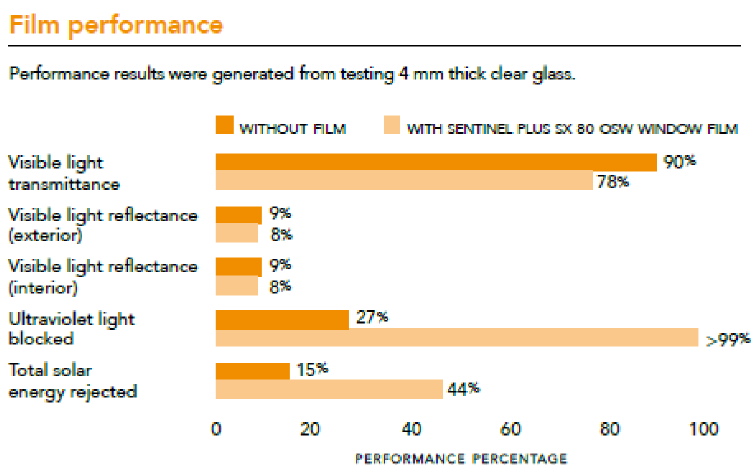


Figure 6 Performance of 4 mm thick clear glass with and without the selected smart film.

As shown in the figure, the difference in visible light transmittance between the one with and without the smart film was only 12%. In addition, the total solar energy rejected by the smart film was 44%, which was mostly in the UV region and infrared region corresponding to the thermal energy.

Detailed spectral measurement of the selected SX80 film was also performed for the entire solar spectrum, which is shown in Fig. 7.

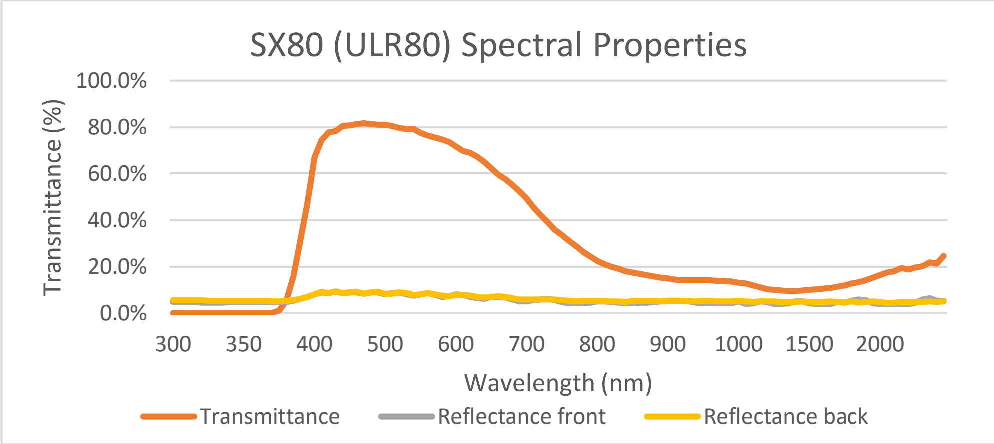


Figure 7 Measured spectra of the SX80 smart film.

As shown in Fig. 7, the reflectance of the front and back sides of the film was less than 10%. In the meantime, the transmittance in the visible region (400 nm to 700 nm) was around 80%. In addition, most of the UV (300 nm to 400 nm) light was blocked by the film. Moreover, the transmittance in the IR region was quite low, around 20%, which meant most of the thermal energy was blocked by the smart film.

Installation of the smart film

The film was installed by directly taping the film on the inside glass surface of the compartments. The photos of the compartments with the smart film were shown in Fig. 8.

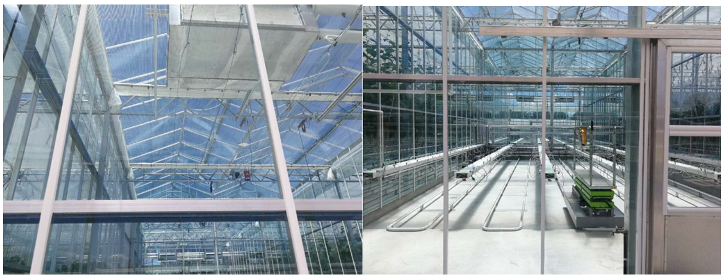


Figure 8 Photos of the compartments, integrated with the smart films. Left: photo of the roof for C3. Right: photo of the entire compartment for C3.

As shown in Fig. 8, the compartments after the film integration did not show significant difference, other than the slightly blue colour due to the higher transmittance of the smart film in the blue region. The smart film strategy is preferred for existing greenhouses since it incurred the least interruption and installation cost.

Optical sensor installation and measurements

The Fig. 9 (a) shows the locations of the installed photodetectors (the photo of the photodetector is shown in Fig. 9(b), which were used for recording the power density of sunlight in greenhouse. Furthermore, radiometer and sunshine sensor were also installed at the top compartment in greenhouse (Fig. 10).

(a) (b)

Figure 9 The photography and locations of the installed photodetectors.

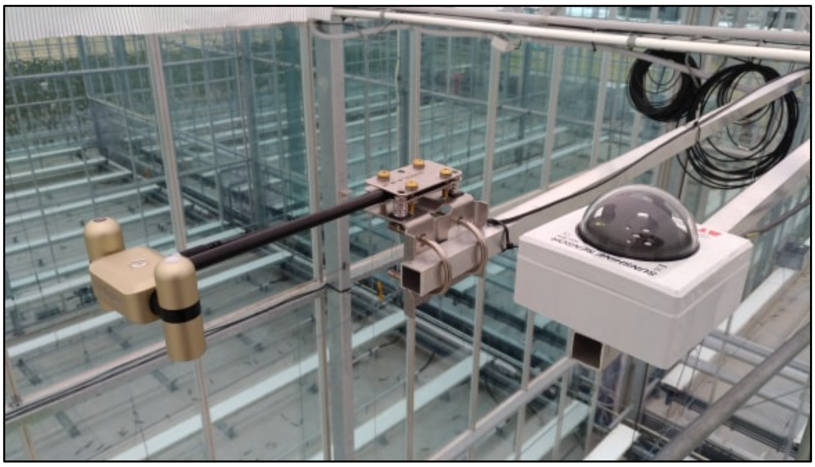


Figure 10 The photography and locations of the installed radiometer and sunshine sensor at the top compartment in the greenhouse.

Fig. 11 shows the incoming radiation, outgoing radiation, and the net radiation in the greenhouse at different times during a day. As we can see, the incoming radiation, outgoing radiation, and the net radiation for both control group (compartment 5 and 6) and Solar Gard® SX80 smart film integrated group (compartment 3 and 4) showed a very similar trend in one day. The highest net radiation in the greenhouse of the control group was approximately 750 W/m^2. In contrast, Solar Gard® SX80 smart film group had a lower net radiation. Therefore, smart film group received less power (energy per second) density from the sunlight.

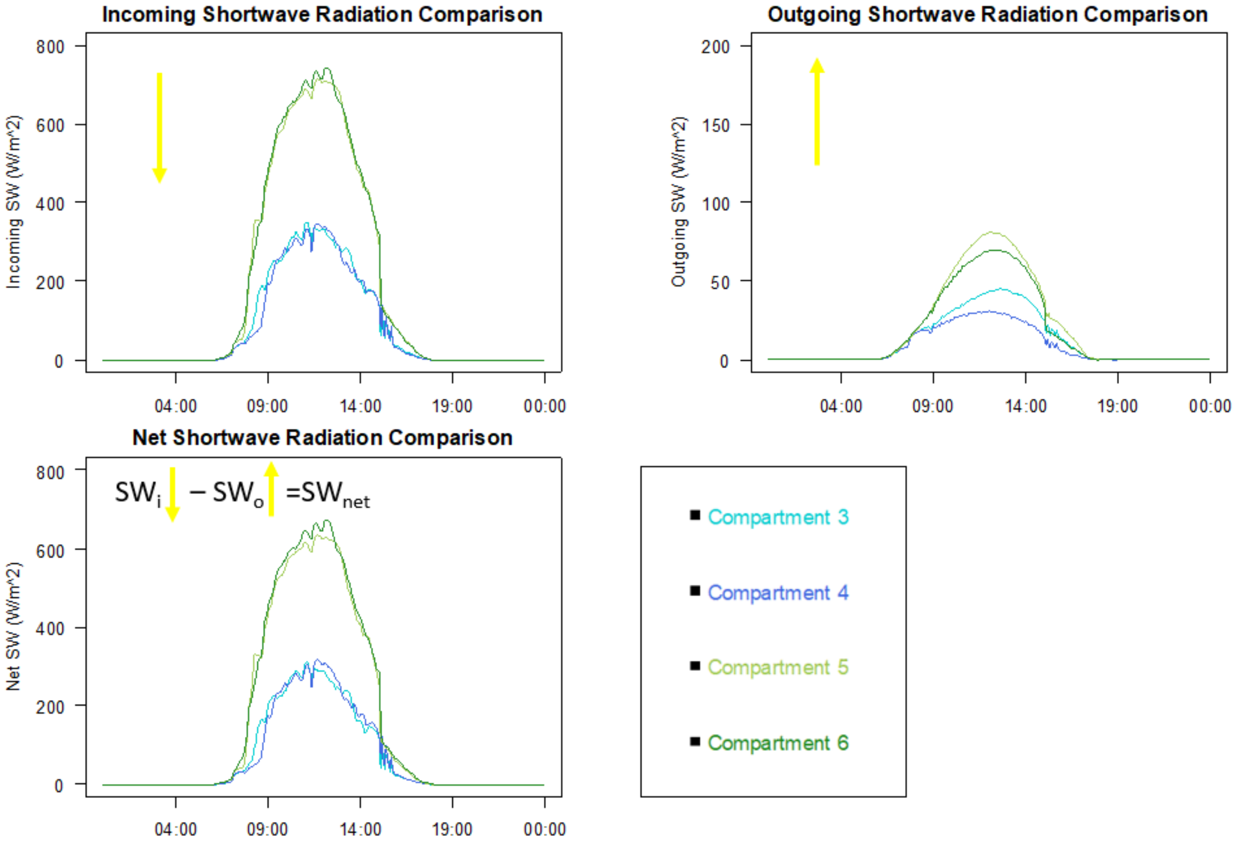


Figure 11 The incoming radiation, outgoing radiation, and the net radiation in the greenhouse.

The measured transmission spectra inside the compartments are shown in Fig. 12.

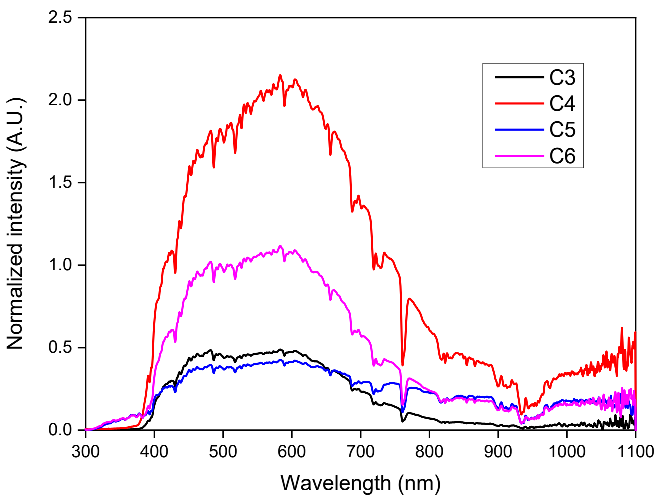


Figure 12 Measured spectra inside different compartments (C3, C4, C5 and C6).

The intensity distribution inside the compartments not only depended on the transmittance of the materials, but also the illumination condition of light. Therefore, the absolute intensity may vary depending on the position and the time of the measurement, which cannot be directly compared. However, we can still compare the relative transmittance by normalizing the intensity. The normalized intensity distributions of the light in each compartment are shown in Fig.13.

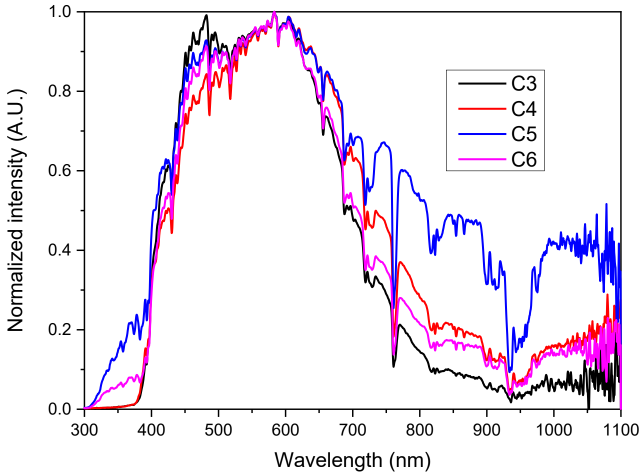


Figure 13 Normalized light intensity distribution in each compartment

For the normalized intensity distributions, one can see that the UV region (300 nm~380 nm) was significantly cut off by the smart film. There is no significant difference in the visible region (400 nm~700 nm). For the transmission in the IR region, which contributes to the heat, the ones with smart film were significantly lower, which confirmed the blockage of thermal energy by the smart film. Such a blockage was expected to effectively cool down the relative compartment.

Benchmark energy cost data obtained of empty greenhouse

We discussed with the grower colleagues in WSU, who managed the greenhouse. They suggested that the greenhouse consumed more energy in maintaining the inner climate condition when it was empty, because the plants themselves stored a lot of energy and were able to help regulate the inner climate conditions, such as temperature and humidity. Therefore, it was not quite meaningful to measure the energy consumption of an empty greenhouse, because it was significantly different in the energy consumptions with and without the plants in it.

Originally the empty greenhouse was run to test the working status of the controlling system. As long as the controlling system worked all right, it was not necessary to test the empty greenhouse again. As a result, the energy cost data of the empty compartments with and without smart film were not compared. It was more meaningful and valuable to see the effects of the smart films with plants inside, as the plants behave differently in the compartments with and without the smart films, which significantly changed the energy consumption, such as cooling, heating and watering. Therefore, direct comparison was conducted between the two smart glass integrated compartments, C3 and C4 with C5 and C6 without the smart glass with plants in all of them.

Cost/benefit data obtained of smart glass integrated greenhouse

As the energy cost of a greenhouse also depended on the species of the plants. Therefore, we needed to obtain data with a certain plant. In the first trial we chose one greenhouse variety of eggplants (Tracey RZ on KaiserR) due to the following reasons:

1. The variety of the eggplant was suitable for greenhouse and consistent.
2. The eggplant did not require bees to enable pollination, therefore, we did not have to consider the effects of the smart film on bees.
3. The eggplant had been studied in the same greenhouse, thus the performance was well understood.

We placed a crop of Tracey RZ on Kasier RZ in 4 x 100 greenhouse compartments. Our aim was to test the smart film integrated greenhouse on 2 compartments against 2 parallel reference compartments without the smart film using eggplant as a test crop running a full year.

Each greenhouse compartment had 6 lines, 4 middle lines with an extra line at each side of the compartment very close to the glass with no real access from the outside. Each line was 10 m with 10 slabs per row (total 60 slabs per compartment).

The actual cropping area of each compartment minus the path is approximately 93 m^2. There was crop in either side of the Tracey RZ compartments (the glasshouse compartment is 8 m x 11.6 m plus path area at the front = 2 m or so).

Table 2 Planted eggplants (Tracey RZ on Kasier RZ) in the compartments

C2:	C4: Tracey RZ on Kasier RZ	C6: Tracey RZ on Kasier RZ	C8:
C1:	C3: Tracey RZ on Kasier RZ	C5: Tracey RZ on Kasier RZ	C7:

Our Options for each compartment (all the same):

Option1: 4 lines x 10 slabs x 3 plant x 3 heads = 360 heads

2 lines x 10 slabs x 2 plants x 3 heads = 120 heads (outer lines) = 5.1 heads/m^2

Total Plants = 160 per compartment x 4 compartments = 640.

Total plants ordered 700.

The plants of the smart film group grew very well as displayed in Fig.14 in terms of leaf development.

Figure 14 Eggplants in the compartments with the smart film. Left: C3 Right: C4.

For comparison, the photos of eggplants in the compartments without smart films as shown in Fig. 15.

Figure 15 Eggplants in the compartments without smart films. Left: C5 Right: C6.

As one can see, the smart films are slightly blue. There are no identifiable differences in the plants between the compartments at the stage of leaf development.

Comparison of energy consumption

The energy consumption can be directly read from the energy meters in each compartment, which were the energy pulses generated by the Priva system (the central control system controlling the operation of the entire greenhouse, including temperature, irrigation, energy curtain, and fertilization) in the time interval of 5 mins. Only compartment C3 has an actual energy meter for heating and it solely measures the floor heating. The wall was related to another compartment, C9. The Priva system calculated approximate heating energy consumption in all compartments based on the demand of each compartment had for heating. It measured this based on the temperature readings of the hot water supply, hot water returned and the required setpoint. Given that we had an energy meter in C3, we compared the Priva system calculated value to the value calculated from the energy meter in C3, calibrating the Priva system and applying that to the other rooms.

All the research compartments had meters for cooling. Each of the research compartments was cooled via two 1.2kW Fan Coiled Units (FCUs). Chilled water, from one of the two 75 kW chillers was supplied in a closed loop to each of the two FCUs in each room. The chilled water flew through these two units and is then returned to the 200,000L storage tank. Priva recorded the supply and return temperature of the chilled water in each room.

The meters did not measure the actual energy in kWh like a meter for electricity. They simply calculated a value based on three variables. They included the water flowing through the flow meter, the temperature of the supplied chilled water and the temperature of the return chilled water. It did not record the ON/OFF of the FCUs. If it read a significant difference in the temperature of the supply and return, it sent a pulse to Priva. It could still have a significant water temperature difference between the supply and the return even if the FCUs were in an idle state and it produced a pulse based on how the chilled water system was designed. As all the numbers were based on the same reading, it is a fair comparison directly using numbers to see the relative energy consumption.

As the measurement was in summer, there was no heating cost involved, we only compared the cooling cost. At the time of the measurement, the energy meters in C3 and C5 were not working properly and under reparation. We compared the energy meter reading in C4 and C6 versus different time in one and a half days, the plots of which are shown in Fig. 16.

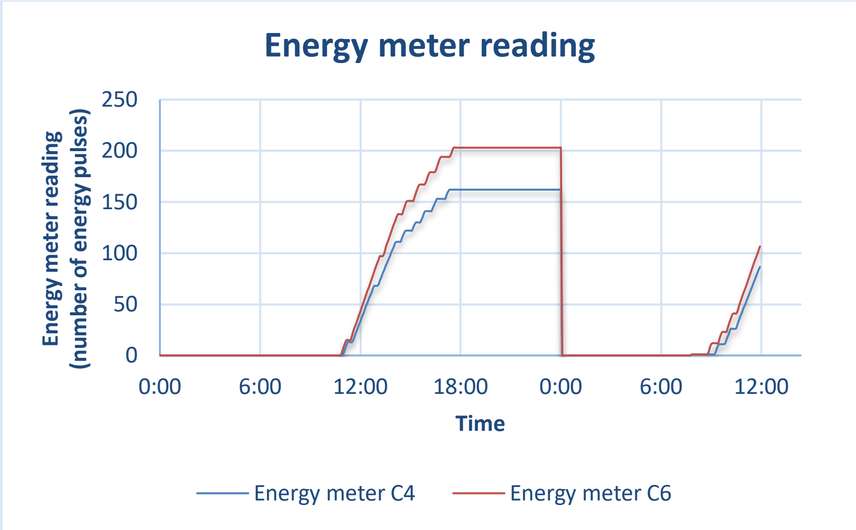


Figure 16 Energy meter reading of compartments C4 (with the smart film) and C6 (without the smart film).

From the reading we can see that cooling energy cost in the compartment without the smart film (C6) is significantly higher than the one with the smart film (C4) based on consecutively 2 days measurement. We calculated the overall energy consumption and present in Fig. 17. The C4 compartment with the smart films consumes around 20.4% less energy than that by C6. Therefore, we can conclude that the smart films are effective in reducing the cooling cost in summer in the WSU greenhouse.

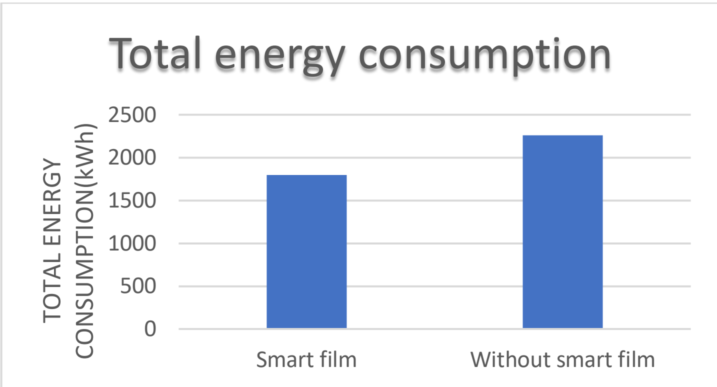


Figure 17 Total energy consumptions in different compartments C4 (with the smart film) and C6 (without the smart film).

Comparison of water consumption

On the other hand, water consumption in different compartments was also measured for comparison. The water was mainly consumed by the plants. The water consumptions were measured on a weekly basis, during which the plants were in all the time. The week number and the corresponding dates are shown in Table 3.

Table 3 Week number and the corresponding dates

Week	From	To	C3(L/m^2)	C4(L/m^2)	C5(L/m^2)	C6(L/m^2)
1	1/15/2018	1/21/2018	46.579	47.045	47.772	46.261
2	1/22/2018	1/28/2018	14.614	15.386	15.182	16.125
3	1/29/2018	2/04/2018	15.625	16.262	15.943	16.829
4	2/05/2018	2/11/2018	23.215	23.749	24.067	24.852
5	2/12/2018	2/18/2018	28.909	29.455	29.102	29.693
6	2/19/2018	2/25/2018	15.556	15.907	17.294	18.009
7	2/26/2018	3/04/2018	17.386	17.693	22.273	23.012
8	3/05/2018	3/11/2018	15.544	15.807	19.408	20.215
9	3/12/2018	3/18/2018	16.734	17.11	20.735	21.838

Two measurements were considered in different units, namely the water consumption per area (unit: L/m^2) and the overall water consumption in volume (unit: m^3). The measured water consumptions per area are plotted in Fig. 18.

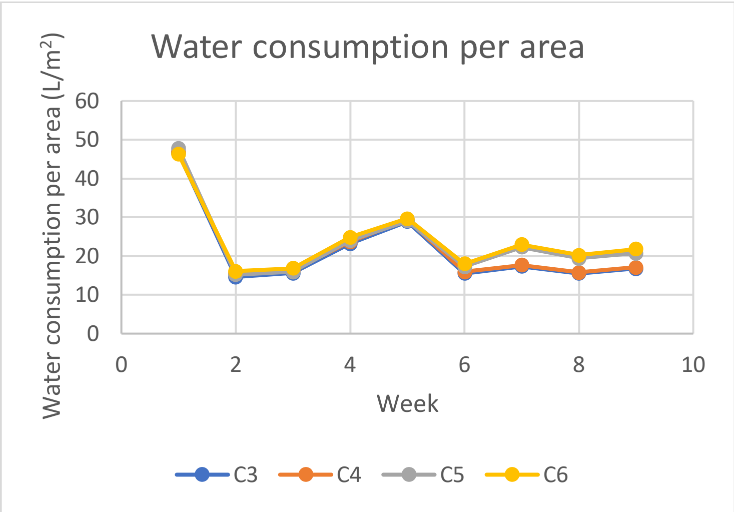


Figure 18 Measured water consumptions per area in different compartments. C3 & C4 (with the smart film) and C5 & C6 (without the smart film).

As shown in the figure, the trends of C3 and C4 were almost identical. And the trends of C5 and C6 are very close. This meant the experiments were quite reproducible. The eggplants consumed less water in the compartments with the smart film (C3 & C4), which further confirms that plants require less water in transpiration due to less thermal energy transmitted through the smart films. Around 10% difference in water consumption per area was observed due to the less heat been generated in the chamber with the smart films. It was noted that at the beginning, the difference was not significant as the plants were small. And the difference became more and more significant as the plants grow bigger and bigger.

In addition, the total water consumption per area of each compartment is plotted in Fig. 19.

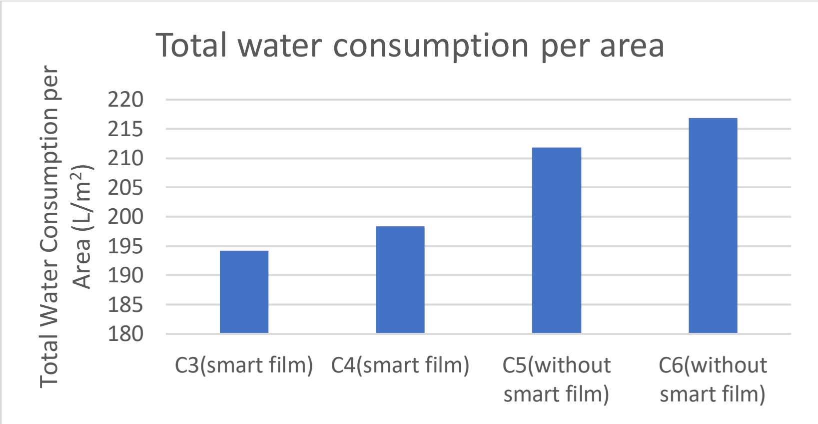


Figure 19 Total water consumption per area, which shows that the C3 and C4 consumed around 10% less water than C5 and C6.

We can see that C3 and C4 consumed around 10% less water than C5 and C6 in general.

In addition, the total water consumption of each compartment is plotted in Fig. 20.

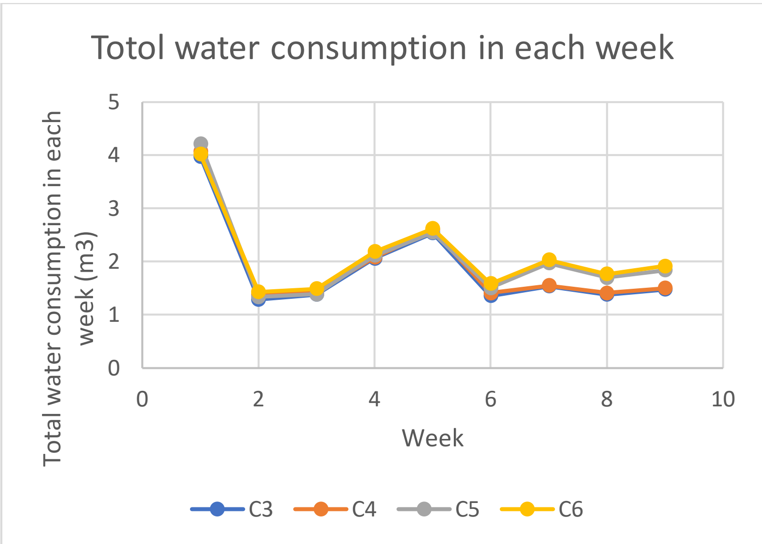


Figure 20 Measured total water consumptions each week in different compartments. C3 & C4 (with the smart film) and C5 & C6 (without the smart film).

The results showed similar effect to Fig. 18. And the overall water consumptions are plotted in Fig. 21. We can also see that C3 and C4 consumed around 10% less water than C5 and C6.

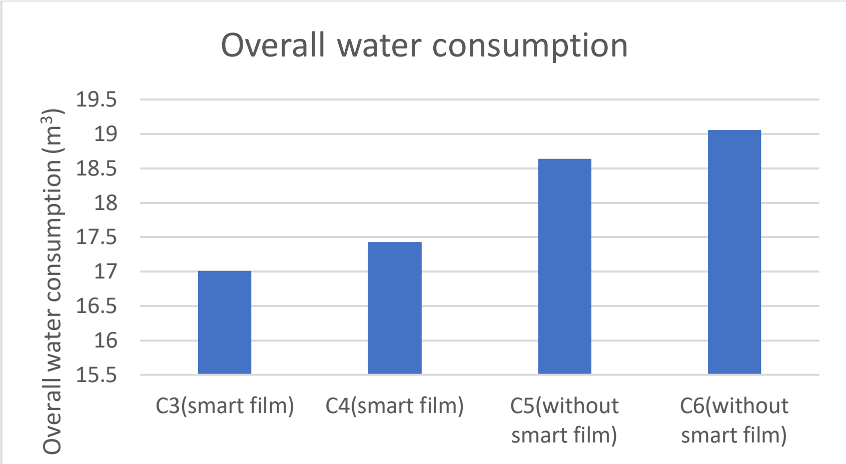


Figure 21 Overall water consumption in each compartment. The compartments with the smart films (C3 & C4) consumed 10% less water compared to the ones without the smart films (C5 & C6).

In conclusion, we have compared both cooling energy consumption and water consumption in the compartments with and without the smart film. The results suggest that smart films were able to significantly reduce both the energy and water consumption simultaneously leading to potential cost savings.

Productivity and quality of eggplants

In the meantime, the mean yields of eggplants in the smart film room are approximately 30% lower than those in the control room (Fig. 22). As displayed in Fig. 23, the height of a typical eggplant in the smart film room was a bit lower than that in the control room. No visible difference in the fruit's appearance can be seen. Meanwhile, there are some differences in the qualities (e.g. sodium, glucose, sucrose, and fructose), as can be seen in Fig. 23, which shows slightly higher quality of the fruit despite of reduction in the overall quantity. Both resulted eggplants are marketable. The difference in the yields and qualities of eggplants are highly attributed to the transmission spectra of the smart film (Solar Gard® SX80). The transmission of the Solar Gard® SX80 is approximately 80% in the visible regime, with significantly lower transmission in NIR region, in which the light is absorbed by the smart film. Due to the relatively low transmission in the red and NIR region (640 nm~ 740 nm), which is vital for flowering, the number of marketable eggplant fruits is relatively smaller in the smart film integrated compartment. The performance of the smart film can be further enhanced by manipulating the transmission spectrum, especially in the red and NIR region. The related effects on the quality and quantity of eggplant can be investigated in the future.

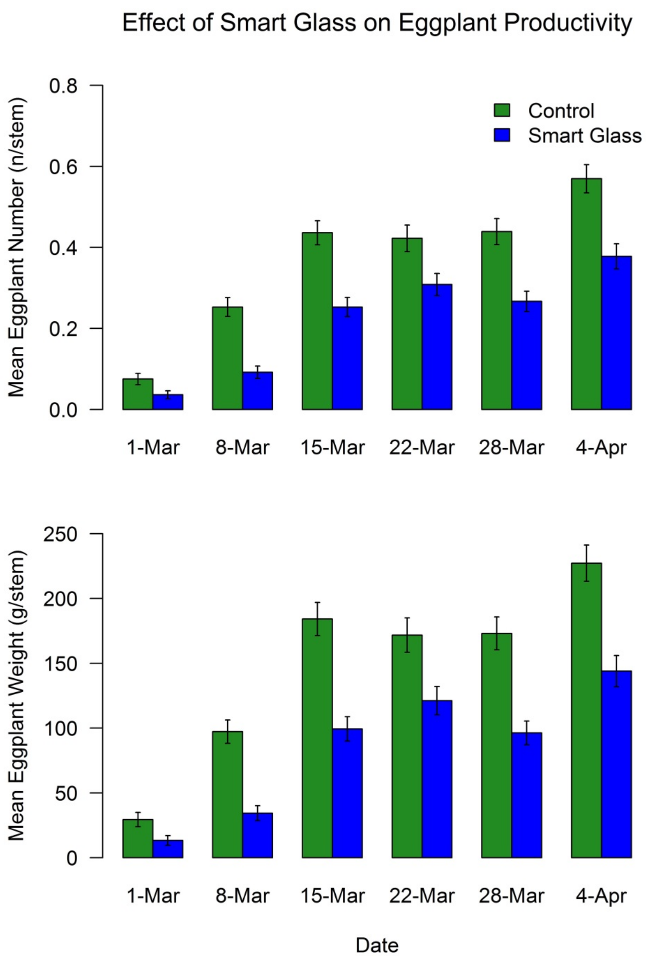


Figure 22 The difference in the quantities of eggplant fruits. Top: comparison of the mean eggplant number; bottom: comparison of the mean eggplant weight for smart film integrated compartment and the control room.

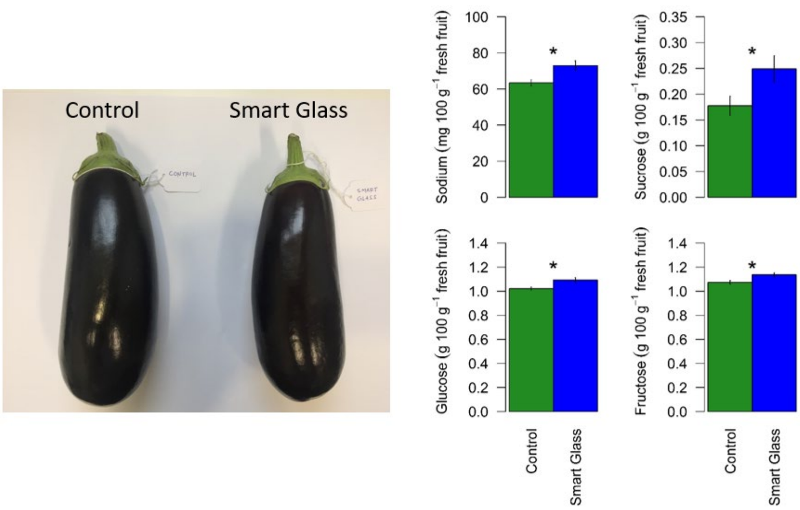


Figure 23 The difference in the qualities of eggplant fruits.

Water consumption for capsicums with smart films

Capsicums were also planted in the WSU greenhouse. The plants in the smart film room were very well grown, as displayed in Fig. 24(a) and no visible difference in the fruits of capsicums can be seen [Fig. 24(b)].

Herein, the water consumption in different compartments was measured for comparison when different plants were grown (e.g. capsicums) in the greenhouse. The water consumptions were measured daily, during which period the plants were in all the time. The water consumption per area (unit: L/m^2) was considered for comparison. The measured daily water consumptions per area of smart film bays (C3 and C4) and those of the control bays (C5 and C6) in three weeks are plotted in Fig. 25 (a). The trends of C3 and C4 were almost identical. And the trends of C5 and C6 were very close. This means the experimental results were quite reproducible. The capsicums consumed less water in the compartments with the smart film (C3 and C4), which further confirms that plants may require less water in transpiration due to less thermal energy transmitted through the smart films. In addition, the total water consumption per area of each compartment is plotted in Fig. 25(b). We found that C3 and C4 consumed approximately 3.1% and 6.2% less water than C5 and C6, respectively, in general. As the C4 and C6 compartments were on the north side of the greenhouse, which experienced stronger sunshine, the overall water consumption in C4 and C6 were higher than C3 and C5. The trends of the total water consumptions in planting capsicums were similar to those in planting eggplants. Therefore, the results suggested that smart films were able to significantly reduce water consumption when different plants were grown in the greenhouse.

Figure 24 (a) Photo of the compartment with smart film and growing capsicums and (b),(c) Planted capsicums in the compartments.

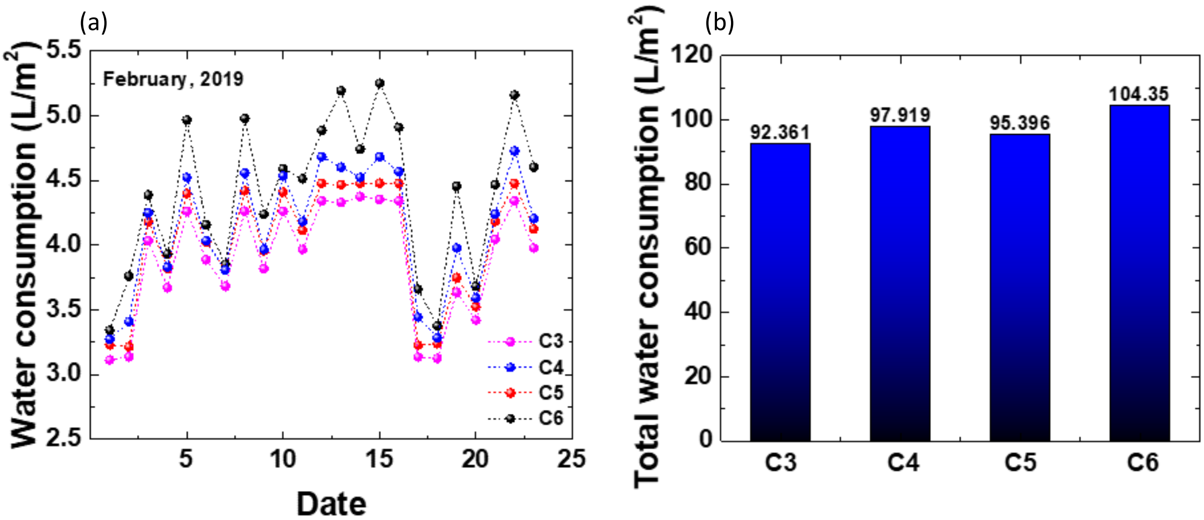


Figure 25 (a) Measured daily water consumptions per area in different compartments. C3 & C4 (with the smart film) and C5 & C6 (without the smart film). (b) Measured total water consumption per area in 3 weeks.

New smart film design

In general, plants are very sensitive to the light with different wavelengths. Table 4 displays the light spectrum and impact on plant growth. The light in UV and visible regime significantly affects the growth of plants. In addition, the light in the infrared (IR) regime (>740 nm) does not relate to any plant activity and generates heat in the greenhouse. Therefore, how to design a smart film simultaneously featuring high transmission in UV and visible regime, low transmission and absorption in IR regime, and tunable transmission spectrum is one of the important and challenging issues for the improvement of the plants' productivity in the greenhouse. In this project based on the light management expertise from the Swinburne team and the trial outcomes, new smart film design that is able to simultaneously address these demands has been proposed. The full details of the design can be found in the IP description document for this project.

Fig. 26(a) displays the schematic representation of the proposed next-generation smart film. The smart film is composed of a thin layer of silver (Ag) mesh and polymer substrate. The key structural parameters of the smart film include the thickness (t) of Ag layer, the width (w) of the mesh, and the period (p) of the mesh. These parameters can be used to precisely manipulate the optical properties of the smart film. Figures 26(b) and 26(c) present the transmission and reflection spectra of the proposed smart film with different parameters. As displayed in Fig. 26(b), the proposed smart films exhibit not only high transmission in UV and visible regime but also tunable transmission spectra in the IR region. The transmissions are higher than 80% in the visible regime and in the range of 10% and 40% in the UV regime. Furthermore, the proposed smart films perform high reflection in the IR regime. Most of the light in the IR regime is reflected instead of transmitting into the greenhouse or being absorbed by the smart films. Therefore, the proposed smart films have a great potential for use in greenhouses to improve plants' productivity and thermal isolation.

Table 4 Light spectrum and impact on plant growth. (sourced from https://www.gogusco.com/)

Light Spectrum	Wavelength (nm)	Impact on Plant Growth
UV	280	Reduces quantum yield and rate of photosynthesis
	315 - 400	Promotes pigmentation, thickens plant leaves and may prevent harmful insects
Visible Spectrum	440 - 470	Most efficiently absorbed and promotes **Vegetative Growth**
	510	Absorption in green and yellow spectrum
	610	No chlorophyll benefit
	640 - 660	**Vital for Flowering**, speeds up germination flower onset
	740	Red and far red together increases the rate of photosynthesis
Infrared	1000 - 1400	No plant activity, heat generated

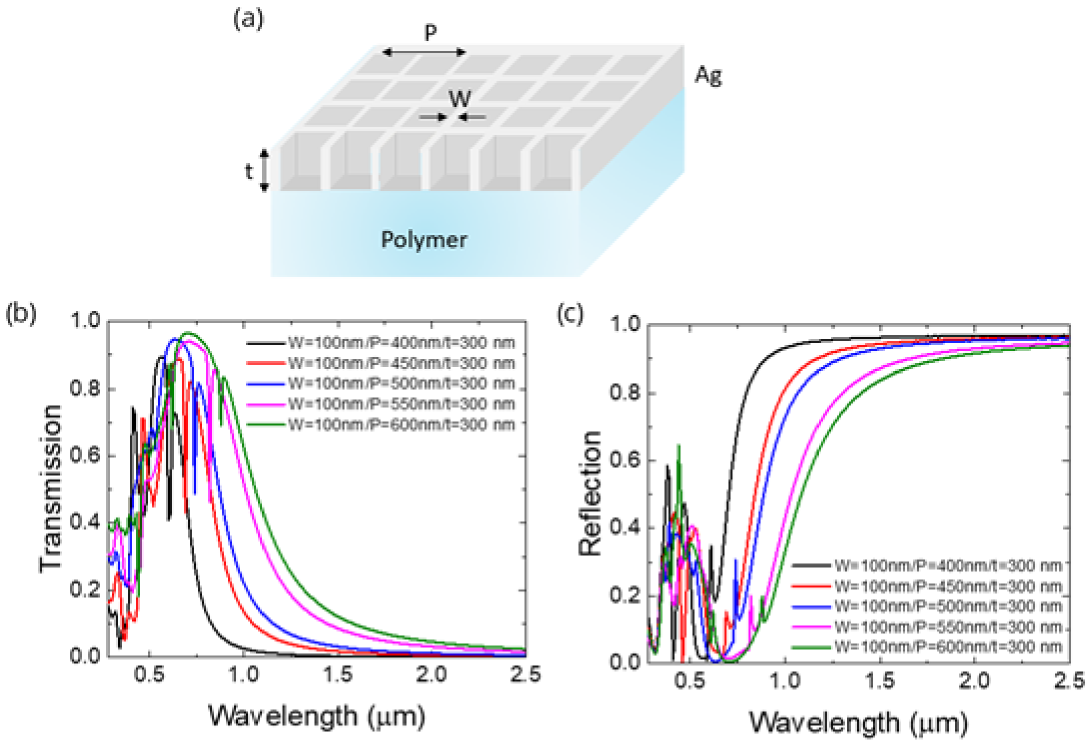


Figure 26 (a) Schematic representation of the proposed smart film. (b, c) Simulated (b) transmission and (c) reflection spectra of the proposed smart film with different structural parameters.

Design of CPV and CSTC technologies

Design based on commercially available CPV and CSTC

The left sub-Fig. in Fig. 27 shows the daily solar exposure at Hawkesbery campus in one year. The total solar exposure in one year was 1561 kWh/m^2. As shown in the right sub-Fig. in Fig. 27, the total solar exposure in spring, summer, autumn, and winter were approximately 475, 492, 304, and 290 kWh/m^2, respectively. As the annual electricity usage for the greenhouse was 160,000 kWh, we could supply enough electricity by CPV and CSTC for the greenhouse.

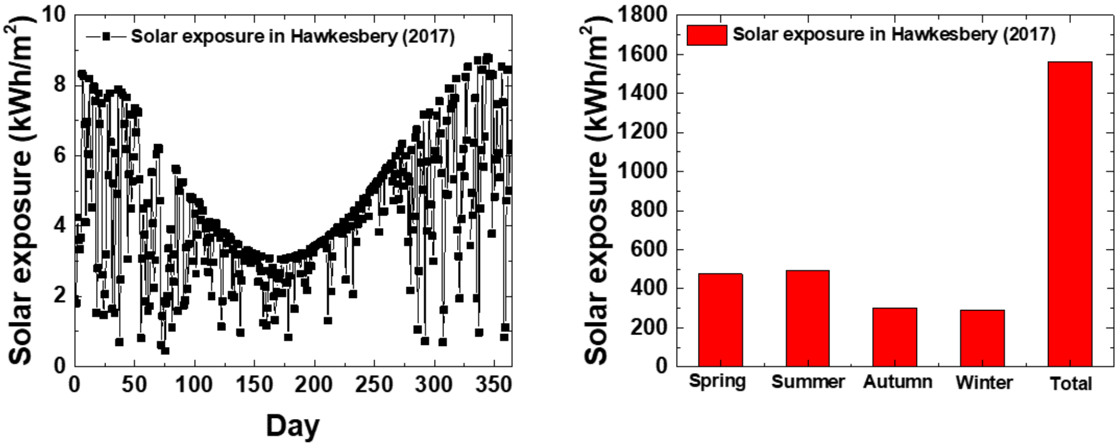


Figure 27 Daily solar exposure at Hawkesbery campus in one year.

The photography, electrical data, mechanical data, dimensions, limits, and temperature characteristics of commercialized CPV module are displayed in Fig. 28. Currently, the efficiency of commercial medium CPV module were greater than 40% from ZYTEC® Solar. Therefore, the annual electricity generated by this medium CPV module reached at least 624.2 kWh/m^2. Furthermore, the electricity generated by the CPV module in spring, summer, autumn, and winter were at least 190, 196.8, 121.4, and 116 kWh/m^2, respectively. As the total electricity consumption was 8,665 kWh per year, 5,000 kWh electricity could be saved when installing the CPV module with an area of 100 m^2.

		MCPV-36	MCPV-48
ELECTRICAL DATA			
Maximum Power*	*Pmax*	115W	150W
Open Circuit Voltage	*Voc*	22.08	29.39
Max Power Point Voltage	*Vmpp*	17.41	23.22
Short Circuit Current	*Isc*	7.18A	7.18A
Max Power Point Current	*Imp*	6.62A	6.62A
Cells per module		36	48
DIMENSIONS			
Cell (L) x (W)	*cm*	2.0 x 2.4	2.0 x 2.4
Module (L) x (W) x (D)	*cm*	102x102x21	134x102x21
Module Weight	*kg*	21	27

MECHANICAL	
Frame:	Pc + ABS
Front	PMMA Lens
Back	Aluminium
Cell Encapsulation	EVA
Junction Box	PPE– Ip65
Connector	MC Type 4
TEMPERATURE COEFFICIENT	
Current Temperature Coefcient	+4.40 mA/K
Power Temperature Coefcient	-0.46 %/K
NOCT Normal Operating Cell Temperature	70°C ± 2°C
LIMITS	
Operating Temperature Limits	-25°C to +85°C
Power Tolerance	±3%
Maximum System Voltage	1,000V DC

Figure 28 Photography, electrical data, mechanical data, dimensions, limits and temperature characteristics of commercialized CPV module.

In general, there are for four types of CSTC systems, including parabolic trough, solar tower, linear Fresnel, and dish stirring, as displayed in Fig. 29. The characteristics of CSTC systems with these four technologies are also shown in Fig. 29. The operating temperatures of the CSTC systems are generally in the range from 350 to 750 °C. In the parabolic-trough CSTC system, a polished metal mirror is curved into a parabola shape to concentrate the sunlight along the focal line, where objects (e.g. water) are placed that are intended to be heated. Furthermore, these CSTC systems are suitable for air cooling. For considering the area of installation of CSTC system, and compared with other CSTC systems, the parabolic-trough CSTC systems are commercially available with low technology development risk, therefore, we suggested that the parabolic-trough CSTC system was a good choice. Fig. 30 displays the photography of the commercialized parabolic-trough CSTC system ABENGOA SOLAR. This type of CSTC system has been widely used in industrial solar thermal systems for energy conversion and is commercially available. Therefore, the CSTC systems could not only sufficiently provide hot water for use in the greenhouse but also regulate the temperature in the greenhouse.

	Parabolic Trough	Solar Tower	Linear Fresnel	Dish-Stirling
Typical capacity (MW)	10-300	10-200	10-200	0.01-0.025
Maturity of technology	Commercially proven	Pilot commercial projects	Pilot projects	Demonstration projects
Key technology providers	Abengoa Solar, SolarMillennium, Sener Group, Acciona, Siemens, NextEra, ACS, SAMCA, etc.	Abengoa Solar, BrightSource, Energy, eSolar, SolarReserve, Torresol	Novatec Solar, Areva	
Technology development risk	Low	Medium	Medium	Medium
Operating temperature (°C)	350-550	250-565	390	550-750
Plant peak efficiency (%)	14-20	23-35*	18	30
Annual solar-to-electricity efficiency (net) (%)	11-16	7-20	13	12-25
Annual capacity factor (%)	25-28 (no TES) 29-43 (7h TES)	55 (10h TES)	22-24	25-28
Collector concentration	70-80 suns	>1 000 suns	>60 suns (depends on secondary reflector)	>1 300 suns
Receiver/absorber	Absorber attached to collector, moves with collector, complex design	External surface or cavity receiver, fixed	Fixed absorber, no evacuation secondary reflector	Absorber attached to collector, moves with collector
Storage system	Indirect two-tank molten salt at 380°C (dT=100K) or Direct two-tank molten salt at 550°C (dT=300K)	Direct two-tank molten salt at 550°C (dT=300K)	Short-term pressurised steam storage (<10 min)	No storage for Stirling dish, chemical storage under development
Hybridisation	Yes and direct	Yes	Yes, direct (steam boiler)	Not planned
Grid stability	Medium to high (TES or hybridisation)	High (large TES)	Medium (back-up firing possible)	Low
Cycle	Superheated Rankine steam cycle	Superheated Rankine steam cycle	Saturated Rankine steam cycle	Stirling
Steam conditions (°C/bar)	380 to 540/100	540/100 to 160	260/50	n.a.
Maximum slope of solar field (%)	<1-2	<2-4	<4	10% or more
Water requirement (m^3/MWh)	3 (wet cooling) 0.3 (dry cooling)	2-3(wet cooling) 0.25(dry cooling)	3 (wet cooling) 0.2 (dry cooling)	0.05-0.1 (mirror washing)
Application type	On-grid	On-grid	On-grid	On-grid/Off-grid
Suitability for air cooling	Low to good	Good	Low	Best
Storage with molten salt	Commercially available	Commercially available	Possible, but not proven	Possible, but not proven

Figure 29 Characteristics of CSTC systems with different technologies.

Figure 30 Photography of commercialized CSTC system, which is an example for demonstration of the design.

Integrated CPV and CSTC design

In general, the conversion efficiencies of CPV modules are in the range from 30% to 40%. Typically, the CPV modules use optical concentrators to focus the sunlight onto solar cells. In this way, more sunlight can be harvested by the solar cells. However, the process is usually accompanied with the generation of large amount of heat. A loss of 5% output power is observed for every 10°C above 25°C. For a cell operating at 50°C, the efficiency can be reduced by over 15%, which is equivalent to a loss of ~40 MWh energy for a typical household for 20 years. Therefore, in order to maintain the high efficiency of CPV modules, generally they are integrated with a cooling system to reduce the temperature of the solar cells.

Here, we propose a concept of integration of CPV and CSTC modules for use in the greenhouse. Fig. 31 displays the schematic representation of the proposed modules for CPV and CSTC systems integration. In our design, the CPV modules with high conversion efficiency can generate the required electricity for use in the greenhouse. On the other hands, the heat generated during the harvesting process can be conducted to the backside of CPV modules for thermal energy harvesting. As displayed in Fig. 31, the water in room temperature will flow through the backside of CPV modules to take the heat away. And then, the hot water can be directly used in the greenhouse. Accordingly, the electricity and hot water can be generated simultaneously for use in the greenhouse. The full details of the design can be found in the IP description document for this project.

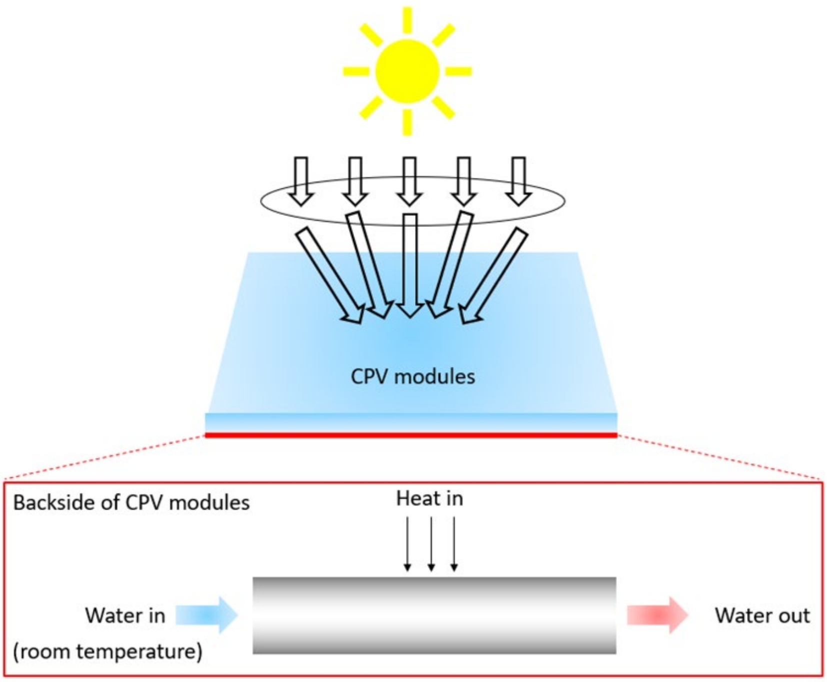


Figure 31 Schematic of the proposed modules for CPV and CSTC systems integration.

Design of ground-mounted FPPV+FPSTC technology

Design of the FPPV module

The photograph, electrical data, mechanical data, operating conditions, and temperature characteristics of commercialized flat panel photovoltaic (FPPV) module are displayed in Fig. 32. At current stage, the efficiency of commercial FPPV module was from 17.6% to 19.7%, which with the highest efficiency of 19.7% from Neo Solar Power (NSP) Corp (the top in the market according to our knowledge). Therefore, the annual electricity generated by this FPPV module could reach 308 kWh/m^2. Furthermore, the electricity generated by the FPPV module in spring, summer, autumn, and winter were 94, 97, 60, and 57 kWh/m^2, respectively.

Electrical Data

Model		D6L295L3A	Bifacial Gain 5%	Bifacial Gain 10%	D6L300L3A	Bifacial Gain 5%	Bifacial Gain 10%
Maximum Rating Power (Pmax)	[W]	295	310	325	300	315	330
Module Efficiency	[%]	17.6	18.5	19.4	17.9	18.8	19.7
Open Circuit Voltage (Voc)	[V]	39.47	39.47	39.47	39.61	39.61	39.61
Maximum Power Voltage	[V]	32.14	32.14	32.14	32.39	32.39	32.39
Short Circuit Current (Isc)	[A]	9.76	10.25	10.74	9.85	10.34	10.84
Maximum Power Current	[A]	9.18	9.64	10.10	9.27	9.73	10.20
Model		D6L305L3A	5%	10%	D6L310L3A	5%	10%
Maximum Rating Power (Pmax)	[W]	305	320	336	310	326	341
Module Efficiency	[%]	18.2	19.1	20.0	18.5	19.4	20.3
Open Circuit Voltage (Voc)	[V]	39.71	39.71	39.71	39.89	39.82	39.82
Maximum Power Voltage	[V]	32.50	32.50	32.50	32.68	32.68	32.68
Short Circuit Current (Isc)	[A]	9.91	10.41	10.90	9.95	10.45	10.95
Maximum Power Current	[A]	9.39	9.86	10.33	9.49	9.96	10.44

*Standard Test Condition (STC): Cell Temperature 25 °C, Irradiance 1000 W/m², AM 1.5
*Values without tolerance are typical numbers.

Mechanical Data

Item	Specification
Dimensions	1681 mm (L)[1] x 998 mm (W)[1] x 35 mm (D) / 66.2" (L)[1] x 39.3" (W)[1] x 1.38" (D)
Weight	25 kg / 55.1 lbs
Solar Cell	60 monocrystalline 6" p-PERC bifacial solar cells
Front Glass	Anti-reflective tempered patterned glass, 2.5 mm
Cell Encapsulation	Polyolefin
Rear Glass	Tempered pattern glass, 2.5 mm
Junction Box	IP 68 rated; Cable: 1,000 mm
Frame	Anodized aluminum frame, original or black
Packaging Configuration	30 pcs Per Pallet, 780 pcs per 40' HQ container

[1]: With assembly tolerance of ± 2 mm [± 0.08"]

Operating Conditions

Item	Specification
Mechanical Load	8100 Pa by IEC 61215
Maximum System Voltage	TUV 1500 VDC (IEC)
Series Fuse Rating	20 A
Operating Temperature	-40 to 85 °C

Temperature Characteristics

Item	Specification
Nominal Module Operating Temperature	40.6°C ± 2°C
Temperature Coefficient of Isc	0.06 % / °C
Temperature Coefficient of Voc	-0.28 % / °C
Temperature Coefficient of Pmax	-0.38 % / °C

*Nominal module operating temperature (NMOT): Air mass AM 1.5, irradiance 800W/m², temperature 20°C, windspeed 1 m/s.
*Reduction in efficiency from 1000W/m² to 200W/m² at 25°C: 3 ± 2%.

Figure 32 Photograph, electrical data, mechanical data, operating conditions, and temperature characteristics of commercialized FPPV module.

In comparison, the WSU has applied the product from 5B *Australia PTY LTD* in Sydney and more specifically, they have the FPPV 'Maverick' modules installed on campus. The same product is required by WSU to ensure the consistency of the solar array across the Hawkesbury campus. Herein, we calculate the required installation area and the daily generated electricity based on the technical data provided by 5B *Australia PTY LTD*. The photo, electrical data and mechanical specifications of the 'Maverick' FPPV modules are shown in Fig. 33. The efficiency of the 'Maverick' modules is approximately 18.01%, which is slightly lower than the one from Neo Solar Power (NSP) Corp. Therefore, the annual electricity generated by this FPPV module is around 281.1 kWh/m^2 [Fig. 34(a)]. Furthermore, the electricity generated by the FPPV modules in spring, summer, autumn, and winter are 85.5, 88.6, 54.7, and 52.2 kWh/m^2, respectively [Fig. 34(a)]. Since the total electricity consumption in greenhouse is approximately 270 kWh per day, the electricity consumption could be covered when installing the FPPV modules with an area of approximately 480 m^2 [Fig. 34(b)] considering sunlight condition and the required energy consumption in winter. The installation area (480 m^2) and annual generated electricity (281.1 kWh/m^2) of the 'Maverick' modules are relatively larger and lower than the FPPV modules from Neo Solar Power (NSP) Corp. To minimize the impact from altering the power supply system of the WSU greenhouse, the generated electricity of the FPPV 'Maverick' modules is fed into the grid on Hawkesbury campus.

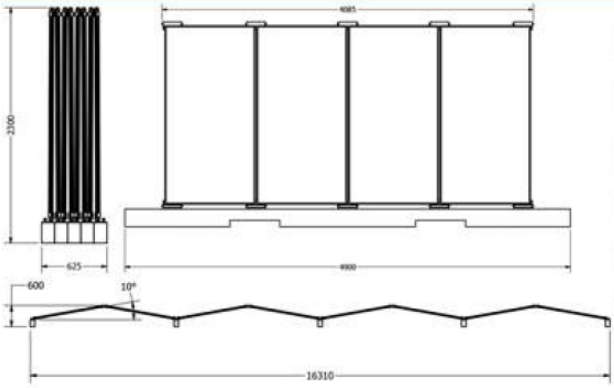
MODULE

PV Module Type	Jinko JKM350M-72	
	STC	NOCT
Maximum Power (Pmax)	350Wp	262Wp
Maximum Power Voltage (Vmp)	39.1V	37.2V
Maximum Power Current (Imp)	8.94A	7.05A
Open-circuit Voltage (Voc)	47.5V	46.0V
Short-circuit Current (Isc)	9.38A	7.46A
Module Efficiency STC (%)	18.01%	
Operating Temperature(℃)	-40~ +85	

ARRAY

Power at MPP	11.2 kW
Short circuit current	9.4 A per string, 18.8 A array output
Open circuit voltage	760 V
Current at MPP	8.9 A per string,17.9 A array output
Voltage at MPP	626 V
Power Density	1.1 ha/MW [2]
String Configuration	16 modules, 2 strings (1 east, 1 west)
Terminations	2 x MC4 connectors
String return cable	6mm x 20m

[2] Fixed tilt 3.0 ha/MW (NREL)



Module Dimensions	1956 x 992 x 40 (mm)
Module Configuration	32 modules per FEWA, 4 wide x 8 long
Packing Configuration	32 modules per unit, 3 units per 20' HQ container
Dimensions	4900 (W) x 600 (H) x 16,310 (L) mm deployed
Installation type	Telehandler or forklift, with 2 installers
Tilt Angle	10 degrees, excluding ground variation
Weight	2400 kg per FEWA
Module connections	Annodised aluminium alloy hinges, module clamps
Tethers	Stainless steel cable
Ballast	Precast 40MPa reinforced concrete beam
Peak wind velocity	Wind region A (60 m/s). Certified for installation up to wind region C, with minor additional ballast
Beam-beam tolerance EW	Maximum 690mm
Beam-beam tolerance NS	Maximum 48mm

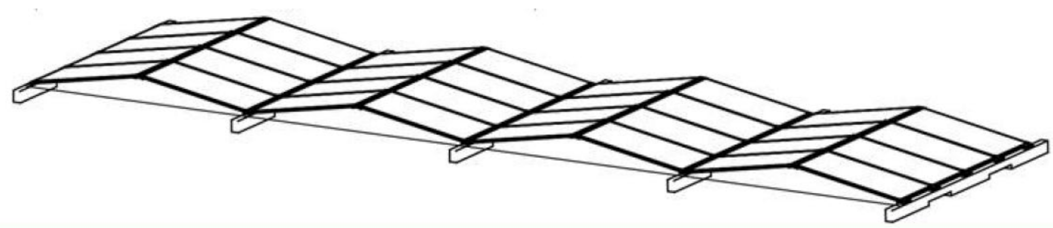


Figure 33 Photograph, electrical data and mechanical specifications of FPPV 'Maverick' modules (sourced from 5B Australia PTY LTD*).*

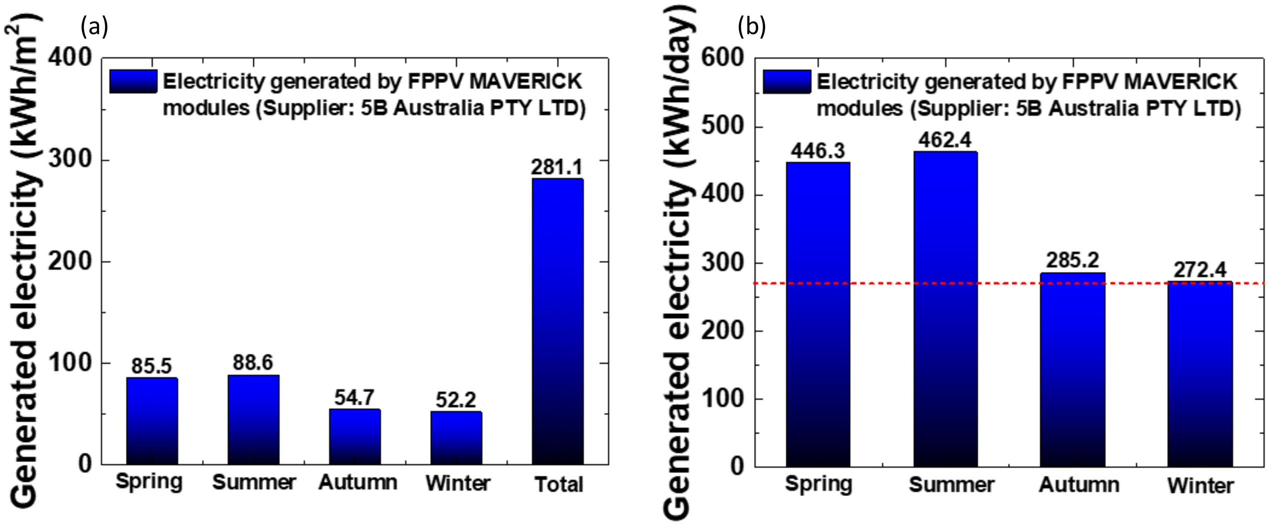


Figure 34 (a) Estimated seasonal electricity generated by commercialized FPPV 'MAVERICK' modules. (b) The average electricity generated by FPPV 'MAVERICK' modules with installation area of 480 m² in one day of each season. The red dash line indicates the average daily power consumption in the greenhouse.

Design of the FPSTC module

		R601	R602	R603	R604	R605	R606	R607
Nominal heat output at 80-60°C max/min*	kW	142.1/23.3	190.1/39.5	237.2/39.5	285.2/39.5	380.2/76.6	475.3/76.6	539.0/76.6
Nominal heat output at 75-60°C max/min*	kW	142.2/23.5	190.3/39.5	237.4/39.5	285.5/39.5	380.6/76.6	475.8/76.6	539.6/76.6
Nominal heat output at 40/30°C max/min*	kW	150.7/26.7	201.6/45.2	251.4/45.1	302.3/45.2	403.1/87.7	503.9/87.7	571.5/87.7
Nominal heat input Hi max/min*	kW	145.0/24.5	194.0/41.5	242.0/41.5	291.0/41.5	388.0/80.5	485.0/80.5	550.0/80.5
Efficiency at 80/60°C max/min	%	98.0/95.1						
Efficiency at 40/30°C max/min	%	103.9/109.0						
Annual efficiency (NNG 75/60°C)	%	106.8						
Annual efficiency (NNG 40/30°C)	%	110.4						
Standstill losses (T_{water} = 70°C)	%	0.21	0.18	0.17	0.16	0.15	0.14	0.13
Max. condensate flow	l/h	11	15	19	22	30	37	42
Gas consumption H-gas max/min (10,9 kWh/m³)	m³/h	13.3/2.3	17.8/3.8	22.2/3.8	26.7/3.8	35.6/7.4	44.5/7.4	50.5/7.4
Gas consumption E-gas max/min (10,9 kWh/m³)	m³/h	13.3/2.3	17.8/4.4	22.2/4.4	26.7/4.4	35.6/8.5	44.5/8.5	50.5/8.5
Gas consumption L-gas max/min (8,34 kWh/m³)	m³/h	17.4/2.9	23.2/5.0	29.0/5.0	34.9/5.0	46.5/9.7	58.2/9.7	66.0/9.7
Gas consumption LL-gas max/min (8,34 kWh/m³)	m³/h	17.4/2.9	23.2/5.8	29.0/5.8	34.9/5.8	46.5/11.2	58.2/11.2	66.0/11.2
Gas consumption Prop. max/min (12,8 kWh/kg)	kg/h	11.3/1.9	15.2/3.2	18.9/3.2	22.7/3.2	30.3/6.3	37.9/6.3	43.0/6.3
Gas pressure natural gas H/E max/min	mbar	20/17						
Gas pressure natural gas L/LL max/min	mbar	25/20						
Gas pressure liquid gas P max/min	mbar	50/30						
Maximum gas pressure	mbar	100						
Flue gas temperature at 80/60°C max/min	°C	78/56						
Flue gas temperature at 40/30°C max/min	°C	56/30						
Flue gas quantity max/min*	m³/h	238/40	318/69	397/69	477/69	636/134	795/134	901/134
CO_2 level natural gas H/E/L/LL max/min	%	10.2/9.4						
CO_2 level liguid gas P max/min	%	11.9/10.0						
NOx level max/min	mg/kWh	35/15						
CO level max/min	mg/kWh	14/8						
Max. permissible flue resistance max/min	Pa	160/10	160/10	200/10	200/10	200/10	250/10	250/10
Water volume	l	27	31	35	61	68	75	82
Water pressure max/min	bar	8/1						
Max. water temperature (High limit thermostat)	°C	100						
Maximum temperature setpoint	°C	90						
Nominal water flow at dT=20K	m³/h	6.1	8.1	10.2	12.2	16.3	20.4	23.1
Hydraulic resistance at nominal water flow	kPa	10	18	28	15	27	42	55
Electrical connection	V	230/400						
Frequency	Hz	50						
Mains connection fuse	A	10						
IP class	-	IP20						
Power consumption boiler max/min (excl. pump)	W	158/43	200/35	230/35	260/35	470/61	650/61	770/61
Power consumption 3-step pump (optional)	W	170/90	190/120	380/210	380/210	530/300	720/380	1150/600
Power consumption speed controlled pump (opt)	W	180/10	180/10	435/25	435/25	450/25	800/35	800/35
Power consumption bypass pump (optional)	W	55/35	85/65	170/90	170/90	190/120	460/225	470/280
Weight (empty)	kg	295	345	400	465	535	590	650
Noise level at 1 meter distance	dB(A)	59						
Ionisation current minimum	μA	6						
PH value condensate	-	32						
CE certification code	-	CE-0063BS3840						
Water connections	-	R2"			DN65 PN16			
Gas connection	-	R3/4"	R1"	R1"	R1"	R1.1/2"	R1.1/2"	R1.1/2"
Flue gas connection	mm	150	150	200	200	250	250	250
Air intake connection (for room sealed use)	mm	125	125	150	150	200	200	200
Condensate connection	mm	22	22	22	22	22	22	22

* min load on gasses H/L/P. For type R602-R607 on gasses LL/E min value is 15% higher.

Figure 35 Photograph and technical data of currently used boiler (Rendamax R600) in the greenhouse.

Currently, the hot water usage in the greenhouse is provided by a boiler (Rendamax R600). By knowing the technical details of the boiler, we are able to design flat panel solar thermal collector (FPSTC) to compensate for the cost of the hot water. Fig. 35 shows the photo and technical data of the current boiler (Rendamax R600) in the greenhouse. Currently, the temperature of hot water used in the greenhouse is approximately 30 °C. The volume of hot water reservoir is approximately 82 L. Fig. 36 displays the photo of a commercial FPSTC module supplied from Apricus Australia PTY LTD. The collector power performance, pressure drop, materials of construction, performance data, physical characterizations, and storage tank specifications are shown in Fig. 36. The optimal efficiency of the collector reaches 68.7%. Therefore, the annual energy generated by this FPSTC module is 1,072 kWh/m^2 [Fig. 37(a)]. As displayed in Fig. 37(a), the energy generated by the FPSTC modules are 326.3, 338.1, 208.5, and 199.2 kWh/m^2 in spring, summer, autumn, and winter, respectively. The maximum energy consumption in the generation of hot and cold water is approximately 119.2 kWh per day (red dash line), the whole energy consumption could be compensated when installing the FPSTC modules with an area of approximately 60 m^2, considering sunlight condition and the required energy consumption in winter. Furthermore, the volume of storage tank of the FPSTC system can be up to 400 L as displayed in Fig. 36. Therefore, the designed FPSTC modules could sufficiently supply hot and cold water for use in the greenhouse.

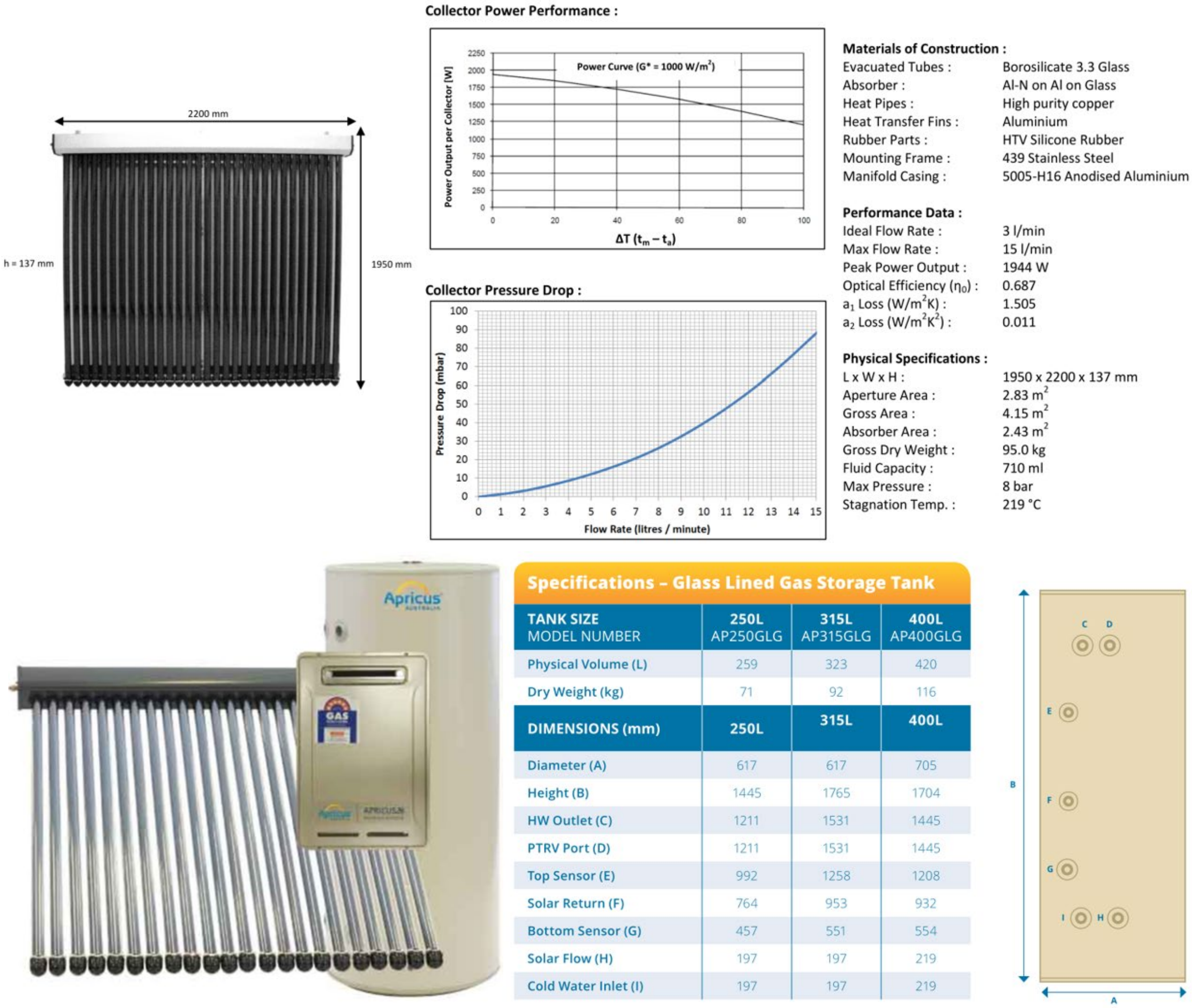


Figure 36 Photography, collector power performance, collector pressure drop, materials of construction, performance data, and physical specifications of commercialized FPSTC module (sourced from Apricus Australia PTY LTD).

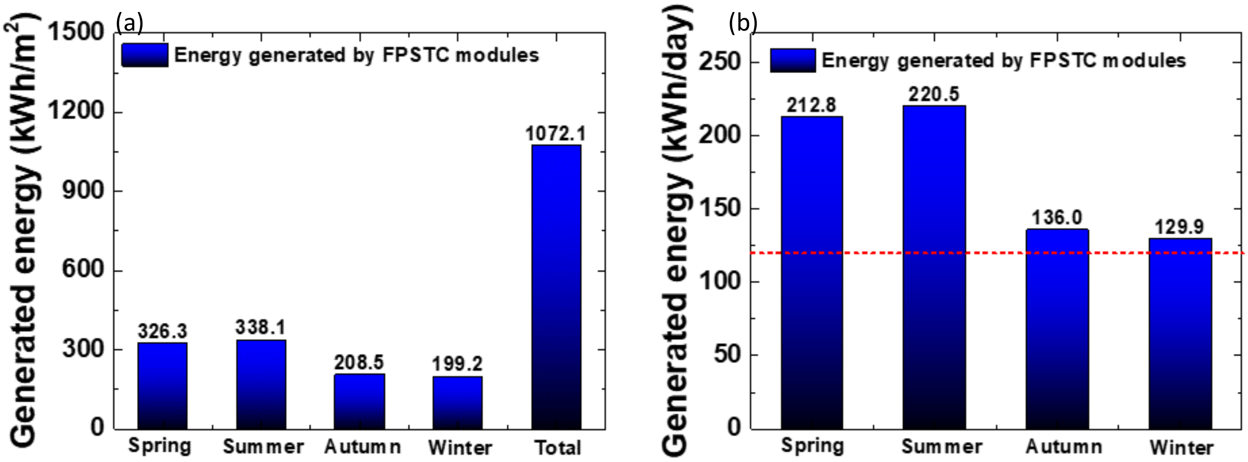


Figure 37 (a) Estimated seasonal electricity generated by commercialized FPSTC modules. (b) The average electricity generated by FPSTC modules with an installation area of 60 m^2 in one day of each season. The red dash line indicates the average daily power consumption for the generation of hot and cold water in the greenhouse.

Here, we design to first save the generated hot water in the storage tank, then build a pipe connecting to the water supply to the current boiler. As the boiler will only turn on when the temperature inside the boiler below a certain temperature, for example 30 °C by the setting, we can supply the hot water with temperature higher than the set temperature, without turning on the boiler. In this way, it is possible to keep the boiler off all the time, thus saving the energy consumption in hot water generation.

Initial cost effectiveness data obtained for technologies

In this project, in order to simulate the cost-effectiveness of the smart glass and renewable energy technologies, we use numerical simulation method to create a model to calculate the cost of a greenhouse and the cost saving by installing the smart films and renewable technologies.

The simulation is divided into two parts:

1) Simulation of the costs, especially the lighting and heating costs of a greenhouse, in which the local weather, the glazing materials, the structure of the greenhouse and the required parameters (light, temperature and CO_2 level) are considered to output the energy consumption of the greenhouse. The energy savings by using the smart glass/film can be shown from the reduced energy consumption.

2) Simulation of the cost saving and the payback period of the renewable technologies, in which the installation and maintenance cost of solar panels and solar thermal collectors are considered. The initial investment is compensated by the saved energy generated by the renewable technologies. Then the payback period is calculated.

Model description

Cost simulation model

In the model, to study the running cost of the greenhouses, four key parameters describing the inner environment of the greenhouses are studied, namely the **light**, **temperature**, **relative humidity**, and **carbon dioxide enrichment.** The running cost of the greenhouses involves ventilation, cooling and heating of the greenhouse, lighting the greenhouse with supplementary light source and humidity control, which are to maintain the required microenvironment inside the greenhouse.

Light

In the daytime, the light in the greenhouses is mainly provided by the sunlight, except for cloudy days. The sunlight conditions depend on the location of the greenhouses and vary from day to day. Therefore, to improve the accuracy of the model, the daily sunlight exposure information is obtained from the Bureau of Meteorology (BOM) website. In addition, the overall sunlight transmitted is calculated using the transmission of the covering material.

Temperature

The temperature inside the greenhouses is set to be a constant. The daily heating costs depend on the daily temperature in different locations. The daily temperature data, including the typical high and low temperatures, is also obtained from the BOM website. To calculate heat loss via conduction and convection over any greenhouse surface, four values are used: the temperatures on either side of the surface (the temperature set point of the greenhouse and the current temperature outside), the surface area of the structure, and the U-value of the surface material. The solar radiation data is used to estimate how much heat the greenhouse will gain from the sun. To calculate the cost for heating the greenhouse, the energy lose is divided by the amount of heat gained from burning fuel or using electricity, adjusted for the given heater or boiler efficiency. Finally, the cost to heat the structure is calculated by multiplying the units of fuel/electricity by the cost per unit specified for that greenhouse.

Relative humidity and carbon dioxide enrichment

The relative humidity and carbon dioxide enrichment are controlled by the ventilation process. Ventilation can be achieved passively or actively. The ventilation requirements are calculated based on the overall air volume of the designed greenhouse model.

Calculating plant growth and development

Crop growth and development depends in large part on light and temperature. For simplicity only, we have decided to assume that the photoperiod required for proper development for each crop is being met. Therefore, in our model, crop development will only depend on the average temperature and light levels during the cropping schedule. For growth, we have used a single leaf photosynthesis model and allowed light to drive growth.

Smart glass modelling

Viridian smart glass website (https://www.viridianglass.com/products/energy-efficiency/smartglass/) and Solar Gard (https://www.solargard.com/au/) as the insulation value (U-value). For other smart glass/film users can add materials by themselves.

Photovoltaic modelling

There are three options to be considered when installing the solar panels. Then the overall available energy in terms of electricity is modelled based on the daily sunlight exposure data, which gives the daily electricity per m^2 and the overall area for sunlight exposure of the greenhouse.

Option 1: Semitransparent roof top solar panel configuration, which uses the central green spectrum (480 nm~ 580 nm). It is less effective for photosynthesis.

Option 2: Concentrating roof top solar panel

Option 3: Ground-mounted full spectrum solar panel.

Solar thermal heating modelling

Here we assume an independent solar heating system without the crosstalk with the solar panel that is installed to provide heating of the greenhouse. The required area of the solar heating device depends on the required energy for maintaining the temperature and the conversion efficiency. The simulation of the heating process is done by using commercial software, System Advisor Model (SAM) (https://sam.nrel.gov/download.html), which is able to calculate the sunshine in certain location.

Cost effectiveness calculation

The cost effectiveness is calculated by comparing the greenhouses equipped with novel technology to those with conversional greenhouse technologies, to study the cost saving. We provide simple payback period, which is the years until the initial additional cost is recuperated where energy price is assumed as constant.

In our continuous time formulation, t ranges between 0 and m = 24 × 365 = 8,760 h, which is for one year. The price per kilowatt hour (kWh) at time t at which the electricity charge is denoted by $p_e(t)$. We obtained the electricity prices from the website https://www.globalpetrolprices.com/Australia/electricity_prices/. The electricity prices for household and for business are A$0.332 and A$0.253/kWh, respectively. The capacity factor per module in 1 m^2 area, $CF(t)$, represents the percentage of the available capacity that is used at time t, which can be expressed as

$$CF(t) = NC \times R(t)/R_0$$

where NC is the nominal capacity of the solar technology modules, R_0 is the theoretical maximum solar irradiance, which is 1 kW/m^2. And $R(t)$ is the actual solar irradiance at different time, which we obtained from the Bureau of Meteorology (BOM) website (http://www.bom.gov.au/climate/data/) .

As a result of the inherent intermittency of renewable power, $CF(t)$ varies with time and generally satisfies $CF(t) \leq NC$. Considering the economic lifetime (N years) of the module is 20 years, which is common for most solar panels on the market, the efficiency degradation in each year of each module is 0.5%. Thus the capacity degradation factor can be expressed as

$$C_d(i) = 0.5\% \times i$$

where i is the number of years of the module has been used. In addition, the efficiencies of solar cells will decrease 0.5% when the temperature of solar cells increases approximately 1°C from the working temperature for a 22% efficiency Si-based solar cell. Thus, the efficiency degradation due to the instant temperature is expressed as

$$C_T(t) = \begin{cases} 0.5\% \times (T(t) - T_w), & if\ T(t) > T_w \\ 0, & if\ T(t) \leq T_w \end{cases}$$

where $T(t)$ it the temperature versus time, which can also be obtained from the BOM website. As one can see, there will be no efficiency degradation if the $T(t)$ is below the named working temperature T_w, which is according to the model specification.

The yearly time dependent nominal capacity of the solar module can be expressed as

$$NC(t,i) = NC - C_d(i) - C_T(t)$$

Thus CF as a function of number of years can be expressed as

$$CF(t,i) = NC(t,i) \times R(t)/R_0$$

Therefore, the generated electricity each year can be expressed as

$$E(i) = \int_0^m CF(t,i) \times A$$

where A is the installed area of the entire renewable energy technologies. The saved cost thus can be expressed as

$$C_s(i) = \int_0^m CF(t,i) p_e(t) \times A$$

Here we can assume an average price (p_e) of electricity without losing the generality, the saved cost becomes

$$C_s(i) = p_e \int_0^m CF(t,i) \times A = p_e E(i)$$

Then the overall cost saving over the entire lifespan of the solar technologies can be expressed as

$$\mathrm{C}_{total} = \sum_{i=1}^{N} \mathrm{C}_s(i)$$

Then the cash flow (C_f), is considered as

$$\mathrm{C}_f = C_{total} - C_I - C_{OM}$$

Where C_I is the installation cost and C_{OM} is the operating and maintenance costs. The operating and maintenance cost were estimated as 3% of installation cost each year.

Calculation output

Because the budgets for purchasing solar modules are limited, we estimate the installation area and payback period of these four technologies based on the budget of each solar technology. Table 5 shows the estimated installation cost, operating and maintenance cost, energy cost, saving energy cost, and payback period of CPV, CSTC, FPPV, and FPSTC modules with installed area of 11 m^2, 50 m^2, 68.5 m^2, 60 m^2, respectively. We found that the budgets for CSTC and FPSTC modules can fully cover the installation cost of the designed CSTC and FPSTC modules. However, the budgets of CPV and FPPV modules could only cover the installation cost of the CPV and FPPV modules with areas of less than 11 and 68.5 m^2, respectively. Therefore, the generated electricity of the installed CPV and FPPV modules were limited to 6,866.57 and 19,252.68 kWh per year, respectively. In this case, the installed CPV and FPPV modules could only generate electricity of 13.9 [Fig. 38 left panel] and 38.9 [Fig. 38 right panel] kWh per day, respectively, which is much lower than the daily electricity (270 kWh) consumption in the greenhouse. In Australia, the average energy cost is approximately $0.3431/kWh [data sourced from *2017* Residential *Electricity Price Trends report, Australian Energy Market Commission* (AEMC)]. Therefore, the saved energy costs of installed CPV and FPPV modules are approximately $2,355.92 and $6,605.60, each year respectively. Based on the information, we could estimate the cash flow and payback period of these two installed modules.

Table 5 Estimated installation cost, operating and maintenance cost, energy cost, saving energy cost, and payback period of CPV, CSTC, FPPV, and FPSTC modules with installation area of 11, 50, 68.5, 60 m^2, respectively.

Modules	Area (m^2)	Installation cost ($)	Operating and maintenance cost ($/year)	Generated energy (kWh/year)	Energy cost ($/kWh)	Saved energy cost ($/year)	Payback period (year)
CPV	11	138,500	7,120	6,866.57	0.3431	2,355.91889	N/A
CSTC	50	49,800	5,650	62,423.30	0.3431	21417.43423	3.2
FPPV	68.5	40,100	4,800	19,252.68	0.3431	6,605.59542	29.9
FPSTC	60	29,350	6,670	64,327.20	0.3431	22070.66232	1.9

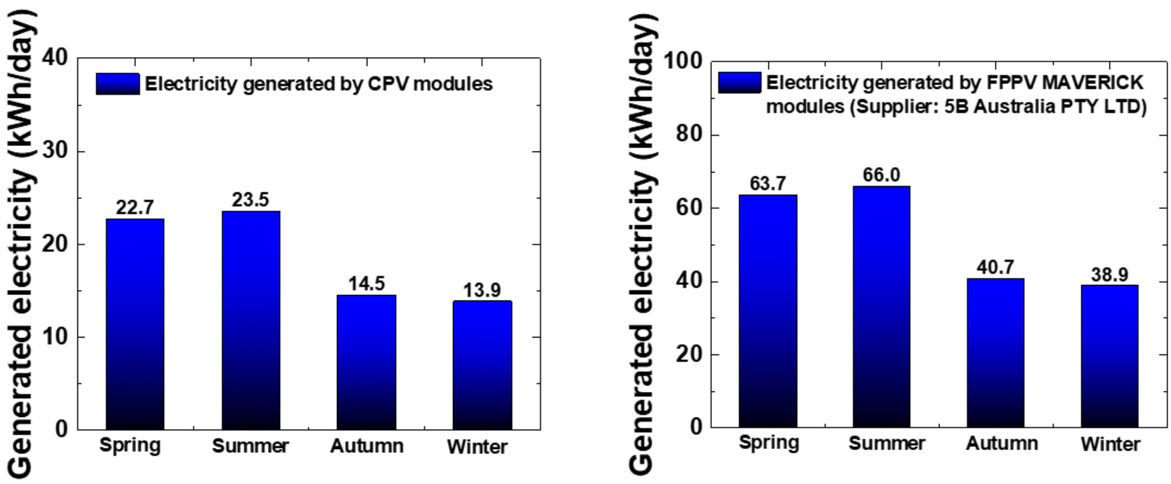


Figure 38 The average electricity generated by CPV modules (left) with installation area of 11 m^2 and FPPV modules (right) with installation area of 68.5 m^2 in one day of each season.

Figs. 39 (a)-(d) display the estimated cash flow of CPV modules with an installation area of 220 m^2, FPPV modules with an area of 450 m^2, CPV modules with an area of 11 m^2, and FPPV modules with an area of 68.5 m^2. Here, we set the efficiency degradation in each year of each module as 0.5%. The installed CPV modules with an area of 220 m^2 and FPPV modules with an area of 450 m^2 could fully cover the total electricity consumption of greenhouse. Moreover, in the entire lifespan of those modules, according to the electricity price, the earnings generated are $230,110 [Fig. 39(a)] and $639,559.6 [Fig. 39(b)], respectively. In this case, the installation cost of CPV modules with an area of 220 m^2 and FPPV modules with area of 450 m^2 would be paid back within 13.7 and 4.1 years, respectively (Fig. 39). In contrast, the CPV modules with an area of 11 m^2 and FPPV modules with an area of 68.5 m^2 cannot cover the total electricity consumption of greenhouse. Furthermore, the installation cost of CPV modules with an area of 11 m^2 would hardly be paid back and that of FPPV modules with an area of 68.5 m^2 would be paid back up to 29.9 years (Fig. 39). Accordingly, we suggest that it's better to carefully evaluate the budget, installation area, payback period, and daily generated electricity before the installation of CPV and FPPV modules since the installation with large areas will be more cost effective and have a shorter payback period compared with those installed with small areas.

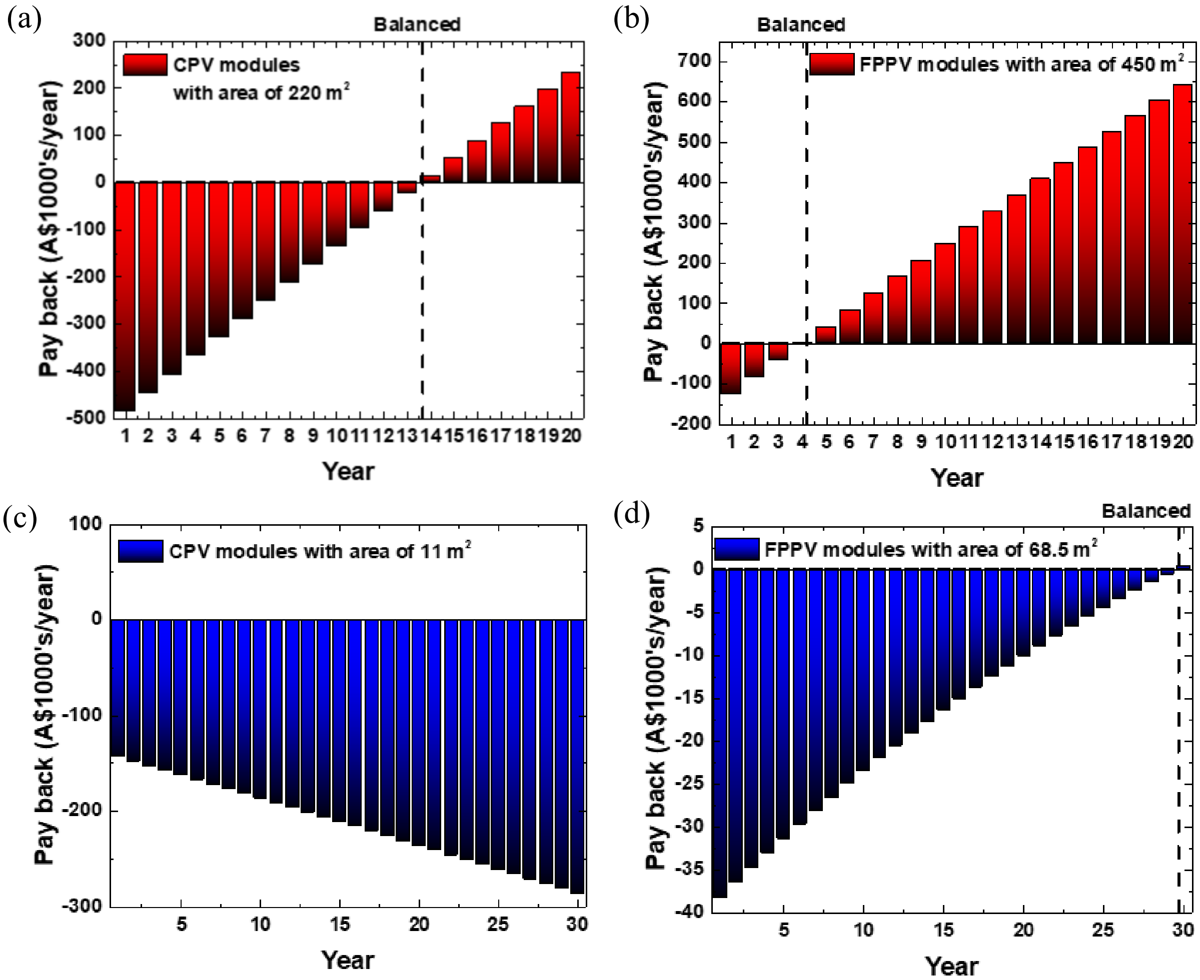


Figure 39 Estimated cash flow of (a) CPV modules with an area of 220 m^2, (b) FPPV modules with an area of 450 m^2, (c) CPV modules with an area of 11 m^2, and (d) FPPV modules with area of 68.5 m^2.

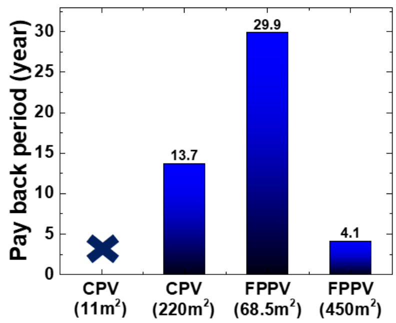


Figure 40 Payback period of CPV and FPPV modules with an installation area of 11, 220, 68.5, and 450 m^2, respectively.

Field data collection and cost-effectiveness evaluation

Small scale field test to prove the cost-effectiveness evaluation model

In order to preliminarily prove the concept and estimate the cost effectiveness of the designed FPPV modules, we bought a flexible solar panel with an efficiency of approximately 15.6% to conduct experiments and then used the recorded data from the experiments to perform further analysis and estimation. In the experiments, the aim was to investigate the difference between our evaluation and the field obtained data. At first, we analysed the daily solar exposure at Hawthorn (Victoria) and the average day length of each month in 2019 as shown in Fig. 41(a) and Fig. 41(b), respectively. The average solar exposure and day length is 4.5 kWh/m^2/day and 14 hours, respectively. And then, we based on the data, which show in Fig. 41(a) and Fig. 41(b), to speculate the data of generated electricity from the flexible solar panel with efficiency of 15.6%. As shown in Fig. 41(c) and Fig. 41(d), we could precisely estimate the daily generated electricity and even further calculate hourly generated electricity in each day for the solar panel with efficiency of 15.6%, respectively.

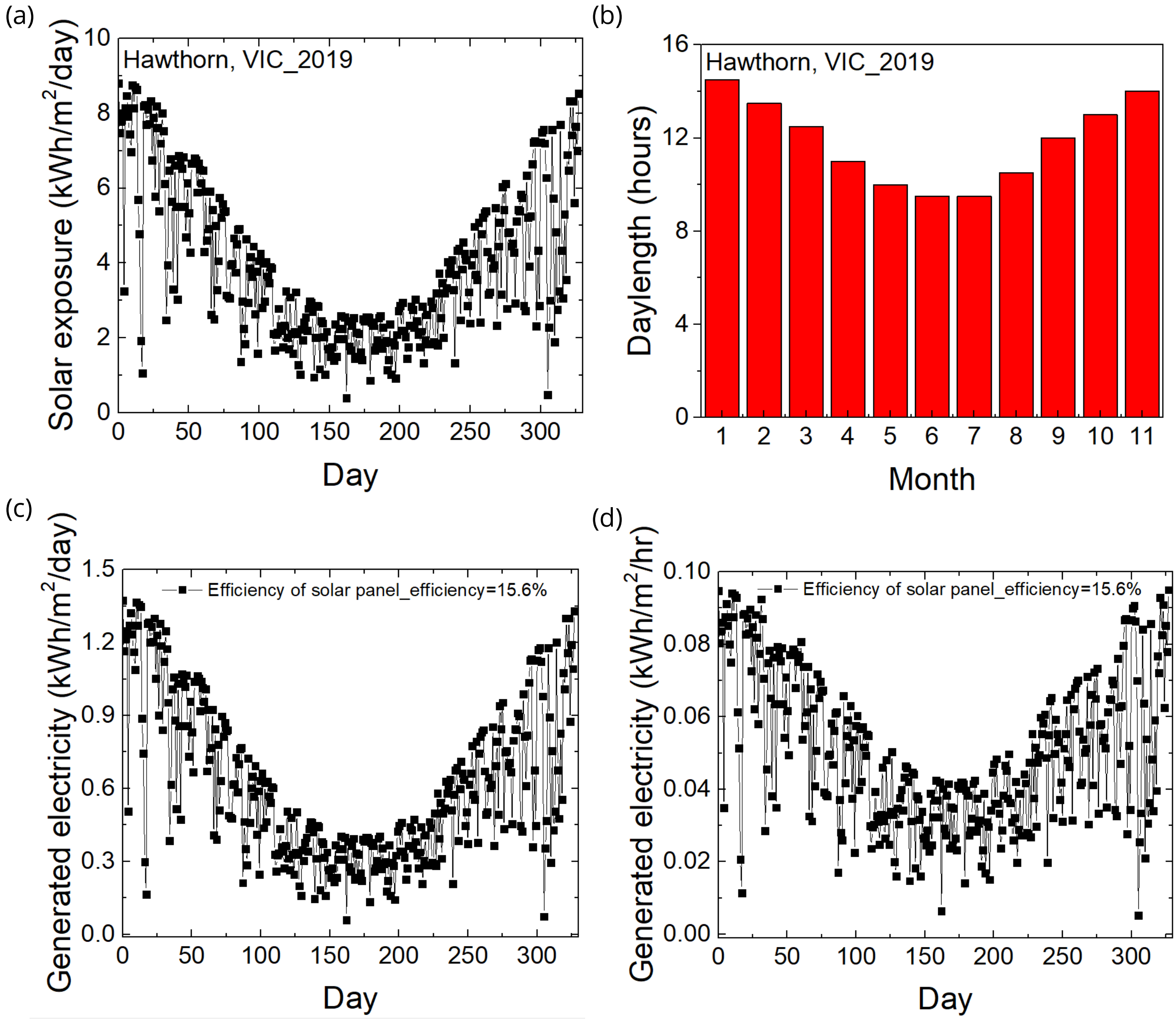


Figure 41 (a) Daily solar exposure at Hawthorn (Victoria) in 2019. (b) Average day length in each month in Victoria. (c, d) Estimated (c) daily and (d) hourly generated electricity from a solar panel with efficiency of 15.6% at Hawthorn (Victoria) in 2019.

Next, we designed an experiment to verify the estimations. Fig. 42(a) shows the photograph of the experimental setup. We connected the flexible solar panel, which has an area of approximately 0.98 m^2, with a battery to record the generated electricity under sunlight illumination at Hawthorn (Victoria). Fig. 42(b) and Fig. 42(c) show the measured data of generated electricity recorded under different dates with different weather conditions. As displayed in Fig. 42(b), the temperature and measured average generated electricity are 14°C and approximately 0.054 kWh/m^2/hr, respectively. Besides, the temperature and measured average generated electricity are 19°C and approximately 0.081 kWh/m^2/hr, respectively (Fig. 42(c)). The data of measured generated electricity (Fig. 42(b) and Fig. 42(c)) are very close to and just approximately 10% variations from the estimated data [Fig. 41(d)]. We attribute the small variations to the difference in the incidence angle of sunlight towards the flexible solar panel during the measurements and the small variations of weather conditions. If we have a sun tracker, it can help minimize the angle of incidence between the incoming light and the panel, and thereby, the measured data would be closer to the estimated data, which proves the accuracy of our model. With this we could use our model to precisely estimate the generated electricity and cost effectiveness of solar technologies based on the local weather conditions.

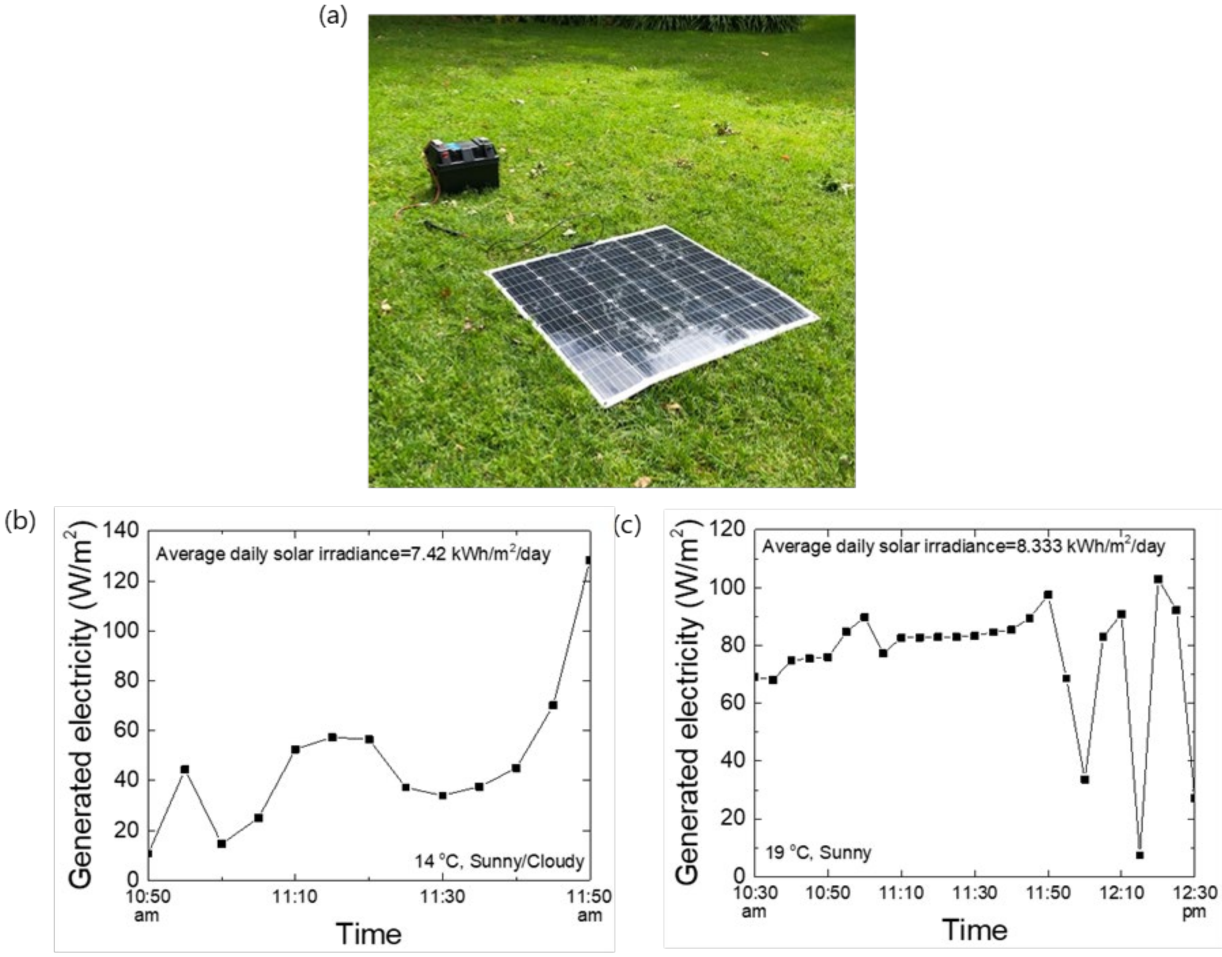


Figure 42 (a) Photograph of the experimental setup. (b, c) Measured data of generated electricity of flexible solar panel, which are recorded under different weather conditions.

Further evaluation using Australia wide data

The experimental results confirmed the accuracy of the evaluation model, based on which we can further analyse the annual generated electricity and cost effectiveness of FPPV with an installation area of 500 m^2 at different cities in Australia. In general, the efficiencies of commercialized FPPV modules are in the range of 18% and 19%. Table 6 displays the system cost, operating and maintenance cost, energy cost, saving energy cost, and payback period of FPPV modules with an installation area of 500 m^2 and efficiencies of 18% and 19%. The system cost and annual operation and maintenance cost of FPPV are approximately $170,000 and $ 4,800, respectively. The annual generated energy of the FPPV modules with efficiency of 19% are 135,560.70, 154,137.87, 174,920.87, 182,421.30, and 178,812.29 kWh in Melbourne, Sydney, Perth, Cairns, and Brisbane, respectively. In Australia, the average energy cost is approximately $0.3441/kWh. Therefore, the saved energy costs of FPPV modules with efficiency of 19% were approximately $46,510.8, 52,884.7, 60,015.3, 62,588.7, and 6,1350.4 in Melbourne, Sydney, Perth, Cairns, and Brisbane, respectively, per year. Estimated savings included a 0.5%/year drop in FPPV system performance over the lifetime.

Based on the information, we could estimate the cash flow and payback period of these installed modules. As displayed in Table 6, the payback periods of the FPPV modules with efficiencies of 19% were approximately 4.2, 3.6, 3.2, 3, 3.1 years as the installed location in Melbourne, Sydney, Perth, Cairns, and Brisbane, respectively. The city located at a lower latitude might obtain longer solar exposure, and therefore, the installed FPPV modules could generate more electricity, which results in the shorter payback period. Besides, we analysed the payback periods of FPPV modules with efficiency of 18% at different cities. In this situation, the payback periods of the FPPV modules are approximately 4.5, 3.8, 3.4, 3.2, 3.3 years as the installed location in Melbourne, Sydney, Perth, Cairns, and Brisbane, respectively. Accordingly, the investment of FPPV technologies with installation area of 500 m^2 can be pay backed within 5 years and even less than 4 years in low-latitude cities due to the enough solar exposure in Australia.

Table 6 Estimated installation cost, operating and maintenance cost, energy cost, saving energy cost, and payback period of FPPV modules with installed area of 500 m2 and different efficiencies at different cities in Australia.

FPPV Module	Location	System cost ($)	Operating and maintenance cost ($/year)	Generated energy (kWh/year)	Energy cost ($/kWh)	Saved energy cost ($/year)	Payback period (year)
Efficiency=19% Area=500 m^2	Melbourne	170,000	4,800	135,560.70	0.3431	46510.87603	4.2
	Sydney	170,000	4,800	154,137.87	0.3431	52884.7032	3.6
	Perth	170,000	4,800	174,920.87	0.3431	60015.3505	3.2
	Cairns	170,000	4,800	182,421.30	0.3431	62588.74803	3
	Brisbane	170,000	4,800	178,812.29	0.3431	61350.4967	3.1
Efficiency=18% Area=500 m^2	Melbourne	170,000	4,800	128,425.93	0.3431	44062.93518	4.5
	Sydney	170,000	4,800	146,025.35	0.3431	50101.29759	3.8
	Perth	170,000	4,800	165,714.51	0.3431	56856.64838	3.4
	Cairns	170,000	4,800	172,820.18	0.3431	59294.60376	3.2
	Brisbane	170,000	4,800	169,401.12	0.3431	58121.52427	3.3

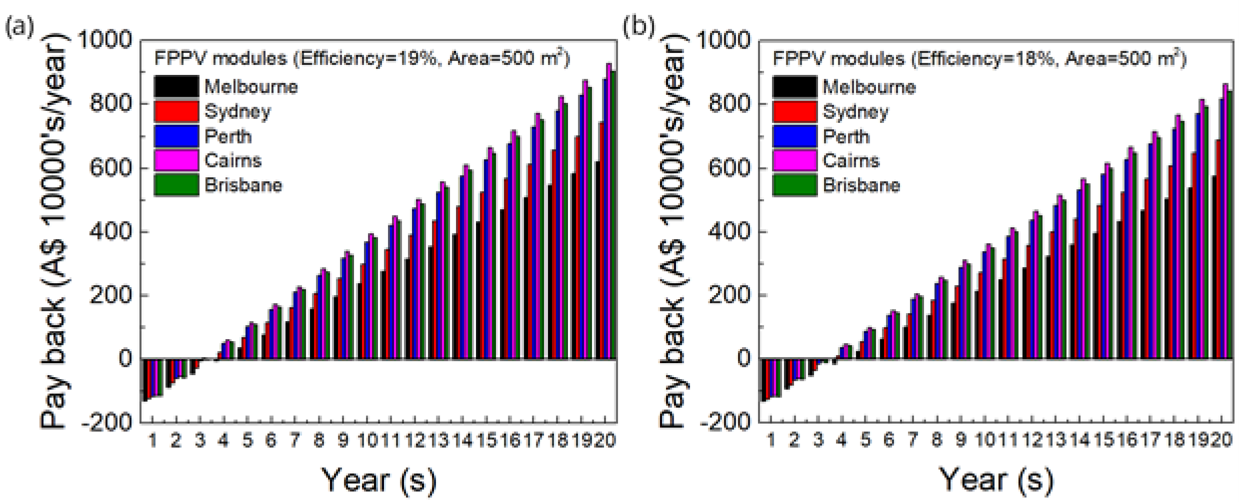


Figure 43 Estimated cash flow of FPPV modules with installation area of 500 m2 and efficiencies of (a) 19% and (b) 18% in different cities in 20 years.

Fig. 43 (a) and Fig. 43(b) display the estimated cash flow of installed FPPV modules with efficiencies of 19%

and 18%, respectively, in different cities in 20 years. Here, we set the efficiency degradation in each year of each module as 0.5%. The installed FPPV modules can not only cover the total electricity consumption of greenhouse, but also bring revenues. In the whole lifespan of the FPPV modules with efficiency of 19%, according to the electricity price, the earning could be generated are $ 621,330, 742,929, 878,967, 928,062, and 904,439 in Melbourne, Sydney, Perth, Cairns, and Brisbane, respectively. Even the FPPV modules with lower efficiency of 18%, the earning generated are still significant at $ 574,628, 689,827, 818,705, 865,216, and 842,836 in Melbourne, Sydney, Perth, Cairns, and Brisbane, respectively, in 20 years. By applying the FPPV technologies, it is possible to realise self-sustained greenhouse, which can be operated in remote area without sufficient power supply.

Potential replacement of energy curtains by flexible or foldable photovoltaics

FPPV is an efficient way to employ renewable energy in compensating the cost of greenhouse. However, it requires additional land, which may incur restrictions for metropolitan area. According to the understanding on different photovoltaics technologies and the trial experience with WSU greenhouse, we recommend the potential replacement of energy curtains in greenhouse by flexible or foldable photovoltaics. Here we demonstrate the cost-effectiveness evaluation of these photovoltaics technologies for this purpose.

Fig. 44 (a) and Fig. 44(b) display the photographs of flexible and foldable solar panels, respectively. The efficiencies of the commercialized flexible and foldable photovoltaics are approximately 7.2% and 12%, respectively. Although the efficiencies are not comparable to that of FPPV, their flexibility provides them the potential to integrate with the greenhouse by replacing the energy curtains with minimum disruption to the greenhouse and without the need for extra land. To characterize the electricity generation capability of the flexible and foldable solar panels, we connected these solar panels, which both have the panel area of approximately 1.04 m^2, with batteries to record the generated electricity under sunlight illumination at Hawthorn (Victoria). Fig. 44(c) and Fig. 44(d) show the measured data of generated electricity of flexible and foldable solar panels, respectively, which were recorded under different dates with different weather conditions.

As the intended use of the flexible and foldable solar panels was to replace the current energy curtain under the glass roof of the greenhouse, it is important to consider the transmission of the glass roof of the greenhouse. The greenhouse in WSU uses frosted glass with high transmission, the transmission of which in the visible spectrum is around 97%. Thus, there would not be significant difference between the measurement with or without the glass. In order to simplify the measurement process, we measured the electricity generation under direct sunlight. In the meantime, we measured the performance of the solar panels under different environmental conditions, such as different temperatures to see the effects of temperature.

As displayed in Fig. 44(c), the measured average hourly generated electricity of the flexible solar panel is approximately 0.022 kWh/m^2 on a partly cloudy day and approximately 0.043 kWh/m^2 on a sunny day. Furthermore, the measured average hourly generated electricity of the foldable solar panel is approximately between 0.042 kWh/m^2 and 0.06 kWh/m^2, as displayed in Fig. 44(d). The data of measured generated electricity (Fig. 44(c) and Fig. 44(d)) were very close to our estimations (Fig. 45(a) and Fig. 45(b)).

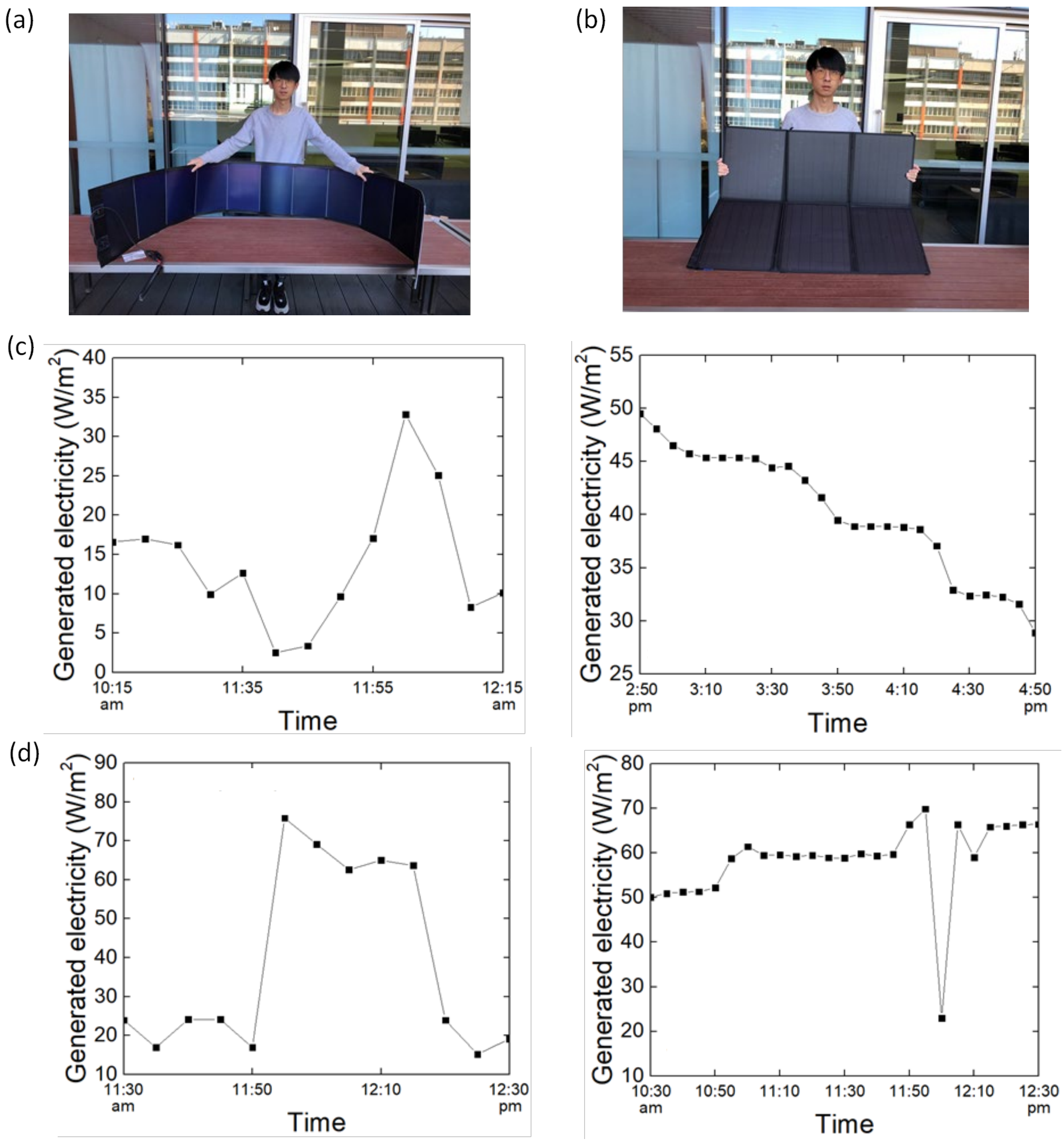


Figure 44 (a, b) Photograph of (a) flexible and (b) foldable solar panels. (c, d) Measured data of generated electricity of (c) flexible and (d) foldable solar panels.

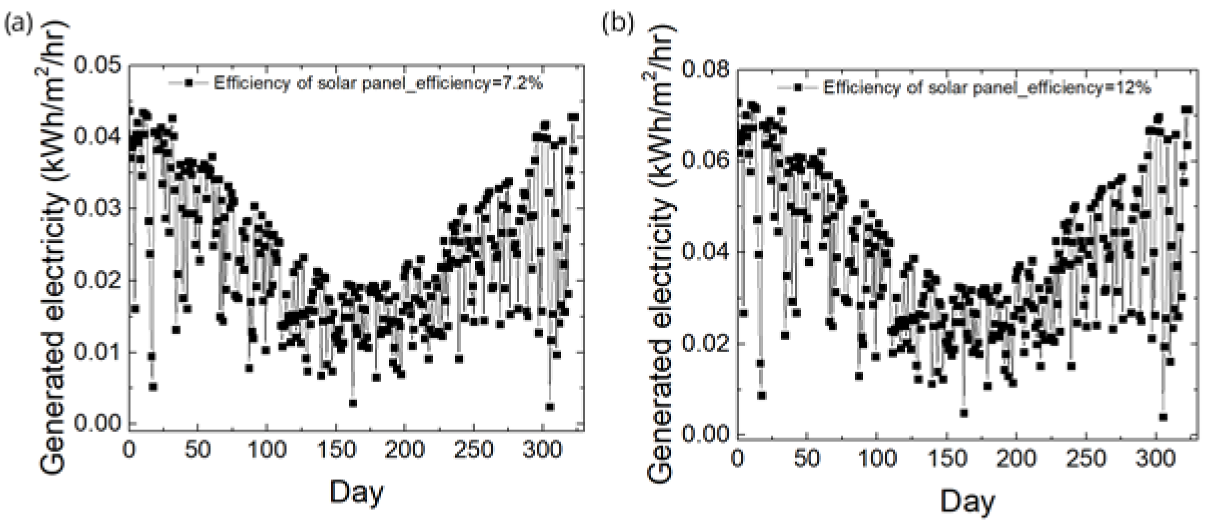


Figure 45 Estimated hourly generated electricity from a solar panel with efficiencies of (a) 7.2% and (b) 12% at Hawthorn (Victoria) in 2019.

Table 7 Estimated system cost, operating and maintenance cost, annual generated electricity energy cost, and saving energy cost of flexible and folding solar panels with installed area of 50 m^2 and 100 m^2 in Sydney.

Module	Installed area (m^2)	System cost ($)	Operating and maintenance cost ($/year)	Generated energy (kWh/year)	Energy cost ($/kWh)	Saved energy cost ($/year)
Flexible solar panel	50	19,950	500	5,814	0.3431	2,004
	100	39,990	500	11,682	0.3431	4,008
Folding solar panel	50	24,590	500	9,735	0.3431	3,340
	100	49,990	500	19,470	0.3431	6,680

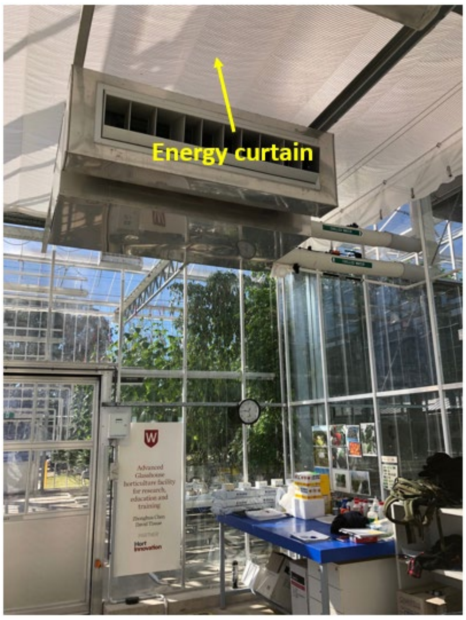


Figure 46 Photograph of energy curtains used in the greenhouse.

In order to reduce the temperature inside the greenhouse, WSU team used the energy curtains in the greenhouse (Fig. 46) to block the sunlight. The energy curtain has a transmission around 25%. According to the data recorded by the Priva system in the greenhouse, the energy curtain was closed (98% cover) up to 8 hours a day in summer. It mainly blocked the excessive light with minimum change on the spectrum of the light. This means 75% of the sunlight has been wasted. Thus, another efficient way to utilize the solar energy is to replace the energy curtain with the foldable and flexible solar panels with sufficient gaps between them to ensure the same amount of sunlight transmission is achieved as that of the energy curtain. This could be achieved through the placement of the flexible and foldable solar panels at designed positions. Since the spectrum of the transmitted light will not be changed, as long as the amount of transmission is guaranteed, the diffused glass can uniform the incident light within the greenhouse. Therefore, it will not change the original condition when an energy curtain is used. Therefore, we suggest that using flexible or foldable solar panels to replace parts of energy curtains represents a good way to produce extra renewable energy without significantly altering the greenhouse configuration.

Table 7 shows the system cost, operating and maintenance cost, annual generated electricity, energy cost, and saving energy cost of the flexible and foldable solar panel with installation areas of 50 m^2 and 100 m^2. Based on our estimations, the annually generated energy of the flexible solar panel with efficiency of 7.2% and installed areas of 50 m^2 and 100 m^2 are 5,841 and 11,682 kWh, respectively in Sydney. Furthermore, the annually generated energy of the foldable solar panel with efficiency of 12% and installation areas of 50 m^2 and 100 m^2 are 9,735 and 19,470 kWh, respectively in Sydney. Considering the electricity prices for household and for business are A$0.332 and A$0.253/kWh (https://www.globalpetrolprices.com/Australia/electricity_prices/), respectively, we used the electricity prices for household for estimation. The saved energy costs of flexible and foldable solar panels with an installation area of 100 m^2 are approximately $4,008/year and $6,680/year in Sydney. The suggested flexible and foldable solar panels could not only block the sunlight to reduce the temperature inside the greenhouse but also generate considerable amount of energy for compensation of electricity usage in greenhouse. Furthermore, the system costs and maintenance fee of flexible and foldable solar panels are much lower than that of the commercialized FFPV systems. Therefore, the replacement of the current energy curtains by the flexible and foldable solar panels represent a cost-effective solution for adapting renewable energy in greenhouses.

In the meantime, as shown in Fig. 46, the opaque flexible solar panels were proposed to be used in the walkway of the greenhouse. It can be used to fully cover the top of the walkway area, blocking the sunlight and reducing the temperature, and eventually decreasing the cooling cost, without affecting the plant activities.

Validating the model with field data

In order to further prove the accuracy of our model for the estimation of electricity generation of the FPPV and CPV modules, we compared the evaluation data calculated by our model with the measured data obtained from Desert Knowledge Australia Centre (http://dkasolarcentre.com.au/download). Here, the aim was to investigate the difference between our estimation and the obtained field data. At first, we analysed the daily solar exposure at Alice Springs (Northern Territory) from 2011 to 2019 as shown in Fig. 47(a). The average solar exposure is 5.83, 6.14, 5.93, 5.84, 5.99, 5.63, 5.95, 6.04, and 6.27 kWh/m^2/day in 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, and 2019, respectively. As displayed in Fig. 47 (b), the annual total solar exposure is in the range from 2059.5 to 2289.3 kWh/m^2 from 2011 to 2019. The average annual solar exposure is approximately 2176.2 kWh/m^2. Furthermore, the average solar exposure in spring, summer, autumn, and winter are approximately 610.7, 650.8, 492.6, and 422.1 kWh/m^2, respectively. And then, based on the data shown in Fig. 47 (a) and Fig. 47 (b), we estimate the daily solar exposure as shown in Fig. 47 (c). The average daily solar exposure in spring, summer, autumn, and winter are 6.71, 7.22, 5.35, and 4.59 kWh/m^2/day, respectively.

We then selected a FPPV module (Trina TSM-195DC01A) with an area of 153.48 m^2 and a CPV module (SolFocus CPV) with an area of 84.16 m^2 for analysing their daily generated electricity in each season. Figs. 48(a) and 48(b) present the photo, electrical data, and efficiency characteristics of the FPPV and CPV modules, respectively. The maximum efficiencies of the selected FPPV and CPV modules are 15.2% and 24%, respectively. Ideally, if the efficiencies of the modules do not decay, the average daily generated electricity of FPPV and CPV modules are in the range from 0.71 to 1.18 and from 1.13 to 1.87 kWh/m^2/day, respectively (Figs. 48(c) and 48(d)). As displayed in Fig. 48(c), the estimated daily generated electricity of FPPV module in spring, summer, autumn, and winter are in the range from 0.99 to 1.09, from 1.02 to 1.18, from 0.76 to 0.84 and from 0.63 to 0.72 kWh/m^2/day, respectively. Furthermore, the estimated daily generated electricity of CPV module in spring, summer, autumn, and winter are in the range from 1.51 to 1.73, from 1.61 to 1.87, from 1.21 to 1.33 and from 1.00 to 1.15 kWh/m^2/day, respectively (Fig. 48(d)).

Figs. 49(a)-(e) display the analysed data of daily generated electricity of CPV module with efficiency of 22% in each season from 2011 to 2019. As displayed in Fig. 49(e), the estimated data match very well with the measured data. The differences in generated electricity between the estimated and the measured data are within 5% for most of years, except for 2015, 2016, and 2017, which may attribute to the repair and maintenance of the solar panels. The differences in generated electricity between the estimated and the measured data are approximately 13.3% and 18.9% in 2015 and 2016, respectively. The main reasons for the differences are attribute to the system outage in 2015, the offline of two Solfocus trackers in 2016, and monitoring interruption for UPS battery replacement in 2017. After addressing these issues, the measured data match well with our estimated data in 2018 and 2019. Therefore, the annual maintenances of the solar modules are one of the important factors for stably obtaining the required electricity after the installation of the solar modules. Moreover, our evaluation model can precisely estimate the daily generated electricity of CPV modules.

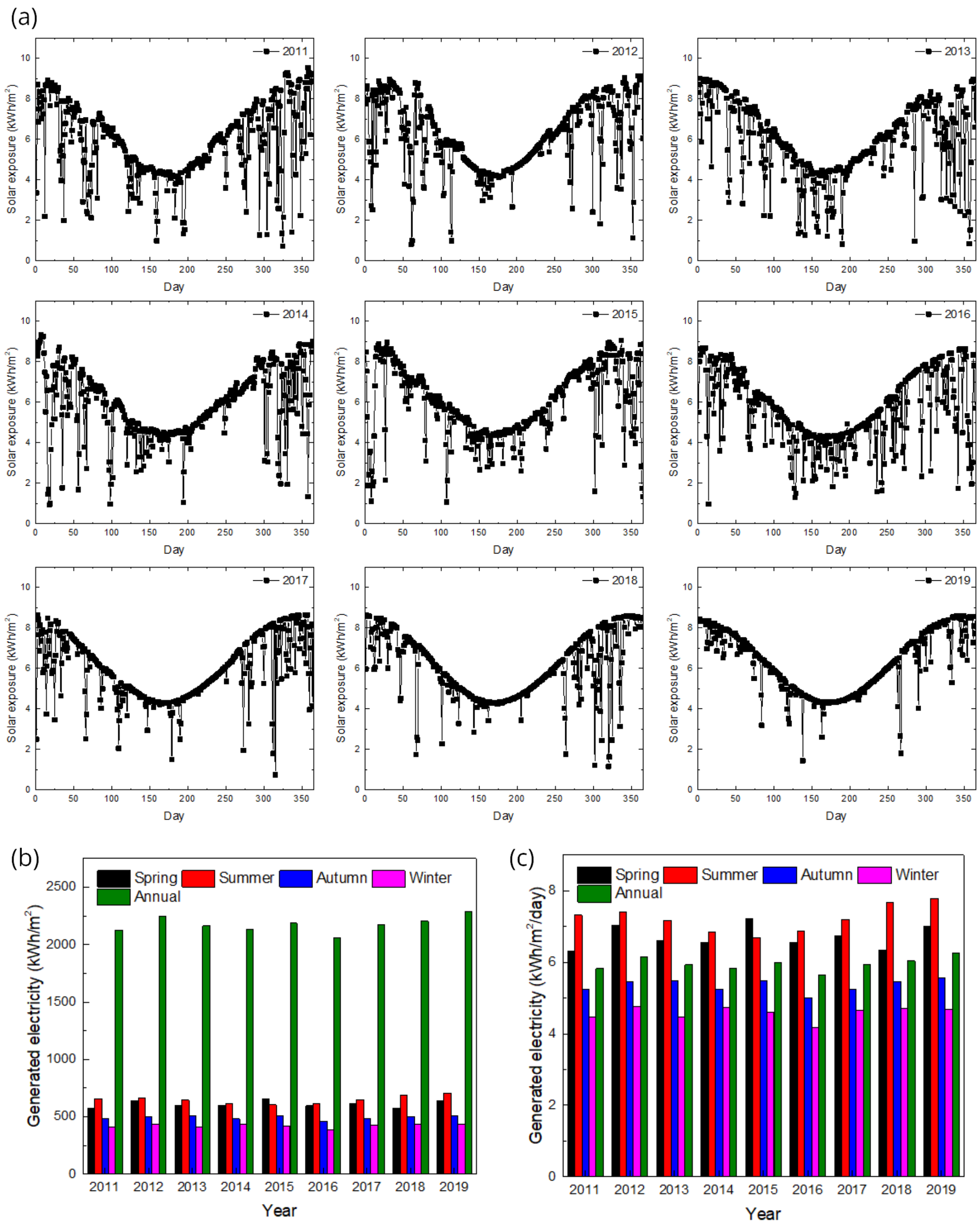
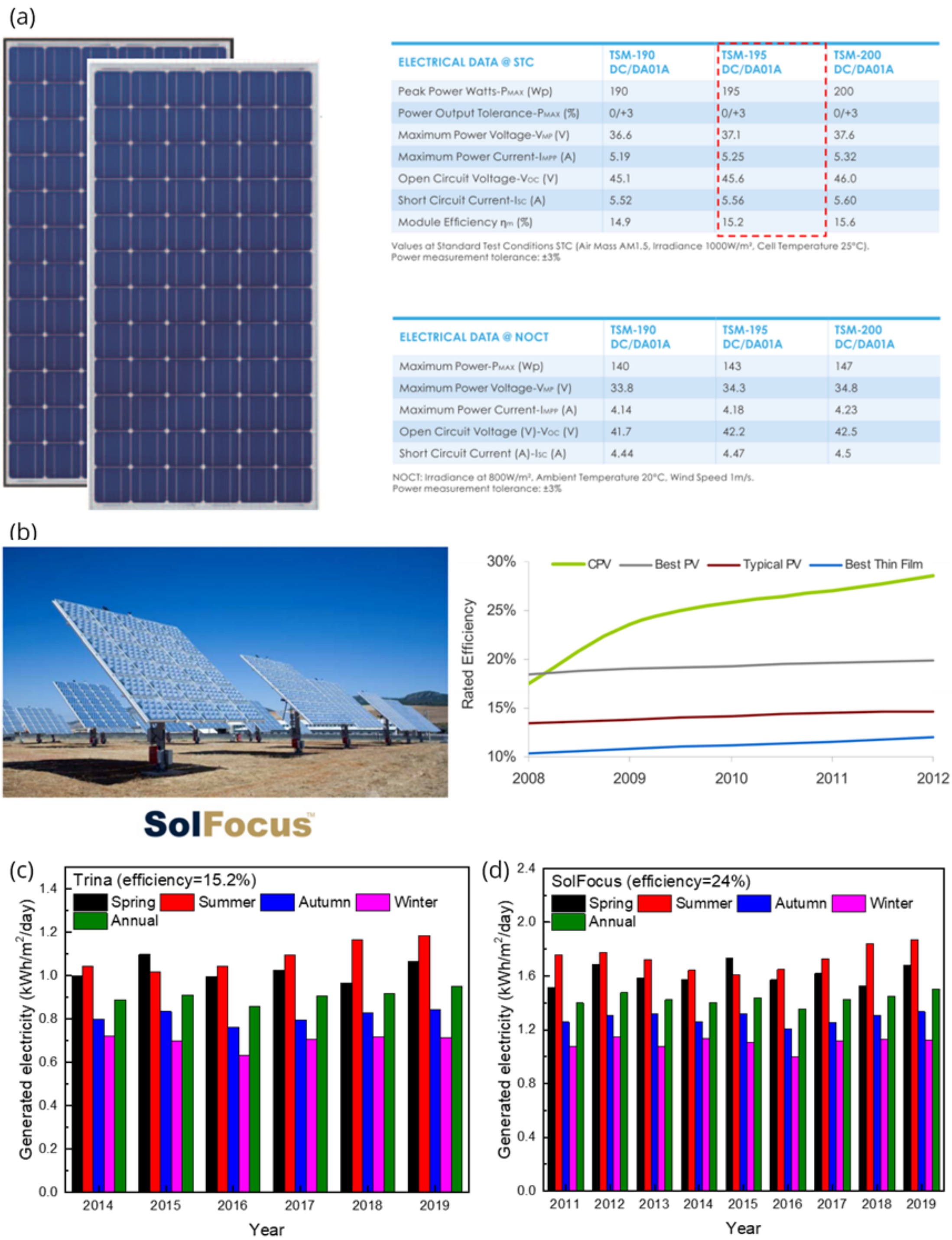


Figure 47 (a) Daily solar exposure, (b) solar exposure in spring, summer, autumn, and winter, and (c) average solar exposure in spring, summer, autumn, and winter at Alice Springs (Northern Territory) from 2011 to 2019.



ELECTRICAL DATA @ STC	TSM-190 DC/DA01A	TSM-195 DC/DA01A	TSM-200 DC/DA01A
Peak Power Watts-PMAX (Wp)	190	195	200
Power Output Tolerance-PMAX (%)	0/+3	0/+3	0/+3
Maximum Power Voltage-VMP (V)	36.6	37.1	37.6
Maximum Power Current-IMPP (A)	5.19	5.25	5.32
Open Circuit Voltage-Voc (V)	45.1	45.6	46.0
Short Circuit Current-Isc (A)	5.52	5.56	5.60
Module Efficiency ηm (%)	14.9	15.2	15.6

Values at Standard Test Conditions STC (Air Mass AM1.5, Irradiance 1000W/m², Cell Temperature 25°C).
Power measurement tolerance: ±3%

ELECTRICAL DATA @ NOCT	TSM-190 DC/DA01A	TSM-195 DC/DA01A	TSM-200 DC/DA01A
Maximum Power-PMAX (Wp)	140	143	147
Maximum Power Voltage-VMP (V)	33.8	34.3	34.8
Maximum Power Current-IMPP (A)	4.14	4.18	4.23
Open Circuit Voltage (V)-Voc (V)	41.7	42.2	42.5
Short Circuit Current (A)-Isc (A)	4.44	4.47	4.5

NOCT: Irradiance at 800W/m², Ambient Temperature 20°C, Wind Speed 1m/s.
Power measurement tolerance: ±3%

Figure 48 Photos, electrical data, and efficiency characteristics of commercialized (a) FPPV and (b) CPV module. (c, d) Estimated generated electricity in spring, summer, autumn, and winter at Alice Springs (Northern Territory) from 2011 to 2019 based the efficiency of (c) 15.2% and (d) 24%.

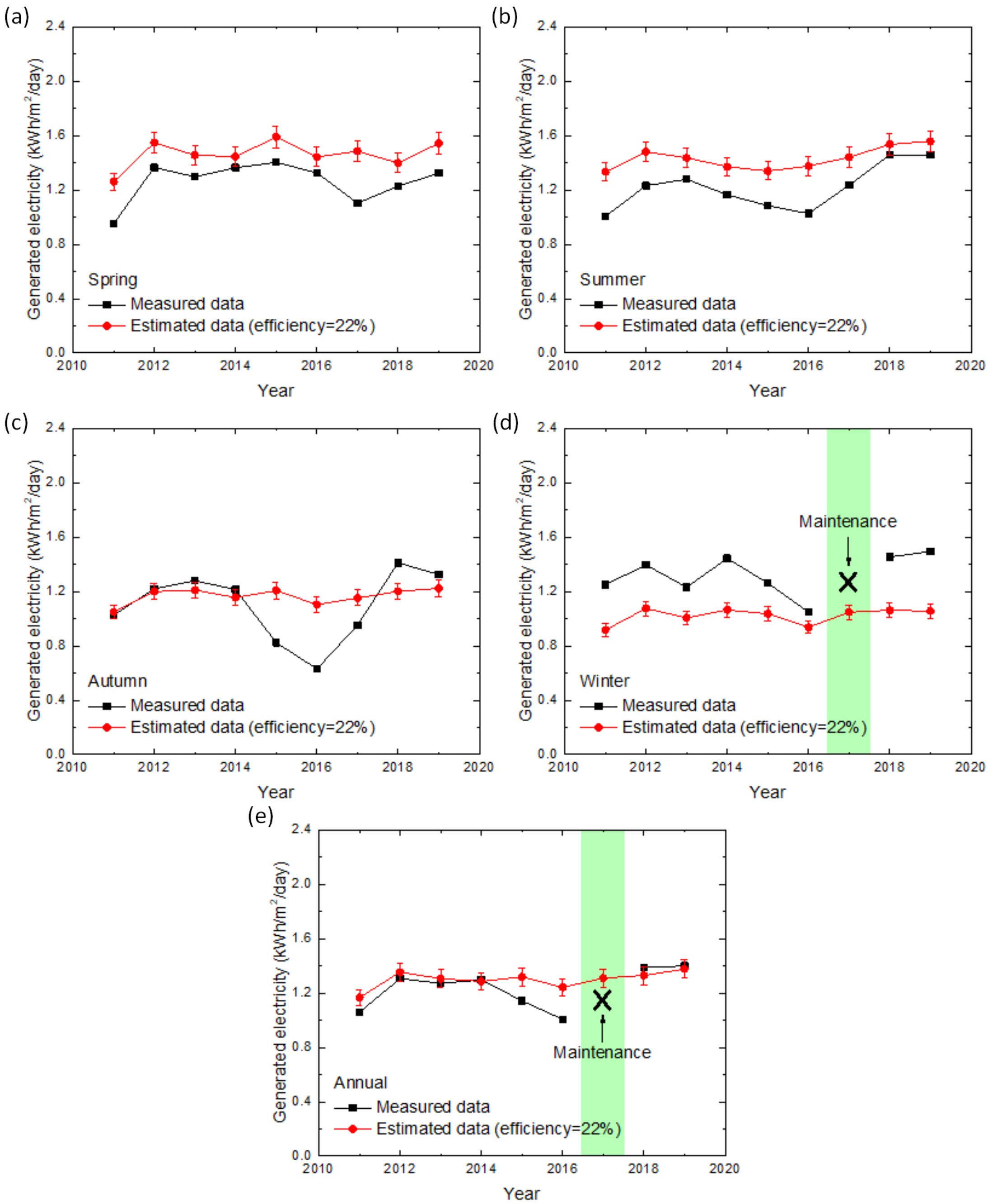


Figure 49 Estimated and measured data of daily generated electricity of the CPV modules in (a) spring, (b) summer, (c) autumn, (d) winter, and (e) each year. The estimated efficiency of the CPV modules is 22% in each year.

In addition, we analysed the daily generated electricity of FPPV modules in each season and year. Figs. 50(a)-(e) display the analysed data of daily generated electricity of FPPV module with efficiency of 15.2% in each season from 2014 to 2019. The estimated data match well with the measured data within 3 years (2014, 2015, and 2016). However, the daily generated electricity decreased significantly in each season in 2017, 2018, and 2019 as displayed Figs. 50(a)-(e). We attributed this result to the decay of efficiency of the FPPV modules. Here, we considered three cases for the efficiency decay of the FPPV modules. As displayed in Fig. 50(a), case 1 and case 2 are the decay of efficiency of 1% and 0.5%, respectively, per year. Case 3 is the non-linear efficiency decay. The differences in generated electricity between the estimated data and the measured data are within 12.4%, 7.7%, and 31.7% in 2017, 2018, and 2019, respectively, for case 1. Furthermore, the differences in generated electricity between the estimated data and the measured data are within 0.1%, 21.6%, and 45.1% in 2017, 2018, and 2019, respectively, for case 2. Therefore, the decay of efficiency of the FPPV modules is most likely a non-linear. In general, many factors would affect the efficiency of the solar modules, such as dust covered on the solar modules and environmental temperature fluctuations. For example, the efficiencies of solar cells will decrease 0.5% when the temperature of solar cells increases approximately 1°C. Therefore, the measured data would be much higher than the estimated data in autumn and winter because the temperatures in autumn and winter are much lower than those in spring and summer at Alice Spring. In other words, the efficiencies of solar cells in autumn and winter are much better than those in spring and summer. For case 3, the estimated efficiency in 2019 is almost 50% of the original efficiency. As displayed in Figures 50(b)-(f), the measured data match well with our estimated data in 2017, 2018, and 2019 based on the model considering the decay of efficiency in case 3. For different solar modules, the efficiencies and efficiency decay are different. Nonetheless, our model can accurately estimate the daily generated electricity of FPPV modules after considering the efficiency decay of the modules. As discussed in the above section, the annual maintenances of the solar modules are very important for stable electricity output. Furthermore, the efficiency of the solar modules can be significantly improved if the working temperatures of the modules can be maintained around 25°C even in summer. Thus, the thermal management of solar modules are also of significant importance in the consistent generation of electricity from the solar modules. This factor should be investigated in-depth to maximize the electricity generation of the solar modules in future. Actually, the estimated data agree well with the measured data only with difference in the range from 5% to 15%. Many factors will influence the generation of electricity from solar panels. The solar panels under maintenance and repair may result in lower electricity generation. We found the estimated data can agree well with the measured data after the maintenance of solar panels. Therefore, the annual maintenance of solar panels is very important to keep their efficiencies.

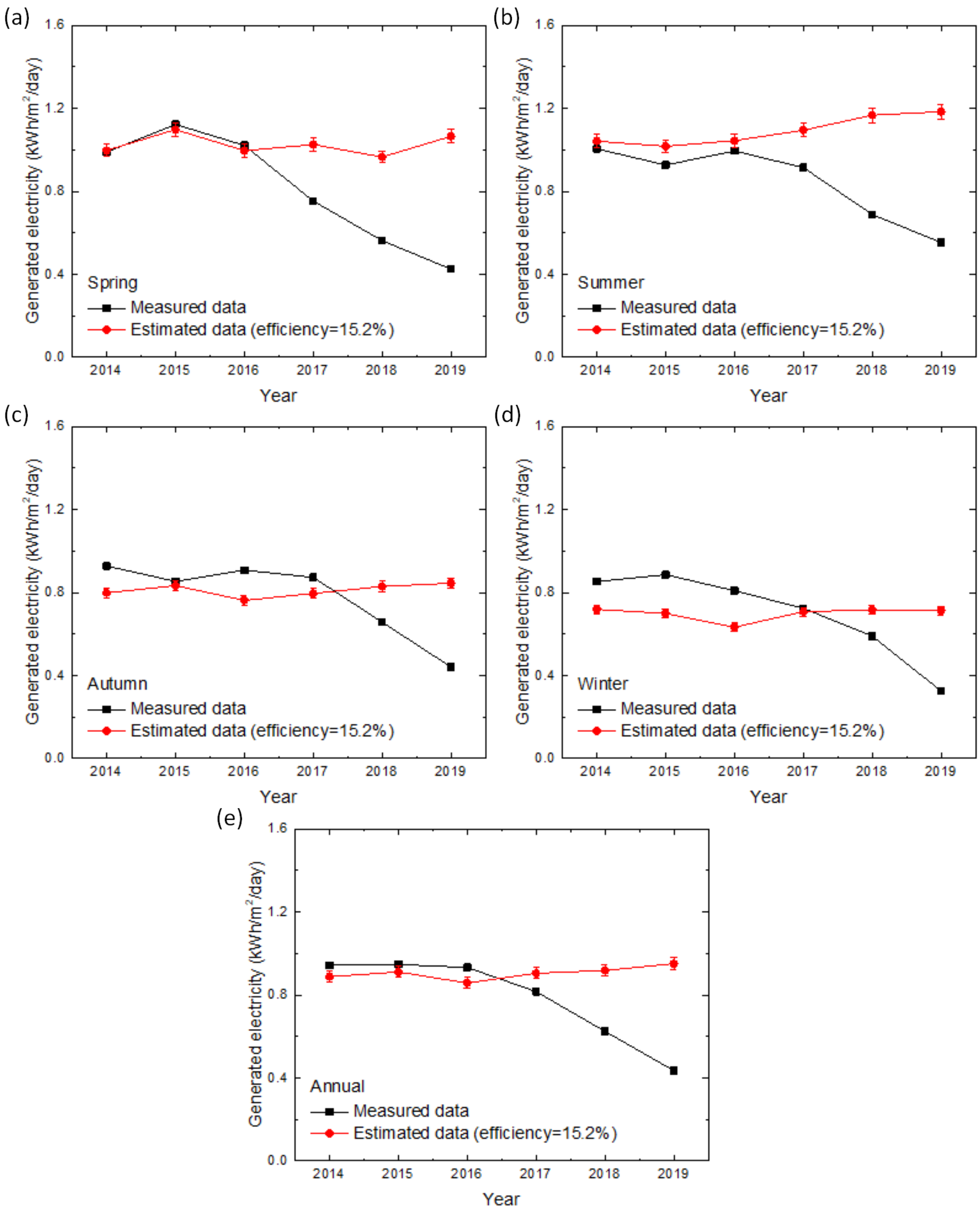


Figure 50 Estimated and measured data of daily generated electricity of the FPPV modules in (a) spring, (b) summer, (c) autumn, (d) winter, and (e) each year. The estimated efficiency of the FPPV modules is 15.2% in each year.

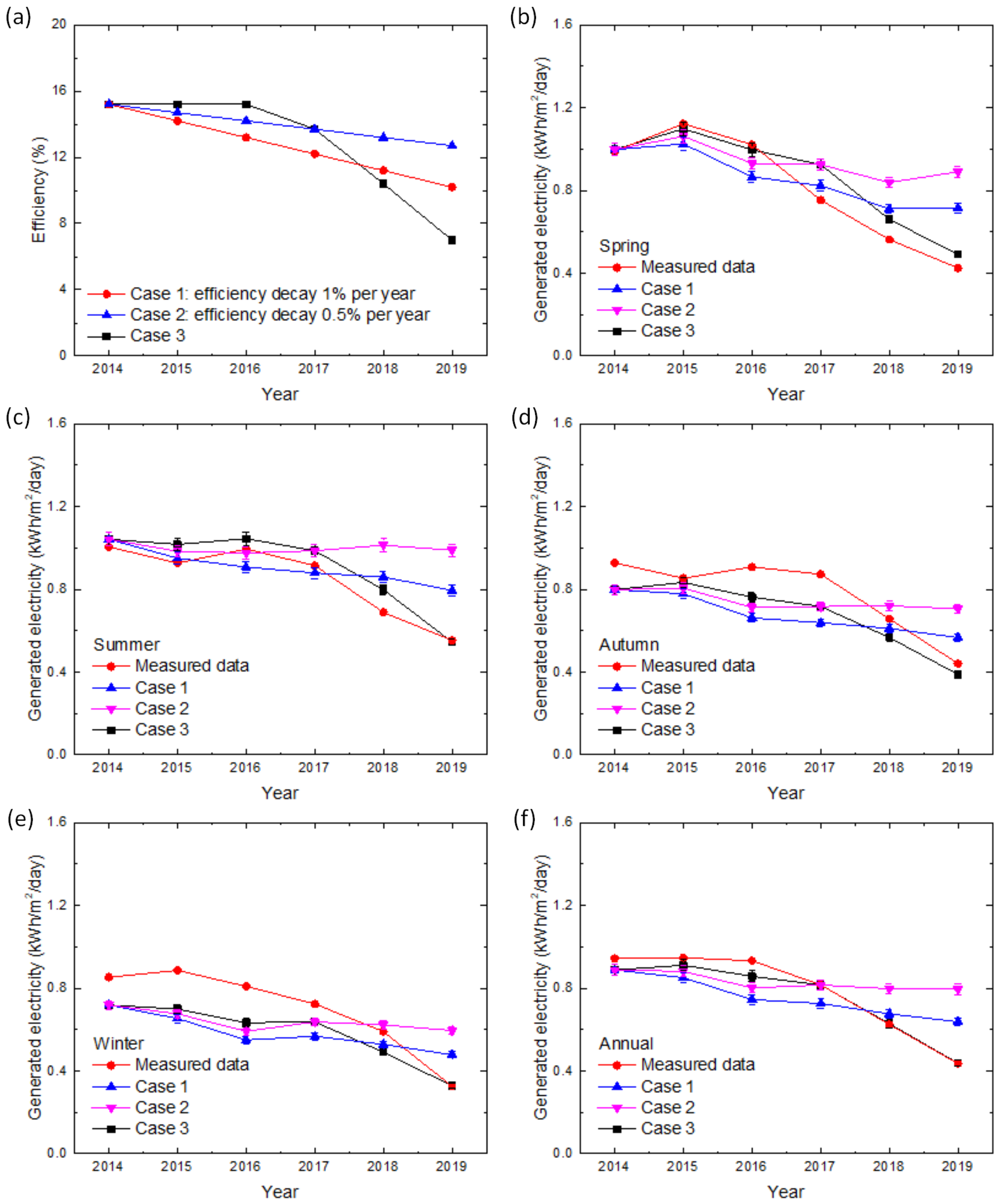


Figure 51 (a) Three different cases for the estimated decay of efficiency of the FPPV modules. (b-f) Estimated and measured data of daily generated electricity of the FPPV modules in (b) spring, (c) summer, (d) autumn, (e) winter, and (f) each year.

Outcomes

Outcomes from cost-effectiveness modeling

Based on our review and simulation, the use of SG in combination with PV cells and a STC is the most promising solution, with the details of the combination dependant on several factors (Table 8).

From a productivity point of view and according to our simulation results of this project, the application of spectrum optimized SG will not compromise the productivity of the plants. It could even slightly improve productivity due to the high transmission of visible sunlight for photosynthesis. At the same time, heating and cooling costs can be significantly reduced, by up to 40% for a 1000 m^2 greenhouse in simulation.

On the other hand, applications of PVs and STCs are able to actively generate energy. While roof mounted designs reduce the light transmission to generate electricity, which could affect plant productivity, the ground-mounted designs have no impact on light transmission and therefore are preferred if there is available space. In addition, the ground-mounted designs do not require significant modification of the existing greenhouse structure.

In addition, FPPV cells have higher efficiency than STPV cells due to their more effective light absorption. Therefore, they produce more energy per cell area, and are much cheaper than STPV considering the life span electricity generation.

Finally, as cooling is required to maintain the performance of PV cells, it becomes a rational option to combine them with STCs to save the heat energy from the cooling process. Several promising solutions for different space availability and costs, based on the combinations of different technologies, are shown in Table 8.

This study reveals enormous potential of energy savings that can be achieved by employing advanced SG and renewable energy solutions. However, the solutions vary significantly depending on environmental conditions, plant species, land size, and the technology status of the greenhouse. One solution may not work for another set of circumstances. Therefore, evaluation software has been developed in this project to help to estimate the cost effectiveness for each option under different light, temperature, relative humidity, and carbon dioxide enrichment condition in the greenhouse, so that optimal solutions for different conditions can be recommended.

Table 8 Promising solutions for using novel smart glass (SG) and renewable energy technologies including semitransparent photovoltaic (STPV), concentrated photovoltaic (CPV), concentrated solar thermal collector (CSTC), flat plate photovoltaic (FPPV) and flat plate solar thermal collector (FPSTC).

Option	Greenhouse conditions	Suitable technologies	Space requirement	Potential cost saving	Installation cost
1	Greenhouse in the area with high land cost	SG + roof-top STPV	No extra space required	40%~50%	★
2	Greenhouse in the area with high land cost	SG + roof-top CPV + CSTC*	No extra space required	60%~70%	★ ★ ★
3	Extra space available around the greenhouse	SG + ground-mounted CPV+CSTC*	Require extra space for CPV setup	Up to 100% (Self-sustain)	★ ★ ★
4	Large extra space available around the greenhouse	SG + ground-mounted FPPV+FPSTC*	This design requires larger extra space than Option 3	Up to 100% (Self-sustain)	★ ★

Outcome from Field data collection

There are several significant outcomes from the field data collection:

Outcomes from the smart glass

1) In the field test with WSU, by installing the smart film on the glass of greenhouse, the smart glass was constructed, We were able to perform experiments to compare the performance of compartments with and without the smart films. The transmission spectra showed that the smart films have high transmittance in the visible region, especially in the region for photosynthesis active radiation (PAR). Meanwhile, the smart films significantly block the UV region (300 nm~380 nm) and thermal energy in the IR region.

2) The compartments with the smart glass consumed much less energy in cooling in the summer time of the Hawkesbury area. The eggplants in the compartments with the smart films consumed less water, especially when they became bigger. The qualities (e.g. sodium, glucose, sucrose, and fructose) of eggplants in the compartments with the smart films improved. The smart glass was able to significantly reduce water consumption and cooling cost was further verified when different plants (e.g. capsicums and eggplants) were grown in the greenhouse. In the meantime, the quality of the fruit (eggplant in this case) can be maintained with observable reduction in the yield.

3) The installation of smart films does not require significant changes of the greenhouse infrastructures, thus reducing the installation costs. The smart films have more than 15 years lifetime, thus it is a cost-effective solution in energy saving.

4) It was found that the smart glass is able to significantly increase the amount of leaves of plants, therefore, it is most suitable for growing leafy vegetables. It was found that the reduction in the yield of the fruit was due to the decrease in the transmission in the red region (wavelength > 600 nm), which is most useful in plants flowering and turning into fruits. According to this understanding, we have further designed a new type of smart film specifically for plants (shown in the Outcome section and full details are presented in the IP description document), which was able to meet the exact spectrum requirements for growing plants. The smart film has a great commercial potential for protected cropping.

Outcome from the renewable energy technologies

1) The theoretical model is experimentally verified by comparing the data from the software for renewable energy with real data from the field study (including Sydney, Melbourne and Alice Spring). The real data agrees well with the calculation results. In addition, it is found that by including the temperature effect on the efficiency of renewable energy products in the model, better agreement can be achieved.

2) The model can be further developed to become user friendly software, which can be used by growers from different locations to predict cost-effectiveness of different renewable energy products according to the weather conditions.

3) From the model we found the solar thermal collector (STC) is a more cost-effective renewable energy solution compared to the photovoltaic (including FPPV and CPV), which has much lower installation cost and much shorter payback period. In addition, the STC technologies, including CSTC and FPSTC, generally require smaller area for solar irradiation due to the higher efficiency. Thus, they are easier to be accommodated in terms of land requirements. Therefore, for cold areas, such as Victoria and Tasmania, where the heating cost takes a significant portion of the overall cost, it is recommended to apply the STC technology to efficiently compensate the heating cost.

4) It is found that for For hot areas, such as in WSU, the electricity used to cool down the greenhouses, including water flow and ventilation, has been found to be the main cost source. Although cold water can be generated during the off-peak time, the cost was still around 80% of the overall cost in running the greenhouse in WSU. Therefore, it is desired to develop new cooling technologies to generate cold water with minimum or without the usage of electricity. For example, a potential renewable solution to reduce the cooling cost is to combine the evaporative cooling strategy with STC technology.

5) It was found that the efficiency of photovoltaic panels dropped significantly during summer due to the high environmental temperature. Thus, effective cooling technology for reducing the solar panel temperature to maintain the efficiency is necessary. Based on this demand, we have designed solar panels combining photovoltaic with photothermal functions, which can simultaneously produce electricity and hot water. By doing this, both the photovoltaic and photothermal devices can be of high efficiency.

6) Energy curtain are often employed in greenhouses to protect the vegetables from over heating. It has been found energy curtain could be replaced by flexible or foldable solar panels to achieve the same function but in the meantime generating additional electricity. This also represented a cost-effective solution, as it does not require extra space and significant infrastructure alternation of the greenhouses.

7) The cost-effectiveness of renewable energy solutions has been found to significantly depend on the scale of installation, the larger the scale the better cost-effectiveness and the shorter payback period. In addition, good maintenance is necessary to ensure high efficiency and long lifetime of solar panels, thus maintenance cost should be considered in the evaluation.

Monitoring and evaluation

The Monitoring and Evaluation (M&E) practice was conducted jointly by the SUT and WSU teams. An M&E expert was engaged to support the development and implementation of a program logic and M&E Plan.

The consortium ensures:

- The delivery of agreed services in a competent, ethical and professional manner
- Quality and value to Hort Innovation on schedule and to budget
- The M&E of the project is undertaken professionally and with a focus on continuous improvement
- Regular reports are provided to Hort Innovation on project outcomes against the critical success factors, mapping/quality assurance process
- Hort Innovation is notified as soon as possible of any major concerns, issues or opportunities relating to the services provided.

Stakeholder engagement meetings

Following a Project Scoping Meeting, SUT and the WSU teams formalised a Stakeholder Committee, including representatives from Hort Innovation, key growers and AUSVEG, and a Communication Plan confirming a timeline for principal teams and committee to meet.

These teams and committees established Terms of Reference and provided input to the management of the program, continuous improvement and planning for future programs.

This project management rigor ensures an effective collaborative approach is developed, which covers:

Partnership Shared accountability and responsibility.

Participation Part of the team, engaged in delivering tasks or with responsibility for a particular area/activity.

Clear communications Information made regularly available to all stakeholders

Meeting / collaboration	**Frequency**	**Key personnel**
Project Scoping Meeting	Commencement of each project phase (I & II)	All Stakeholders
Progress Meeting	Quarterly	SUT and WSU Project Team
Steering Committee Meeting	Every half a year	All Stakeholders
Project completion and review meeting	On delivery of final material for each phase (I & II)	All stakeholders

The full M&E report is attached in Appendix 2.

Recommendations

1. Recommend installing smart films/smart glass to reduce the heating and cooling cost, and water consumption. The type of smart films should be chosen according to the weather condition of the location
2. Recommend growing leafy vegetables in the greenhouse with smart films/smart glass, which will significantly increase leaf yield
3. Recommend proceeding field test with newly designed smart film for plants, which is expected to improve the quality and quantity of fruits, and save the costs
4. Recommend further developing the evaluation software to be more user-friendly for growers to estimate the cost-effectiveness of different renewable technologies according to the weather conditions and the structure of their greenhouse
5. Recommend installing solar thermal collector in most of the cases, especially in cold areas to compensate the heating and cooling cost
6. Recommend introducing new technology, such as radiative cooling to reduce the cooling cost
7. Recommend integrating photovoltaic with solar thermal technology to simultaneously generate electricity and hot water, and save the required land
8. Recommend replacing energy curtain with flexible solar panels to generate electricity without modifying the infrastructure of greenhouse or requiring extra space

Refereed scientific publications

Journal article:

1. Lin, K. T., Lin, H., Yang, T., Jia B., 2020. Structured graphene metamaterial selective absorbers for high efficiency and omnidirectional solar thermal energy conversion. *Nature Communications* **11**, 1389 (2020).

2. Lin, K. T., Lin, H., Jia B., 2020. Plasmonic nanostructures in photodetection, energy conversion and beyond. *Nanophotonics* (In press).

3. Sachin Gorakshnath Chavan, Ph.D.; Chelsea Maier; Yagiz Alagoz; Joao C Filipe; Charles Warren; Han Lin; Baohua Jia; Maichael E Loik; Chris I Cazzonelli; Zhonghua Chen; Oula Ghannoum; David T. Tissue, Light Limited Photosynthesis under Energy-Saving Film Decreases Eggplant Yield, *Journal of Cleaner Production* (under review)

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6. *More light at dark times of the year - Homepage - Glascomtuinbouw*. 2017; Available from: http://www.glascomtuinbouw.nl/en/home-uk/.

7. *Viridian SmartGlass – affordable energy efficient glass*. 2016; Available from: www.smartglass.com.au/.

Intellectual property, commercialisation and confidentiality

1. The new smart film design, and potential commercialisation of the new smart films
2. The new design for integrating photovoltaic with solar thermal technology
3. The evaluation model software for grower to evaluate the cost-effectiveness of the renewable energy technologies

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	Org/Ind	Name	Position
1	PCA	Nicky Mann	Chair PCA
2	Agrology	Levi Nupponen	MD Agrology Pty Limited
3	Sun Beam Technology	Stephen Wee	Director
4	Greenworks	Scott Featherston	National Sales manager
5	Sumitomo	Frank Palatucci	Deputy General Manager Business Development Division
6	Graeme Smith Consultancy	Graeme Smith	Founder and Director
7	ECS group	Lucie Paulet	Senior Project Manager
8	Innofocus Photonics Technology	Frank Yao	Director, CEO
9	SAINT-GOBAIN SOLAR GARD	Robert Hamilton	Managing Director
10	Window energy solutions	Colin Craig	Director

Appendices

Appendix 1

Output of literature review

Thermal performance of different glazing materials

To summarize the thermal performance of different glazing materials, a list of comparison of thermal performance of different types of glazing units are given in Table A1_1.

Table A1_1 Thermal insulation performance of glazing systems [1]

Type of Glazing	Description	U-value (W/m^2 K)
Single	One glass sheet	5.79–6.30
Double	Air filled	2.78–3.24
Double	Argon filled	2.61–2.95
Double	Argon filled and night insulation	1.50–1.99
Double	Vacuum	0.86
Double	Monolithic aerogel filled	0.63
Double	Granular aerogel filled	1.69
Electrochromic vacuum	Two glass pane forming evacuated glazing with a third pane having EC layer	Less than 1.00
Triple evacuated	Three glass panes with two evacuated space in between	0.26
Single*	Viridian smart glass (EnergyTech Clear)	3.6
Insulated Glass Unit*	Viridian smart glass (EnergyTech Clear)	1.6
Insulated Glass Unit with EnergyTech on surface #3*	Viridian smart glass (EnergyTech Clear)	1.5

*means commercially available products. Others are not commercialized yet. Current development in STPV

Since 2006, the Cooperative Research Centre for Polymers (CRCP) (www.crcp.com.au) has been developing materials and fabrication methods for dye sensitized solar cell (DSSC) technology. This has led to the development of a polymer-based flexible, solar cell technology or light to electricity by artificial photosynthesis (LEAPH) photovoltaic technology [2]. This module was made for the University of Wollongong researchers and contains a CRCP-produced green porphyrin (artificial chlorophyll) dye. The key advantage of the technology, aside from lower production cost, is that DSSC cells operate efficiently in low light levels such as on cloudy days or even when shaded. Currently, it is possible to reel-to-reel print titanium dioxide onto metal foil for photo anodes and produce printed silver grid-based transparent electrodes.

The cost of the LEAPH GP and MP technologies at \$60 – 80/m^2 and \$15 – 20/m^2 (Table A1_2), respectively, indicating that these technologies are likely to offer the benefits of energy generation at a cost comparable to the existing roof structures. The economies of introducing the LEAPH technology into new structures versus retrofitting established structures needs to be determined.

Table A1_2. The characteristics of different light to electricity by artificial photosynthesis (LEAPH) dye sensitized solar cell (DSSC) technologies

Technology	Platform	Cost ($/m^2)	Power Output (W/m^2)	Energy Output (kWh/m^2/year)	Lifetime (Years)
LEAPH GG	Glass/glass	100-120	60	109	>15
LEAPH GP	Glass/plastic	60-80	40	73	>5
LEAPH MP	Metal foil/plastic	15-20	30	55	3-5
LEAPH BP	Back contact metal foil/plastic	20-40	50	91	3-5
LEAPH PP	Plastic/plastic	<15	15	27	<3

Applications of PV in greenhouses

The summary of the applications of PV in greenhouses is shown in Table A1_3. Out of various semiconductor material, about 36% and 55% of the PV modules available in the market are mono (m-Si) and poly-silicone type (p-Si), respectively. M-Si and p-Si PV modules are widely used in greenhouses for clean energy generation [3-5]. The results achieved also reveal that PV modules are good at providing ideal temperature conditions inside the greenhouses as well as enabling notable energy savings and remarkable reductions in carbon emissions. The highest efficiency range of PV modules available in the market belongs to multi-junction type [6, 7]. However, this type is expensive and as such, in general, it is rarely used in greenhouse applications.

Several works are in progress to predict the overall performance of greenhouses with PV modules through reliable computational fluid dynamics (CFD) software [8]. The greenhouse applications of conventional PV modules are mostly for electricity to be used as artificial heater and lighting. However, in most cases, the electricity production depends on the PV array, the efficiency of the employed module, and geographical location. As has been mentioned previously, PV modules experience a drastic rise of cell temperature especially in areas with high intensity of solar radiation [9]. For four-seasoned countries, the average temperature difference between the PV module temperature and the ambient temperature is around 18°C. Therefore, it is suggested that passive or active cooling systems be used to decrease the operation temperatures of PV modules and to make them widespread in greenhouse applications. It is emphasized by Chow [10] that more than 50% of the incoming solar radiation is converted into heat, which causes the PV module temperature to rise 50°C above the ambient temperature.

Table A1_3 Type of PV used on greenhouse for heating, cooling and lighting.

Type of PV	Country	Result	Ref.
p-Si solar cells	Turkey	Total electricity based energy consumption is 8.10 kW h/day. 34.55% is provided from PV cells, others from grid. Temperature inside the greenhouse could be decreased by 19.9 °C.	[11]
a-Si thin film	Spain	Electricity production is 8.25 kW h/m2 with roof coverage ratio of 9.79%.	[12]
m-Si solar cells	Netherlands	Annual electrical energy is expected to be 29 kW h/m2. Energy conversion efficiency of the system is 11%.	[13]
Semi-transparent c-Si, spherical solar microcells	Japan	The peak power output is 540 W for solar intensity of with 1223 W/m^2, The conversion efficiency is 4.5%.	[14]
a-Si solar cells	Japan	The straight-line PV arrays generate electricity of 4.08 GJ/year. Electrical energy generation using PV cells is valid for use in sustainable greenhouse crop production.	[15]
m-Si solar cells	Italy	Energy saving is approximately 30% for summer cooling and 11% for winter heating.	[16]
Multi c-Si solar cells	Italy	The annual electricity production is 107,885 kW h. The overall conversion efficiency of the PV system is 11.4%. Yearly average temperature inside the greenhouse 19.8 °C and the range is 12–30 °C.	[9]
Semi-transparent c-Si	India	The highest electrical energy is 1.9 kW h/day.	[3]
c-Si solar cells	India	The peak power is 3825 W. The module strengthens the viability of a greenhouse grid-independent.	[4]
c-Si solar cells	India	The annual overall electrical energy savings is 1185 kW h. Electricity production factor (EPF) is 2.04.	[5]

Application of Solar thermal collectors

The countries, which include four seasons are usually more in the need of a technology that can provide heating for most of the year. For example, the countries of the Mediterranean, China, Netherlands and some parts of the Middle East are mostly cold, and thus more energy is required for heating. Therefore, in such climates, thermal energy storage systems have been used. For instance, Benli and Durmus [17] investigate the thermal performance of a greenhouse in Turkey shown in Figure A1_1 integrated with ten pieces of flat plate water solar collectors, in which phase change material (PCM) is used as thermal energy storage. The tests conducted in Turkey reveal that the proposed system can provide 18–23% of total daily thermal energy requirements of the greenhouse for 3–4 hours, compared to the conventional heating system.

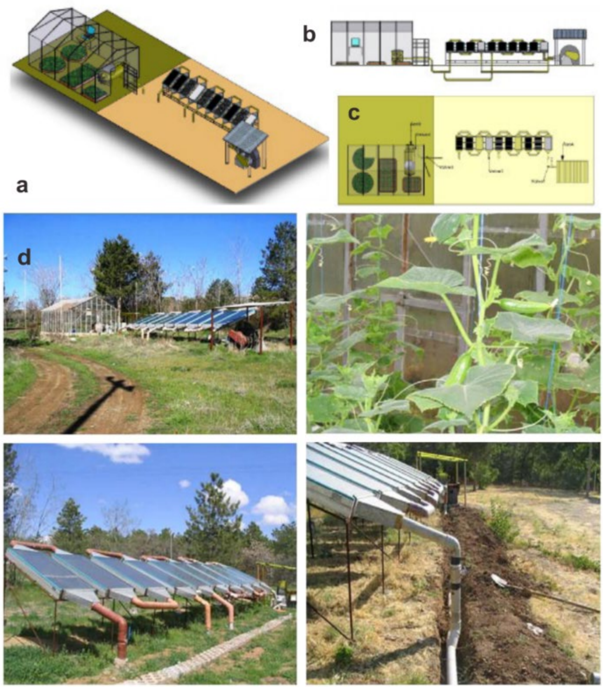

Figure A1_1. Various views of experimental equipment of greenhouse heating system (a) isometric, (b) front and (c) top. Photos of the greenhouse integrated with flat plate solar thermal collectors (FPSTC) and air circulation lines. [17]

Application of Photovoltaic/thermal modules

Table A1_4 provides a comparison of works for different coolers and climatic conditions with the characteristic results. It can be concluded from the works on different coolers that water based Photovoltaic/thermal (PV/T) modules are much more appropriate to reduce PV module temperatures especially in extreme weather conditions [18].

Table A1_4 A comparison of photovoltaic/thermal (PV/T) technologies used for greenhouses

PV/T module	Cooler	Result	Ref.
8 PV modules connected in series.	Air	7–8 °C enhancements in greenhouse temperature during day and night in sinter season owing to the waste heat recovery. Annual efficiency of greenhouse is 5.5%. Annual thermal energy is found to be around 24,729 kW h. Annual electrical energy saving is 805.9 kW h.	[19]
Semi-transparent PV module Hybrid PV/T double pass glaze 0.6 m^2 surface area	Air	Annual thermal energy is 480.81 kW h. Annual electrical energy is 469.87 kW h. 5–6 °C enhancements in indoor temperature for a typical winter day in New Delhi. Thermal efficiency is 42% and electrical efficiency is 8.4%.	[20]
0.605 m^2 surface area, 75 W	Water	Annual electrical energy saving is 716 kW h. Annual waste heat recovery is 12.8 kW h. Efficiency of PV/T integrated greenhouse is 4%.	[21]
10.53 m^2 surface area, 1200 W	Water	Annual overall thermal energy is 29,157 kW h. Annual electrical energy saving is 1185 kW h. Annual thermal energy is 1366 kW h.	[5]
Semi-transparent PV modules 0.648 m^2 surface area, 280 W	Water	Daily overall thermal energy is 20.5 kW h. Payback is 3.74 and 4.10 years for load and no load condition.	[3]

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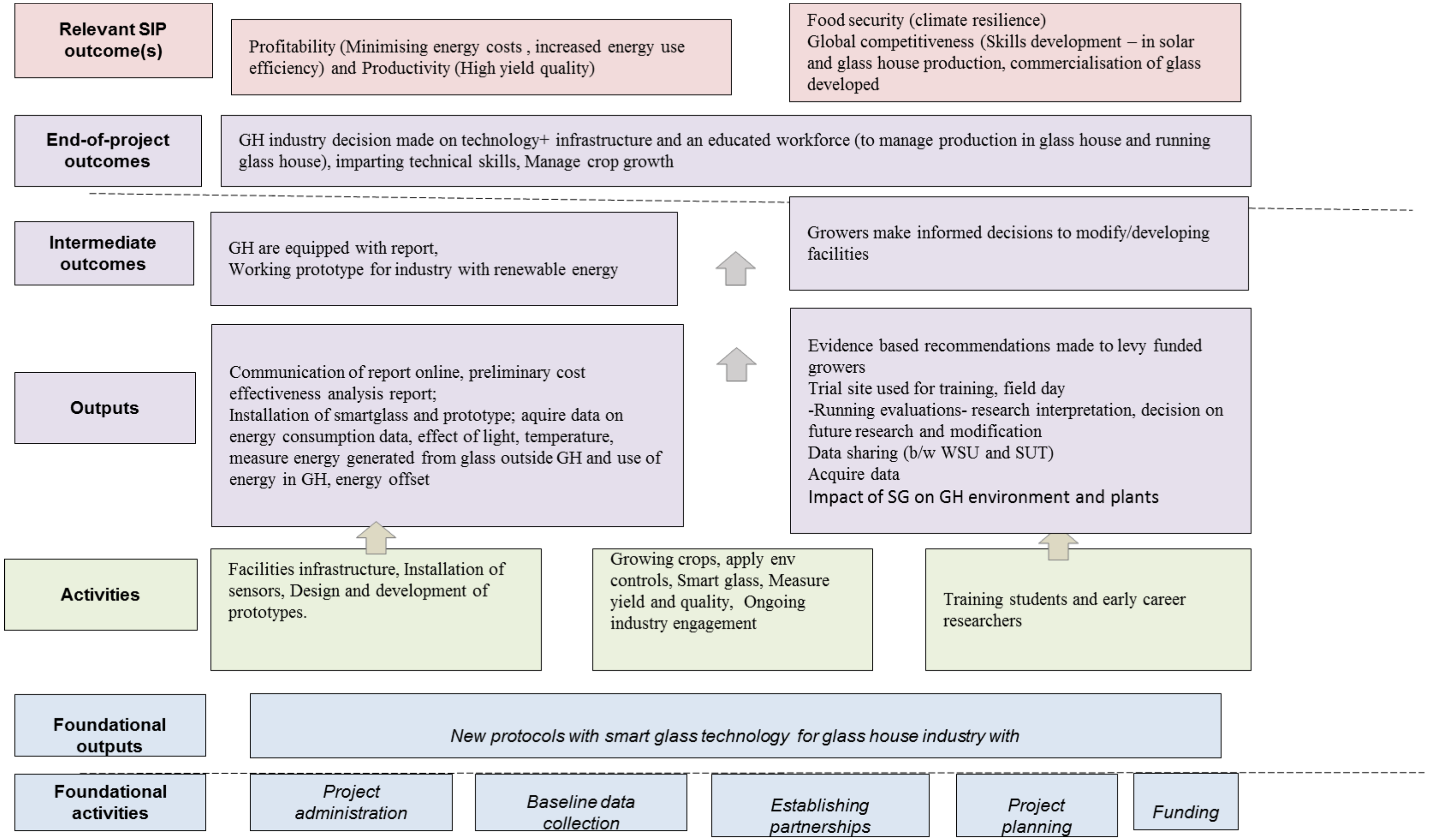
Appendix 2

M&E report

Investigating novel glass technologies and photovoltaics in protected cropping

Program Logic

Figure A2-1 Program logic model for the Smart Glass project



Project M&E scope

a) Audience

Table A2-1: M&E audience and their information needs

Audience	Information
Primary	
Project team (Primary) SUT Team- Prof. Baohua Jia, Dr Han Lin	Learn and adapt, modify as we move and also provide accountability to funders and levy payers
WSU Team- Prof David Tissue, A/Prof Zhonghua Chen, A/Prof Oula Ghannoum, Dr Chris Cazzonelli, Prof Ian Anderson, Dr Nisha Rakhesh, Mr David Thompson	Response for growing plants, plant development, study of the effect of the smart glass and renewable energy on plants.
Hort Innovation (Primary)	Feedback to stakeholder Justification for levy payers Feedback into HIA plan
Secondary	
Glass house industry	Energy/cost savings Water savings Drive to have food production closer to urban cities Decisions for future investment.
Dept of Agriculture	Return on investment
Smart glass industry	Research findings and implications Potential for commercialisation.
University	Public interest
General public	Food produced sustainably.

Syngenta and other private companies	Potential for commercialisation

b) Key Evaluation questions

Table A2: Project key evaluation questions

Key evaluation questions	Relevant?	Project-specific questions
Effectiveness		
1. To what extent has the project achieved its expected outcomes?	Hypothesis- Savings in energy without impacting productivity	Has the project developed new technology that is now available for industry uptake? Outcome: We have found the commercially available smart films, which can be directly installed in any existing green houses for industry uptake. The solar technologies considered in this project are commercially available.
Relevance		
2. How relevant was the project to the needs of intended beneficiaries?		To what extent has the project met the needs of Glass house/Protected cropping and veg levy payers? Outcome: it met the needs of veg levy payers in understanding the cost effectiveness of applying smart glass and renewable energy technologies in green house and the impact on the plant growth.
Process appropriateness		
3. How well have intended beneficiaries been engaged in the project?		Have regular project updates been provided? Outcome: the updates have been provided in the form of milestone reports every six months. How accessible were extension events to industry levy payers? Outcome: the reports are accessible to industry levy payers though HIA. The developed evaluation software can also be made available to industry levy payers.
Efficiency		
5. What efforts did the project make to improve efficiency?		How project has adapted to maximise benefits? Outcome: we have developed software models to calculate the energy consumption of greenhouses (with and without smart films/glass) and cost effectiveness of renewable energy technologies, which can be broadly adapted for growers. What influence is this having on profitability and

Key evaluation questions	Relevant?	Project-specific questions
		productivity? Outcome: we have provided the influence of the technology on energy saving, including the water and electricity consumptions. In addition, we have proved that quality of the plants can be largely maintained with slightly decrease in yields. In addition, according to the understanding of the effects of transmittance spectrum of smart film on the plants, we have developed new design of smart film specially for greenhouse as well as the manufacturing technology, which does not exist in the current market.

Performance expectations, data collection and analysis

Table A3 Project monitoring plan

Logic level	What to monitor (see logic)	Performance expectation (KPIs) and/or monitoring questions	How to monitor (suggested methods)	Data collection – method and source	When	Responsibility (who is responsible for the monitoring and how will results be reported)	If the plan has been carried out?
Foundational activities (list)	***Project planning*** Baseline data collection Steering committee establishment	Baseline data without plants in the glass house collected and analysed Steering committee established	Record keeping	Glass house facility	Before experiment start	Six months after project initiation	Yes
Activities and outputs (list)	• Installation of sensors • Design and development of prototypes. • Growing crops • Apply environmental controls • Measure yield and quality • Training students and early career researchers • Ongoing industry engagement through Workshops; Publications; Training;	On going data collection and analysis Extension participation (number of growers and other stakeholders)	Record keeping Observation Interviews	On going experiments • Growers • Advisors	On going As required for evaluation	Project team member Milestone Reports Final Reports Industry reports/publications	Yes

Intermediate outcomes (list)	Working prototype for industry with renewable energy Interim report on smart glass technology	Increased percentage of growers makes informed decisions to modify/developing facilities.	Participatory group discussions during event days and field site visits	• Growers • Advisors	As required for evaluation	Intermittent (Project Team member) Independent reviewer Milestone Reports Final Reports Industry reports/publications	Yes
End-or-project outcomes (list)	GH industry decision made on technology+ infrastructure and an educated workforce (to manage production in glass house and running glass house), Manage crop growth with smart glass technology	Savings in energy without impacting productivity Improved understanding on smart glass technology Growing interest in practice change Cost effective analysis report An educated workforce (to manage production in glass house and running	Data on crop growth collected and analysed at regular intervals Participatory	Experiments	As required for evaluation	Organisation/specific project team member Independent reviewer Final Report Evaluation Report	Yes

		glass house) Global competitiveness (Skills development – in solar and glass house production, commercialisation of glass developed)	discussions during event days and field site visits	• Growers • Advisors			

Evaluation

Table A4 Additional evaluation data requirements

KEQ	Data collection requirement	Source and method
To what extent has the project achieved its expected outcomes?	Our hypothesis here is savings in energy without impacting productivity. On going data collection on • The light irradiance and spectrum change due to smart film • The temperature change due to smart film • The humidity change due to the installation of the smart film • Plant response to the environmental changes including the productivity and the usage of the nutrient. • Energy consumption change including the energy cost of heating and cooling	1. Plant information from the greenhouse. 2. Energy consumption of the greenhouse 3. Measured internal climate of the greenhouse
How relevant was the project to the needs of intended beneficiaries?	Data on • Profitability (like increased energy use efficiency, minimised energy costs). • Productivity (like high yield and improved quality). • Global competitiveness (like skill development in solar and glass house production) • Increased knowledge and improved understanding on the best practice with associated cost benefit data;	1. Plant yield and quality from the greenhouse. 2. Energy saving of the greenhouse 3. Modelling of the greenhouse energy consumption 4. Modelling of the renewable energy technologies
How well have intended beneficiaries been engaged in the project?	Study the quality of engagement through extension and training programmes	Information collected through group discussions and using questionnaires during workshops and trainings Number of quality science and communication articles published in high impact journals and industry magazines.
What efforts did the project make to improve	Identify measures to adapt to maximise benefits.	How many times information from steering committee and

efficiency?	How best resources are used to deliver the best? How flexible the project is made to suit levy payers needs?	other industry committees have been taken on board and the project modified accordingly? Eight project committee meetings have been carried out.

Table A5 Independent evaluation studies

Type of evaluation	When (start and finish)
Mid-term evaluation	*1/11/2018-1/12/2018*
Final evaluation	*11/03/2020-11/04/2020*

Reporting, learning and improvement

Table A6 Project progress reporting

Report type	To whom	Timing	Achieved or not
Milestone Reports	Hort Innovation	Six-monthly	Yes
Final Reports	Hort Innovation	At end of project	Yes
Articles	Industry magazine	Annually	Yes
Written and verbal update	Project Reference Group	Six-monthly	Yes

Table A7 Project continuous improvement activities

Continuous improvement process	Details	Timing	Achieved or not
Reflection meeting with Hort Innovation R&D Manager	Meeting between R&D Manager, SUT and WSU researchers to discuss progress to-date and what's working well/not, and agree any follow up actions	Six-monthly	Yes
Team meetings	Meeting between project team members from SUT and WSU to discuss project trials and their timing. Meeting between project team members to discuss feedback from extension event participants to determine gaps in adoption and preferred learning styles for incorporation into project	Quarterly	Yes
Project Steering committee meetings	Meetings between project team members, Hort Innovation and industry representatives to gain feedback on project activities and refine methodology	Six monthly	Yes