Modeling and Optimization of crop production and energy generation for economic profit in an organic photovoltaics integrated greenhouse

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ABSTRACT

Farming with greenhouse is a complex interaction between crops, greenhouse structure and environment, and economic market for crops. Agrivoltaics with greenhouse has been receiving attention which can potentially contribute to economic profit, mitigation of energy consumption by greenhouse operation, land competition for solar power generation and food production, and off-grid farming. New technologies such as organic photovoltaics (OPV) also offer new possibilities for greenhouse based Agricvoltaics. There is no research found in literature integration all relevant models to calculate economic profit from the environment data and specification of greenhouse integrated with photovoltaics, with which farmers can simulate various farming strategies to maximize profit. This study aimed to develop a comprehensive model which combined model predicting solar irradiance to a tilted surface, electric energy generated by photovoltaic (PV) modules on a greenhouse roof, transmittance through multi-span greenhouse roof, solar irradiance to lettuce in the greenhouse, lettuce yield and growth transition, energy consumed by cooling and heating, cost and sales of electric energy and lettuce for optimized economic profit, The optimization evaluated various coverage ratios of PV modules on greenhouse roof as part of covering, the period of summer period when no crop production is considered.

MIDACO solver (http://www.midaco-solver.com/) was adopted for the optimization. It solved mixed integer non-linear programming (MINLP) problem by combining an extended evolutionary Ant Colony Optimization (ACO) algorithm with the Oracle Penalty Method for constrained handling (MIDACO-SOLVER, 2018). The optimization results showed that, in Tucson, a semi-arid climate condition, the overall profitability could be increased by extending the cultivation of the lettuce into summer, using both the shading curtain and OPV modules while decreasing high solar irradiance transmitted into the greenhouse and air temperature inside. The optimal OPV module coverage ratio was less than 58.0% assuming its depreciation was finished, the cell efficiency was 4.3%, visible light transmittance was 30%, the overall temperature coefficient was

0.02%, and the selling price of generated electricity was same as the purchase price, which was around 0.11 to 0.12 USD kWh^{-1} in Arizona. These results indicated that the profit of lettuce cultivated in summer exceeded the cultivation cost in summer (labor cost and cooling cost) with a combination of PV module and shading curtain with a simple method that changes its deployment time each month according to the monthly average DLI: no high-tech equipment for curtain control could not be necessary. Per unit greenhouse floor area, under the optimal condition, the total annual lettuce yield was 57.9 kg m^{-2} and annual electricity produce was 47.7 kWh m^{-2} (satisfying 45.7% of the electricity consumption by greenhouse cooling, which was assumed to be the only factor consuming electricity) for the whole simulation period (for one year in 2015) with an economic profit generated at 460.5 USD/m2. Although further analyses should be conducted with experimental data for some of the assumptions used, the results of this simulation-based study suggested consideration and needs of alternative shading curtain and lettuce crop cultivation strategies in an OPV integrated greenhouse located in arid and semi-arid regions with potentials to improve the overall profitability.

Keywords: Agrivoltaics, lettuce, arid climate, semi-arid climate, PV.

Nomenclature

Symbol	Default Value	Unit	Description
Greenhouse model default setting			
$Width_{GH}$	9.6	M	greenhouse width
$Height_{GH}$	1.8288	M	greenhouse height
$Depth_{GH}$	45.72	M	greenhouse depth
S_{GH}	$Width_{GH} \times Depth_{GH}$	m^{-2}	greenhouse floor area
$S_{cultivation}$	0.9 × greenhouse floor area	m^{-2}	cultivation floor area
S_{roof}		m^{-2}	greenhouse roof area
$T_{GHStructure}$	0.95	-	transmittance through greenhouse inner structure, actuator (e.g. sensors and fog cooling systems) and farming equipment (e.g. gutters)
m_{MAX}	10		The number of greenhouse roof spans
PV module model default setting			
C_{cell}	0.043		cell efficiency of the given PV module
P_{mpp}	$V_{mpp} \times I_{mpp}$	W	Nominal power
C_{Pmpp}	0.02	% K^{-1}	overall temperature coefficient to generated power
	200	USD m^{-2}	Real OPV price per area including the cost for shipment, connectors and cables
T_{PV}	0.3	%	PAR Transmittance ratio
r_{PV}	0.2 (by default)		coverage ratio of PV module on the roof
Solar irradiance to tilted PV module			
δ		Rad	The declination angle
n		day	the number of the day in a year from January 1st (n = 1 for January 1st and 365 for December 31st)
ω		rad	solar hour angle
α		rad	solar altitude angle
φ	0.563	rad	the latitude of the greenhouse location
ψ_s		rad	solar azimuth angle
γ		rad	incident angle of the beam sunlight to the module surface (greenhouse roof)

ψ_p	$\pi/2$ for east facing roof, $-\pi/2$ for west facing roof	rad	module azimuth angle - the angle between the normal to the PV module surface (greenhouse roof) and the true south
β	0.588	rad	the tilt angle of PV module
I_{DH}		W m^{-2}	estimated direct irradiance to horizontal surface
I_0	1367	W m^{-2}	solar constant
p	0.583		atmospheric transmissivity
I_S		W m^{-2}	estimated diffuse irradiance to horizontal surface
I_{TD}		W m^{-2}	direct beam radiation on the tilted surface
I_{TS}		W m^{-2}	diffused radiation on the tilted surface
$I_{T\rho}$		W m^{-2}	albedo radiation on the tilted surface
ρ_g	0.1		ground reflectance
I_T	$I_{TD} + I_{TS} + I_{T\rho}$	W m^{-2}	total solar irradiance to tilted surface
Electric energy yield			
$C_{degrade}$			the degradation ratio of cell efficiency each hour
$C_{DegradePerHour}$	1.82648×10^{-5}		the decrement value of $C_{degrade}$ at each simulation hour
C_{Pmpp}	0.0002	$°C^{-1}$	overall temperature coefficient to generated power
T_{pvHour}	T_{meter}	°C	hourly mean of PV body temperature
T_{meter}		°C	Hourly mean of body temperature of the meter (Kipp & Zonen Model CMP22) measuring the total shortwave solar irradiance.
$hour_{end}$	24	Hour	End of hour in a day
$W_{pvoutDaily}$		kWh m^{-2}	electric energy generated by PV module per square meter during a day
$W_{opvoutTotal}$		kWh m^{-2}	The electric energy generated by PV during the whole simulation period
$DAYS_{simulation}$		days	Number of simulation days
Electric energy sales and cost			

$Area_{roof}$		m^2	total roof area of the modled greenhouse
$Sales_{monthlyRetailEle}$		USD kWh^{-1}	residential electricity price each month per kWh
$Cost_{monthlyRetailEle}$	= $Sales_{monthlyRetailEle}$	USD kWh^{-1}	residential electricity price each month per kWh
$Sales_{ele}$		USD	total sales price of electricity during the simulation period
$Cost_{pvPerArea}$		USD m^{-2}	PV module purchase cost per area
$Cost_{pv}$		USD	PV module purchase cost
$Cost_{ele}$		USD	electricity cost during the simulation period
Overall transmittance through multi-span greenhouse			
α		rad	greenhouse roof angle of east facing roof
β	α	rad	greenhouse roof angle of west facing roof
θ_i		rad	incident angle of solar radiation
θ_t		rad	refractive angle of solar radiation
n_i	1.000293		refractive index of air
n_t	1.5		refractive index of polyethylene (PE) film
$r_{SPolarize}$			reflectivity in S polarization
$t_{SPolarize}$			transmissivity in S polarization
$r_{PPolarize}$			reflectivity in P polarization
$t_{PPolarize}$			transmissivity in P polarization
$r_{unpolarize}$			overall reflectivity of solar radiation
$t_{unpolarize}$			overall transmissivityof solar radiation
T_1			transmissivity of the modeled greenhouse room facing west
T_2			transmissivity of the modeled greenhouse room facing east
F_1			reflectivity of the modeled greenhouse room facing west
F_2			reflectivity of the modeled greenhouse room facing east
E		rad	Angle between the perpendicular vector component of the solar radiation and horizontal axis perpendicular to greenhouse spans

L_1		m	length of the west-facing side of the roof
L_2		m	length of the east-facing side of the roof
l_a			Portion of the direct solar radiation resulting from the separation by the ridge of the first greenhouse roof, enters through the second front row of the roof span
l_b			Portion of the direct solar radiation resulting from the separation by the ridge of the first greenhouse roof, enters through the first front row of the roof span
m			number of interacting spans
$T_{MATWest}$			transmittance through multi-span roof facing west
$T_{MATEast}$			transmitance through multi-span roof facing east
T_{MAT}			overall transmittance through multi-span roof
l_1			the portion of the beam of incident light traveling through the first (west) side of the roof
l_2			the portion of the beam of incident light traveling through the second (east) side of the roof
$T_{1,2}$			radiation directly transmitted inside the greenhouse through roof surfaces 1 and 2
$T_{r,x}$			Radiation reflected by roof surface x (x = 1 or 2) and then transmitted into greenhouses. The letter x are replaced with 1 or 2, each of which indicates the roof surfaces
$T_{rx,y}$			Transmittance of direct solar radiation reflecting the x (if 1, west facing, if 2, east facing) roof and penetrating the y (if 1, west facing, if 2, east facing) roof
$F_{rx,y}$			Reflectance of direct solar radiation reflecting the x (if 1, west facing, if 2, east facing) roof and penetrating the y (if 1, west facing, if 2, east facing) roof
Light intensity to plants in greenhouse			

$I_{multispan}$		W m^{-2}	light intensity after penetrating multi-span greenhouse
I_{PV}		W m^{-2}	solar irradiance after traveling through PV module and greenhouse roof surface
$I_{GHStructure}$		W m^{-2}	solar irradiance considering the light attenuation by inner equipment and greenhouse structures
$T_{shadingCurtain}$	0.45		shading curtain transmittance
I_{plant}		W m^{-2}	solar irradiance to plants
Lettuce growth model			
X_{nsdw}		g m^{-2}	state variable of non-structural dry weight (NSDW)
X_{sdw}		g m^{-2}	state variable of structural dry weight (SDW)
f_{phot}		g m^{-2} s^{-1}	gross canopy photosynthesis
r_{gr}		s^{-1}	specific growth rate
f_{resp}		g m^{-2} s^{-1}	maintenance respiration
DW		g m^{-2}	final dry weight
FW		g m^{-2}	final fresh weight
c_{FWToDW}	0.045		conversion ratio from DW to FW
c_{α}	30/44		ratio of the molecular weights of CH_2O to CO_2
c_{β}	0.8		coefficient for respiratory and synthesis losses of non-structural material due to growth
U_T	U_{Tday} or U_{Tnight}	℃	
U_{Tday}	19	℃	setpoint temperature at day time
U_{Tnight}	24	℃	setpoint temperature at night time
$c_{gr,max}$	5×10^{-6}	s^{-1}	saturation growth rate at 20 ℃
c_{γ}	1.0		a parameter for r_{gr}
$c_{Q10,gr}$	1.6		Q_{10} factor for grwoth
$c_{resp,sht}$	3.47 × 10-7	s^{-1}	maintenance respiration coefficients for shoot
$c_{resp.rt}$	1.16 × 10-7	s^{-1}	maintenance respiration coefficients for root

$c_{Q10,gr}$	2.0		Q_{10} factor of maintenance respiration
c_{τ}	0.15		ratio of the root dry weight to the total crop dry weight
$f_{phot,max}$		$g\ m^{-2}\ s^{-1}$	gross carbon dioxide assimilation rate of the canopy having an effective canopy surface of 1 m2 at solid covering
c_K	1.0		extinction coefficient
c_{lar}	75×10^{-3}	$m^2\ g^{-1}$	structural leaf area ratio
ε		$g\ J^{-1}$	light use efficiency
U_{PAR}		$W\ m^{-2}$	incident photosynthetically active radiation to plants
g_{CO2}		$m\ s^{-1}$	canopy conductance to CO2 diffusion
c_{ω}	1.83×10^{-3}	$g\ m^{-3}$	density of CO2
U_{CO2}	400	ppm	CO2 concentration in the greenhouse
Γ		ppm	CO_2 compensation point accounted for photorespiration at high light level
g_{bnd}		$m\ s^{-1}$	boundary layer conductance
g_{stm}		$m\ s^{-1}$	stomatal conductance
g_{car}		$m\ s^{-1}$	carboxylation conductance
DW_{Init}	2.7	$g\ m^{-2}$	initial weight of lettuce dry weight
$DW_{Init,NSDW}$	$DW_{Init} \times 0.75$	$g\ m^{-2}$	initial NSDW
$DW_{Init,SDW}$	$DW_{Init} \times 0.25$	$g\ m^{-2}$	initial SDW
Energy consumption for greenhouse heating and cooling			
Q_{SR}	I_{plant}	W	solar radiation into greenhouse
Q_{LH}		W	latent heat from crop
Q_{SH}		W	sensible heat from conduction and convection through greenhouse covering material
Q_{LW}		W	net thermal longwave radiation through greenhouse covers to the atmosphere
Q_V		W	energy controlled by heating or cooling equipment
$Q_{SRperArea}$	I_{plant}	W	solar radiation into greenhouse
$Q_{LHperArea}$		$W\ m^{-2}$	latent heat from crop per greenhouse floor area

$Q_{SHperArea}$		W m^{-2}	sensible heat from conduction and convection through greenhouse covering material per greenhouse floor area
$Q_{LWperArea}$		W m^{-2}	net thermal longwave radiation through greenhouse covers to the atmosphere per greenhouse floor area
$Q_{VperArea}$		W m^{-2}	energy controlled by heating or cooling equipment per greenhouse floor area
U	6.3	W m^{-2} °C^{-1}	overall heat transfer coefficient
T_{air}		°C	temperature of outside air
T_{sp}	U_T	°C	setpoint temperature inside greenhouse
δ	5.67×10^{-8}	W m^{-2} K^{-4}	Stefan-Boltzman's constant
τ			transmissivity of thermal radiation of greenhouse covering material
ε_i			thermal emissivity of greenhouse covering material
ε_{sky}			thermal emissivity of the sky
T_{sky}		K	temperature setpoint of the sky
RH			relative humidity outside greenhouse
RH_{GH}			relative humidity inside greenhouse
e_a	$RH \times e_s$	Pa	ambient vapor pressure
e_s		Pa	saturated vapor pressure
s		g m^{-3} K^{-1}	slope of the saturation vapor pressure-temperature curve
R_n		W m^{-2}	net all-wave solar radiation
F		W m^{-2}	soil flux
ρ	1.204	kg m^{-3}	density of the air
c_p	1010	J kg^{-1} K^{-1}	specific heat of the air
D		g m^{-3}	humidity deficit
γ		g m^{-3} K^{-l}	psychrometric constant
r_c		s m^{-1}	crop resistance
r_b		s m^{-1}	aerodynamic resistance of crop as a whole
L	c_{lar} $(1-c_\tau)$ X_{sdw}		leaf area index
r_s		s m^{-1}	stomatal resistance

r_a		s m^{-1}	aerodynamic resistance of the leaf
I_s	I_{plant}	W m^{-2}	shortwave radiation to plant canopy
$\lvert T_l - T_{sp} \rvert$	2	°C	difference between leaf temperature and greenhouse air temperature
d	0.14	m	characteristic dimension of leaf (average between the length and the width of free standing leaves)
z	700	m	elevation of modelded greenhouse
Lettuce sales and cost			
$FW_{headHarvest}$	200	g $head^{-1}$	harvested fresh weight
FW_{head}	FW/d_{plant}	g $head^{-1}$	fresh weight per head
d_{plant}	25	head m^{-2}	density of lettuce
$FW_{harvest}$	$FW_{head} \times d_{plants} \times S_{cultivation}$	kg	total fresh weight at each harvest
$Sales_{lettuceTotal}$		USD	total lettuce sales price for whole simulation period
$Sales_{LettuceKg}$		USD kg^{-1}	lettuce sales price per kg
$Sales_{headLettuce}$	1.99	USD $head^{-1}$	lettuce sales price per head
$Cost_{lettuceTotal}$		USD	total cost for lettuce cultivation
$Cost_{labor}$		USD	labor cost for lettuce cultivation
$Cost_{coolingEle}$		USD	cooling cost for lettuce cultivation by pad and fan cooling system
$Cost_{NG}$		USD	heating cost for lettuce cultivation by natural gas heating system
$Labor_{lettuce}$	0.315	person $(10000\ kg)^{-1}$	necessary labor per 10000 kg yield
Wage	12.79	USD $person^{-1}$ $hour^{-1}$	hourly wage per person
Q_{VCool}		W m^{-2}	required energy for cooling

$COP_{padAndFan}$	15		COP of pad and fan cooling system
Q_{VHeat}		W m^{-2}	required energy for heating
c_{heater}	0.9		thermal efficiency of heating equipment
$Cost_{monthlyGas}$		USD ft^{-3}	price of natural gas delivered to residential consumers at Arizona
$C_{MJPerm3}$	38.7	MJ m^{-3}	volumetric energy conversion ratio of natural gas
Total economic profit and loss			
$Profit_{plnat}$		USD	The profit of plant sales for a given simulation period
$Profit_{ele}$		USD	The profit of electricity sales for a given simulation period
$Profit_{all}$	$Profit_{plnat}$+ $Profit_{ele}$	USD	The total profit for a given simulation period
Optimization			
$Date_{endSpring}$		Days	shading curtain deployment spring end date
$Date_{StartFall}$		Days	shading curtain deployment fall start date

1. Introduction

Greenhouse farming is affected by various factors such as crop (e.g. crop types, planting density, crop architecture) and its surrounding environment (e.g. greenhouse temperature, relative humidity, light intensity and spectrum, wind speed and direction, CO_2 concentration and nutrient solution condition), as well as greenhouse structure and materials (e.g. structure shadows, cover material transmittance, greenhouse orientation) and outer climate conditions. Greenhouse environment is controlled based on these factors to maintain desired crop yield and quality and optimize resource use in production.

Many studies have been done with various methods and physical principles to unravel this complicated system and developed useful models and control algorithms. Fitz-Rodríguez et al. (2010) summarized the previous modeling studies focusing on specific aspects of greenhouse farming such as natural and forced ventilation, evaporative cooling, and heating system. They also referred newer research approaches based on optimization for energy saving, water consumption,

CO_2 usage, and humidity control.

However, since the greenhouse and cropping system is highly complex to generalize, many of the models require large number of parameters and equations and can be applied to only specific weather conditions and crops. Furthermore, to the best of our knowledge, there is no research found in literature integration all relevant models to calculate economic profit from the environment data which can be acquired before actually starting cultivation and specification of greenhouse integrated with photovoltaics, with which farmers can simulate various farming strategies to maximize profit.

Agrivoltaics combine electricity production with photovoltaic (PV) modules and agricultural production using the same land without competing with the existing agricultural land, enabling full use of the solar energy which is especially in arid and semi-arid climates. For greenhouse farming, PV modules are put on the roofs which generate electricity with excessive solar radiation for plants grown in greenhouse.

Research on Agrivoltaics for greenhouse systems based applications have progressed using traditional inorganic silicon photovoltaic (PV) modules (Yano, et al., 2009; Yano, et al., 2010; , Juang and Kacira, 2014; Cossu et al., 2017).

Various research for new PV technology has been conducted, especially with third generation PVs such as with organic photovoltaics (OPV), Most of the present study are about its fundamental properties of OPV modules (Gebhardt, Du, Wodo, & Ganapathysubramanian, 2017; Gevorgyan et al., 2016; Lucera et al., 2017; Valle et al., 2012; Yang et al. 2015). Since this technology is fairly new, its integration to agricultural applications and specifically those within greenhouse-based food production systems have been limited.

Previous studies about OPV modules revealed various advantages and disadvantages (Table 1). For instance, the advantages include flexibility of OPVs for tuning light quality for crop growth (Mohammad Bagher, 2014; Emmott et al., 2015), selectively transmitting specific wavelength beneficial for the crop (Mohammad Bagher, 2014; Emmott et al., 2015), decreased manufacturing cost due to common printing technologies on bendable thin plastic sheets (Mohammad Bagher, 2014, Lucera et al, 2017), and reduced environmental impact during manufacturing and operation (Mohammad Bagher, 2014). On the other hand, the disadvantages are low OPV cell efficiency compared to common PV modules, especially at large scale processing while this has been improving (NREL, 2017), shorter longevity, for instance ten years in lab conditions (Lucera et al, 2017). It was still unknown how durable and stable OPV modules could be under various climatic conditions and operational practices (Gevorgyan et al., 2016).

Indeed, limited research on OPV integrated greenhouse system has been conducted, thus restricting its adaptation to greenhouse operations and business. For instance, the relationship between OPV's characteristic in a real deployment and various environmental conditions (e.g. OPV's width and deployment pattern, resistance to non-uniform light irradiation and temperature, and light transmittance and quality under dynamically changing climate conditions) and the farming-related factors such as types of crops, crop yield and quality, effect on greenhouse microclimate, effect on economic profitability for greenhouse farming system have not been adequately verified.

Emmott et al. (2015) studied the application of OPV module to greenhouse farming. They depicted the impact of OPV to crop productivity in greenhouse and its profitability by modeling and simulation: They concluded that, assuming Spanish electricity the baseline scenario, where OPV modules remain reasonably expensive, a cell efficiency of 10.2% (equivalent to module cost of 0.46 €/W) and 8.63 % module efficiency would be required at least for a PV greenhouse to be economically justified, which was far more than the efficiencies researched in Emmott et al. (2015).

This paper aimed to develop a comprehensive model which combined the models of solar irradiance to a tilted surface, electric energy generated by PV modules on a greenhouse roof, transmittance through multi-span greenhouse roof, solar irradiance to lettuce in the greenhouse, lettuce yield and growth transition, energy consumed by cooling and heating, cost and sales of electric energy and lettuce respectively, and finally, the total economic profit. Using the climatic condition for Tucson, Arizona, the model also used computed optimal OPV coverage ratio that should be installed on greenhouse roof, the summer period when it was assumed not to grow lettuce. The optimization model is used to evaluate alternative strategies for the use of both shading curtain and OPV module for maximum profit. The developed model is flexible and allows users to simulate various cases and strategies under various climatic conditions and locations with various input variables.

2. Methods

2.1. Default settings: Initial constant values and parameters for modeling

For modeling, the initial constant values related to weather, PV module, and greenhouse specifications were required, all of which were imported to the program. The measured weather data for Tucson, Arizona, for modeling (i.e. ambient air temperature and relative humidity) was obtained from "Solar Resource & Meteorological Assessment Project (SOLRMAP) Observed Atmospheric and Solar Information System (OASIS) University of Arizona database (https://www.nrel.gov/midc/ua_oasis/) , (Latitude: 32.22969° N, Longitude: 110.95534° West, Elevation: 786 meters AMSL, Time Zone: -7.0). The obtained weather data was hourly data, which meant each number indicated the average value during each hour. Therefore, all the values derived were hourly data.

Direct, diffuse, and albedo solar irradiance were estimated using the models by Yano et al. (2009). For OPV system electricity generation, hourly body temperature of the module was assumed to be the temperature measurement device (Temperature CMP22 (platform) at https://midcdmz.nrel.gov/ua_oasis/). The setpoints for the air temperature, and CO_2 concentrations in the model greenhouse were assumed to be 24 °C in the daytime and 19 °C in the night time, and 400 ppm respectively.

In addition to weather data, the specifications of OPV module (e.g. cell efficiency, temperature coefficient, degradation ratio) and greenhouse (e.g. height, width depth, cultivation area, covering material) were also defined (see nomenclature and Fig. 1).

In the simulation, 10 span gutter connected greenhouse (each span with 1.83 m side wall height, 4.9 m eaves height, 9.6 m span width and 14.6m length) was studied. The greenhouse was north-south oriented with roof facing east and west. All the modeled greenhouse covering materials were assumed single layer polyethylene with 0.85 light transmittance (Sabeh, Higgins, Kuack and Millett (2014)). The OPV module technical specifications used in the simulations are presented in the Nomenclature.

2.2. Overall integrated model flow

Fig. 2 shows the overall flow of the integrated model. Having imported necessary input data on weather, OPV module, and greenhouse specifications, each sub-model was executed as part of the integrated greenhouse economic profit model Initially, the simulator calculated solar irradiance to a tilted surface, greenhouse roof (1). Based on the irradiance, it estimated the electric energy generated by PV modules (4). Next, it calculated the transmittance through multi-span greenhouse roof with greenhouse (roof angle) and covering material specification (2), which was used to calculate the solar irradiance to lettuce in the greenhouse (3). The model predicted solar irradiance to the crop was used in the lettuce growth model (6) and the energy greenhouse energy balance model (5) estimating cooling and heating energy required to maintain the greenhouse air temperature and relative humidity setpoints. Finally, using market prices for electricity, lettuce, labor and gas, the model calculated the profit of electricity generated by PV modules and lettuce, respectively (7 and 8). The total profit was output by combining these profits or losses (9).

2.3. Model description

2.3.1. Solar irradiance to tilted PV

Kacira et al. (2004) and Yano et al. (2009) models were used to estimate solar angles and especially the direct, diffuse and albedo solar irradiance to horizontal and tilted surfaces. A simplified solar hour angle ω (rad) was used from Kacira et al. (2004):

$$\omega = \frac{\pi}{180}\left(60\ \frac{hour - 12}{4}\right) \tag{1}$$

where $hour$ was hourly time step (e.g. if it is 6 am, it is 6). 60 is multiplied to convert from hour to minute, and $\pi/180$ was for conversion from degree to radian. All the other solar angels to estimate the irradiances on horizontal and tilted roof and OPV panel surfaces were predicted using the model described in Yano et al (2009).

The goal of this model was to estimate the direct irradiance to horizontal surface I_{DH} (W m^{-2}), diffuse irradiance to horizontal surface I_S (W m^{-2}), direct beam radiation on tilted surface I_{TD} (W m^{-2}), diffused radiation on the tilted surface I_{TS} (W m^{-2}), albedo radiation on the tilted surface $I_{T\rho}$ (W m^{-2}), and total solar irradiance to tilted surface I_T (I_{TD} + I_{TS} + $I_{T\rho}$ W m^{-2}). When validating the estimation result with the actual data imported from the weather station, I_{DH} and I_S were replaced with the real data. I_{TD}, I_{TS}, and $I_{T\rho}$ were calculated at:

$$I_{TD} = I_0\, p^{\left(\frac{1}{\sin(\alpha)}\right)} cos(\gamma) \tag{2}$$

$$I_{TS} = \frac{I_s(1 + cos(\beta))}{2} \tag{3}$$

$$I_{T\rho} = \rho_g \frac{(I_{DH} + I_S)(1 - \ cos(\beta))}{2} \tag{4}$$

where α (rad) was solar altitude angle, γ (rad) was incident angle of beam sunlight to module surface, I_0 (1,367 W m^{-2}) was the solar constant, I_S (W m^{-2}) was the estimated diffuse irradiance to horizontal surface, β (rad) was tilt angle of PV module (0.588 rad in this study), which was same as the roof angle, I_{DH} (W m^{-2}) was the estimated direct irradiance to horizontal surface, ρ_g is the ground reflectance, which was assumed to be 0.1 (Kacira et al., 2004). The total of I_{TD}, I_{TS}, and $I_{T\rho}$ denoted by I_T (W m^{-2}) was the total solar irradiance to tilted surface, which were used to estimate the electric energy generated by PV module. Also, the total irradiance to the horizonal surface (I_{DH} + I_S) was applied to calculate the solar irradiance to lettuce in the modeled greenhouse.

Yano et al. (2009) who reported, on sunny days, p value ranging between 0.7 to 0.8, thus the measured peak solar irradiance corresponds to the estimated peak irradiance by the model. In the current study, p value was assumed 0.643 considering the local climate data. This parameter should be modified depending on the climate condition of simulated locations provided that the local measured data is available.

2.3.2. Electric energy yield

The global solar irradiance to tilted greenhouse roof (I_T) was assumed to be equivalent to the irradiance to the PV module on the roof. The total electric energy generated by the PV module $W_{outDaily}$ (kWh m^2) was defined as:

$$\mathrm{W_{outDaily}} = \mathrm{C_{cell}}\, \mathrm{C_{degrade}} \sum_{\mathrm{hour}=1}^{\mathrm{hour_{end}}} \left\{ \left(1 + \mathrm{C_{Pmpp}}(\mathrm{T_{pvHour}} - 25[°\mathrm{C}])\right) \mathrm{I_T} \right\} \tag{5}$$

where C_{cell} was the cell efficiency of given PV module, $C_{degrade}$ was the degradation ratio of its cell efficiency which decreased every simulation hour as time elapsed, C_{Pmpp} (°C^{-1}) was the overall temperature coefficient to generated power, T_{pvHour} (°C) was the hourly mean of PV body temperature which was assumed to be same as T_{meter} (°C) - hourly mean body temperature of the equipment measuring the total (direct and diffuse) shortwave solar irradiance. $C_{degrade}$ was calculated assuming the lifespan of PV module is 20 times shorter (the cell efficiency degrades 20 times faster) than that of inorganic PV module because the warranty period of the PV module (365 days) while the general lifespan of inorganic PV module (20 years) (Jordan & Kurtz, 2013). $C_{degrade}$ decremented at each simulation hour by $C_{DegradePerHour}$, both of which were calculated as below. The yearly degradation ratio of PV was assumed 20 times larger than that of inorganic PV (0.008 $year^{-1}$) (Jordan & Kurtz, 2013).

$$C_{degrade} = 1 - C_{degradePerHour} \times numer\ of\ simulated\ hours \tag{6}$$

$$C_{degradePerHour} = \frac{20 \times 0.008}{365 \times 24} = 1.82648 \times 10^{-5} \tag{7}$$

The detail of T_{meter} (°C) is described at OASIS (https://www.nrel.gov/midc/ua_oasis/instruments.html#GHP). Finally, $W_{pvoutDaily}$ (kWh m^{-2}) was the electric energy generated by PV during a day. The unit of time was converted by the summation in the equation. By summing $W_{pvoutDaily}$ during the whole experiment period, the total electric energy generated by the PV film was calculated:

$$\mathrm{W_{pvoutTotal}} = \sum_{\mathrm{day=1}}^{\mathrm{DAYS_{simulation}}} \mathrm{W_{pvoutDaily}} \tag{8}$$

where $W_{pvoutTotal}$ (kWh m^{-2}) was the electric energy generated by PV during the whole simulation period, $Days_{simulation}$ (days) was the number of simulation days.

2.3.3. Electric energy sales

By multiplying $W_{pvoutDaily}$ (kWh m^{-2}) with the monthly electric unit sales from US Energy Information Administration (EIA) (http://www.eia.gov/electricity/), the electric energy sales price was calculated. The equation was:

$$Sales_{ele} = (r_{pv} Area_{roof}) \sum_{month=1}^{Months} Cost_{monthlyUnitEle} \sum_{day=1}^{DAYS_{month}} W_{pvoutDaily} \tag{9}$$

where r_{PV} was the coverage ratio of PV module on the greenhouse roof, $Area_{roof}$ (m^2) was the total roof area of the modeled greenhouse, $Sales_{monthlyRetailEle}$ (USD) was the residential electricity price each month per kWh in Arizona (10.99, 11.52, 11.46, 12.21, 12.64, 12.71, 12.78, 12.59, 12.69, 12.16, 11.24, and 10.4 USD/kWh from January to December 2015 in this study) (US Energy Information Administration, www.eia.gov) The residential electricity price was adopted as the economic value of the electricity generated by the PV module, which means it was assumed the generated electricity does not exceed the amount consumed by greenhouse operation: If the generated electricity is more than the consumption, the excessive amount supposed to be spent by other buildings or sold to grid at a market sales price, which is generally much cheaper than the electricity purchase cost.

2.3.4. Overall transmittance through multi-span greenhouse

The transmittance through greenhouse cover and availability of solar irradiance for crops is required to determine the crop growth and yield. Kozai and Kimura (1977) modeled the direct solar radiation and transmission into a multi-span greenhouse. Rosa (1988) computed solar irradiance and net infrared thermal radiation inside a multi-span greenhouse when outside solar radiation, optical and radiometric properties of covering material and the temperature of the ground and covering are known. A restriction of this model was it was valid only when the interchange of radiation takes place between diffusely emitting, diffusely reflecting and diffusely transmitting surfaces, indicating that the effect of direct solar irradiance is not significant. This situation can occur at very cloudy and rainy seasons. Soriano et al. (2004) constructed a model calculating the transmittance of direct solar radiation into a greenhouse with asymmetric roof slopes ($\alpha \neq \beta$) and validated the model with computed results against those measured in a scaled model. This model was a revised version of Bot's model (1983) which described the light transmittance only for symmetric multi-span roof ($\alpha = \beta$). In other words, if the roof angles were same, Soriano et al. (2004) model was similar to that of Bot (1983).

Soriano et al. (2004) classified the light penetration through multi-span roof into four cases based on the magnitude relation between E – the angle between the incident solar beam irradiance with the horizontal axis horizontal to the ground – and the angle of greenhouse roof which located on the opposite side of solar irradiance incidence. Although both Bot (1983) and Soriano et al. (2004) modeled the transmittance only for the east-west oriented greenhouse (north-south oriented roof), the current study used a modified version of the Soriano et al. (2004) considering a north-south oriented greenhouse.

The transmittance and reflectance of each facing roof covering materials were required before implementing the model. These values were calculated by Snell's law and Fresnel equations. Snell's law was given:

$$n_i \sin\theta_i = n_t \sin\theta_t \tag{10}$$

for greenhouse covering materials, where n_i is the refractive index of air, θ_i is the incident angle of solar radiation, n_t is the refractive index of polyethylene (PE) film, θ_t is the refractive angle. θ_i is calculated with Equation 11 in the model for solar irradiance incident on the tilted PV module. n_i and n_t are constant values dependent on the types of media. Assume the first medium is the atmospheric air, n_i is 1.000293 (https://en.wikipedia.org/wiki/List_of_refractive_indices#cite_note-ref1-1), and if the second is PE film greenhouse cover, n_t is 1.5 (https://www.filmetrics.com/refractive-index-database/Polyethylene/PE-Polyethene). Thus, θ_i can be calculated with the Snell's equation as:

$$\theta_i = \begin{cases} \frac{\pi}{2} - (\mathrm{E} + \alpha)\ if\ \mathrm{E} + \alpha < \frac{\pi}{2} \\ (\mathrm{E} + \alpha) - \frac{\pi}{2}\ if\ \mathrm{E} + \alpha \geq \frac{\pi}{2} \end{cases} \tag{11}$$

Fresnel equations are the formulas calculated the transmittance and reflectance when electromagnetic waves including light penetrating the border of different light-transmissive media. Fresnell equations have different formulas from the types of polarization (the direction of planes where light oscillates) - P polarization and S polarization. In S (slapping) polarization, light vibrates perpendicular to the plane of incidence, and in P polarization, it vibrates in parallel to the plain of incidence. Since natural sunlight generally mover forward in various planes, it is unpolarized light. Thus, the model in the current study calculated the transmittance and reflectance by averaging values by P and S polarization:

$$r_{SPolarize} = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t} \tag{12}$$

$$t_{SPolarize} = \frac{2n_i \cos\theta_i}{n_i \cos\theta_i + n_t \cos\theta_t} \tag{13}$$

$$r_{PPolarize} = \frac{n_t \cos\theta_i - n_i \cos\theta_t}{n_t \cos\theta_i + n_i \cos\theta_t} \tag{14}$$

$$t_{PPolarize} = \frac{2 n_i \cos\theta_i}{n_t \cos\theta_i + n_i \cos\theta_t} \tag{15}$$

$$r_{unpolarize} = \frac{\left(r_{SPpolarize} + r_{PPolarize}\right)}{2} \tag{16}$$

$$t_{unpolarize} = \frac{\left(t_{SPpolarize} + t_{PPolarize}\right)}{2} \tag{17}$$

where $r_{SPolarize}$ was the reflectivity in S polarization, $t_{SPolarize}$ was the transmissivity in S polarization, $r_{PPolarize}$ was the reflectivity in P polarization, $t_{PPolarize}$ was the transmissivity in P polarization, $r_{unpolarize}$ was the overall reflectivity of solar radiation, $t_{unpolarize}$ was the overall transmissivity of solar radiation. $r_{unpolarize}$ of the roof facing west and east was denoted by F_1 and F_2 respectively. Likewise, $t_{unpolarize}$ of each facing roof was denoted by T_1 and T_2 respectively.

The angle E (in rad), the angle between the incident solar beam irradiance with the horizontal axis horizontal to the ground – and the angle of greenhouse roof which located on the opposite side of solar irradiance incidence (Fig. 3), was calculated using the solar angles since the position of the sun is not always at the same plane perpendicular to the greenhouse. Thus, for accurate calculation of angle E, the following conversion was required:

$$E = \sin^{-1}\left(\frac{\sin\alpha}{\sqrt{\sin\alpha^2 + \cos\alpha\ \cos\left(\Psi_p - \Psi_s\right)^2}}\right) \tag{18}$$

where α (rad) was the solar altitude angle, Ψ_p was the module azimuth angle of greenhouse roof Ψ_s was the solar azimuth angle. The model in the current study calculated the angle E for each direction of roof (west and east) separately. When the solar radiation to the roofs were significantly small (e.g. almost 0), the angle E was assumed to be zero in the simulation. For example, in the morning when the sunlight was only from the east, only east facing roof receives the light, the west facing roof did not receive direct solar radiation.

Having evaluated all the solar angles and other variables presented in the previous section per hour basis for each facing roof, the transmittance and reflectance through/from each greenhouse roof was calculated. As mentioned before, the model has four different cases depending on the relationship between E and α (or β if the roof is symmetric). Soriano et al. (2004) denoted the transmittance of west facing roof as $T_{MATWest}$. In the current study, $T_{MATEast}$ was used to calculate transmittance for the east facing roof. When assuming symmetric roof (α=β), the transmittance calculations are simplified to only one variable either $T_{MATWest}$ or $T_{MATEast}$, which are the same. The difference from the original source was model was modified to calculate the transmittance for east and west facing roofs instead of north and south, which meant the sun moved across the meridian over both roof directions, leading E can be more than π/2. After calculating the transmittance of west facing roof ($T_{MATWest}$) and east facing roof ($T_{MATEast}$), the overall transmittance through multi-span roof (T_{MAT}) was calculated by integrating both as shown below.

$T_{MAT} = T_{MATWest}$ if I_T to the east facing roof is 0. (19)

$T_{MAT} = T_{MATEast}$ if I_T to the west facing roof is 0. (20)

$T_{MAT} = \frac{(T_{MATEast} + T_{MATWest})}{2}$ if IT to both of the facing roof are not 0 (both roofs receive solar radiation). (21)

where I_T was the total solar irradiance to tilted surface, which was estimated as described in Section 2.3.1.

2.3.5. Light intensity to plants in greenhouse, considering shading curtain

To estimate the light intensity to lettuce crop, several light transmission limiting factors were considered such as greenhouse covering material, structure and mechanical instruments at canopy and shading curtain if used and OPV coverage ratios:

$$I_{multispan} = T_{MAT}(I_{DH} + I_S) \tag{22}$$

where I_{DH} (W m^{-2}) was the estimated direct solar irradiance to horizontal ground out of greenhouse and I_S (W m^{-2}) was the estimated diffuse solar irradiance to horizontal ground out of greenhouse, which were calculated for I_{TS} and $I_{T\rho}$ (Equation 3 and 4). T_{MAT} was the transmittance through multi-span greenhouse roof, $I_{multispan}$ (W m^{-2}) was the light intensity after penetrating multi-span greenhouse.

The light transmission limiting factor of the OPV module was considered by:

$$I_{PV} = T_{pv}\, r_{PV}\, I_{multispan} + (1 - r_{pv}) I_{multispan} \tag{23}$$

where T_{pv} was the transmittance of PV module (if 0, the module is not transparent), and I_{PV} (W m^{-2}) was the solar irradiance after traveling through OPV module and greenhouse roof surface. The limiting factor for light transmission due to greenhouse inner structure was considered using:

$$I_{GHStructure} = T_{GHStructure}\, I_{PV} \tag{24}$$

where $T_{GHStructure}$ was the transmittance through greenhouse inner structure, which was assumed to be 0.95, and $I_{GHStructure}$ (W m^{-2}) was the solar irradiance considering the light attenuation by inner equipment and greenhouse structures.

The model included shading curtain model. The deployment time each day was determined by the average daily light integral (DLI) (mol m^{-2} day^{-1}) per month so that the average DLI did not exceed the value which may cause tipburn. The maximum DLI which does not cause tipburn depends on the environment condition in experiment and the characteristics of cultivars. According to Both (2003), when average DLI during cultivation period was less than or equal to 17 mol m^{-2} day^{-1}, no tipburn was observed. Brechner and Both (1996) mentioned "For some cultivars, 15 or mol m^{-2} day^{-1} is the maximum amount of light that can be used before the physiological condition called tipburn occurs". On the other hand, Frantz, Ritchie, Cometti, Robinson, and Bugbee (2004) did not observe almost no tipburn (0% for the cultivar called "Waldmann's Green" and 5% for "Buttercrunch") under 57.6 mol m^{-2} day^{-1} with appropriate air blowing onto meristem. Furthermore, Kacira, Jensen, Robie, Tollefson, and Giacomelli (2017) grew five lettuce (Lactuca Sativa) cultivars (Magenta, Rex Green Butterhead, Cherokee, Salanova Red Butterhead and Salanova Incised) under 34.96 mol m^{-2} day^{-1} on average and did not observe significant tipburn issues. Thus, DLI of 17 mol m^{-2} day^{-1} was assumed in this study.

In the simulation, shading curtain opening or closing at each simulation hour was determined the monthly average DLI after considering the effect of greenhouse structure for light transmission ($I_{GHStructure}$). If the DLI was less than or equal to 17 mol m^{-2} day^{-1}, no shading curtain was deployed during the month. Otherwise, the curtain closing hour was gradually increased from noon. For example, it was firstly assumed the curtain was deployed only at noon for 1 hour (12:00 to 13:00), and if the DLI was still more than 17 mol m^{-2} day^{-1}, the shading time was increased from 12:00 to 14:00, and if it was still more, the time was further increased from 11:00 to 14:00. This increment continued until the average DLI became less than or equal to 17 mol m^{-2} day^{-1} or the shading curtain was deployed for whole day.

Having determined the shading curtain deployment and OPV coverage, the DLI to lettuce was finally calculated.

$$I_{plant} = T_{shadingCurtain}\ I_{GHStructure} \text{ if shading curtain was deployed.} \tag{25}$$

$$I_{plant} = I_{GHStructure} \text{ if shading curtain was not deployed.} \tag{26}$$

where $T_{shadingCuratain}$ was the transmittance of shading curtain, and I_{plant} (W m^{-2}) was the solar irradiance to plants in greenhouse.

2.3.6. Lettuce crop growth model

There has been diverse research on modeling lettuce crop growth considering various environmental variables (Shimizu, Kushida, and Fujinuma, 2008; Both, 2003; Pearson, Wheeler, Hadley, and Wheldon, 1997; Sweeney et al., 1981; Van Henten, 1994). The models have been developed with certain varieties and under certain environmental conditions, thus it can be difficult to generalize models for variety of growing systems, with crops and environmental conditions (e.g. air temperature, cultivation period, plant density, cultivars, light intensity are among few). Therefore, in the current study, four models (Shimizu, Kushida & Fujinuma, 2008; Both, 2003; Pearson et al., 1997; Van Henten, 1994) were evaluated comparing model computed results with crop fresh weight to those measured values from Kacira et al. (2017) who evaluated five lettuce cultivars grown in a greenhouse and using the same environmental conditions from the experiments.

Shimizu et al. (2008) grew the cultivar called Greenwave at the growth chambers where they could control dry bulb temperature, photosynthetic photon flux (PPF) and CO_2 concentration.

They changed PPF and CO_2 concentration with two different conditions and developed a model based on the Gompertz function. The limitation this model was that this model needed the final fresh weight (the lettuce fresh weight per head at harvest) beforehand, which means the users of this model must run a real cultivation at least once to determine the final fresh weight, and that value should be acquired again when the growing conditions are changed. This limitation may not be a major issue when crop is grown under more controlled conditions such as in plant factories with artificial lighting, however, it can have a confining factor for greenhouse based farming where environment conditions are not fully controllable.

Both (2003) grew Butterhead lettuce in a greenhouse and analyzed crop growth under various environmental conditions. The study evaluated the transitions of shoot dry mass at different daily light integrals (DLI) and CO_2 concentration. The relationship between leaf and shoot dry mass were also developed. Both (2003) provided a numerical model estimating the final fresh weight which required time and the uniform DLI during the cultivation period using supplemental lighting for the uniformity. This model can be modified to estimate final fresh weight with fluctuating solar irradiance by Taylor expansion so that the model calculates the fresh weight increase each time step.

These four models were evaluated for validation by comparing the computed final fresh lettuce weight to those measured values of Kacira et al. (2017) considering the same cultivation days and DLI for Tucson, Arizona, obtained from the local weather station. The Both (2003) model significantly overestimated the fresh weights observed by Kacira et al. (2017). The final fresh weight continued to increase as the cultivation time took longer without the final fresh weight reaching to a stationary phase eventually leading to unreasonably large final fresh weight values (e.g. 500 g head^{-1}). Therefore, this model was not selected for the current study.

Pearson et al. (1997) used a lettuce cultivar called Rosana and validated the fresh weight transition output with that of other seven studies having different cultivars and CO_2 concentration. The model provided reasonable predictions with a few outliers, indicating that the model could be used for growth predictions under various environment conditions. Nevertheless, this model also overestimated the final fresh weight compared to those measured values by Kacira et al. (2017). Also, the model predicted overall shape of the fresh weight growth curve did not result in a reasonable and expected sigmoid shape.

Van Henten (1994) used two cultivars, Berlo and Norden in the modeling study. This model required air temperature, CO_2 concentration and solar irradiance to the crop as input variables. This enables using the model for various environmental conditions. The Van Henten model reasonably predicted final lettuce fresh weights compared to measured values from Kacira et al. (2017) under the same weather conditions of Tucson, Arizona. Therefore, this model was used in the current study. In Van Henten (1994), the lettuce dry weight was divided into two components: non-structural dry weight (NSDW) consisting of the non-structural part of lettuce as the name indicates (e.g. glucose, sucrose and starch), and structural dry weight (SDW) consisting of the rest representing the weight of structural portion (e.g. cell walls and cytoplasm). The change of these weight at each unit time was given as:

$$\frac{dX_{nsdw}}{dt} = c_\alpha f_{phot} - r_{gr}X_{sdw} - f_{resp} - \frac{1 - c_\beta}{c_\beta} r_{gr}X_{sdw} \tag{27}$$

$$\frac{dX_{sdw}}{dt} = r_{gr}X_{sdw} \tag{28}$$

$$DW = NSDW + SDW \tag{29}$$

$$FW = \frac{1}{c_{FWToDW}} DW \tag{30}$$

where X_{nsdw} (g m^{-2}) and X_{sdw} (g m^{-2}) were the state variables of NSDW and SDW, f_{phot} was the gross canopy photosynthesis, r_{gr} (s^{-1}) was the specific growth rate, f_{resp} (g m^{-2} s^{-1}) was the maintenance respiration, c_α was the ratio of the molecular weights of CH_2O to CO_2 (30/44), c_β was the coefficient for the respiratory and synthesis losses of non-structural material due to growth, which was estimated at 0.8 for lettuce following the source, and DW (g m^{-2}) was the final dry weight at harvest per area, FW (g m^{-2}) was the final fresh weight per area, and c_{FWToDW} was the conversion ratio from DW to FW (0.045 in the current study). The variables which did not have constant values were derived with the equations in Van Henten (1994). The incident photosynthetically active radiation (PAR) to the crop U_{PAR} (W m^{-2}) was estimated from the predicted solar irradiance available for the crop (I_{plant}). The canopy temperature at each unit time U_T (°C) was assumed to be same as the greenhouse air temperature at the day and night time setpoint temperature (24 °C for day time and 19 °C for night time). The CO_2 concentration in the greenhouse U_{CO_2} (ppm) was assumed to be at ambient level as 400 ppm.

There were two modifications to the original Van Henten model used in this study. . First, the extinction coefficient c_K was changed from 0.9 into 1.0 due to larger crop density used in the current study as 25 heads m^{-2} compared to 18 heads m^{-2} in Van Henten (1994). Van Henten (1994) stated 0.9 was for planophile and 0.3 was for erectophile canopies. Second, the time interval in this study was hours compared to seconds used in the original model.

When the simulation period was longer than the lettuce cultivation cycle, it was assumed to take three days to begin the next cultivation when the simulation period was more than one cultivation cycle. The initial lettuce weight was assumed to be 2.7 g m^{-2} from Van Henten (1994), and initial X_{nsdw} (g m^{-2}) and X_{sdw} (g m^{-2}) was 2.7×0.25 g m^{-2} and 2.7×0.75 g m^{-2} respectively.
In a common cultivation custom, lettuce is not cultivated in summer at semi-arid and arid regions including Arizona due to high temperature and extremely strong sunlight for lettuce cultivation even with shading curtain. The model in this study also duplicated this tactic by defining the shading curtain deployment period which is except the summer period. In the program, the summer period was defined as the days between the spring end date ($Date_{endSpring}$) and the fall start date ($Date_{StartFall}$). If the summer period or the end of simulation period arrived while the simulator was virtually growing lettuce and has not finished, it forcefully harvested the immature lettuce. When the sales price was calculated based on weight (kg), the weight of immature lettuce was simply added to the total harvested weight. When it was sold per head, the immature lettuce was counted if the head weight is more than 90 % of the harvest weight. If not, the harvest was ignored. The summer period ($Date_{endSpring}$ and $Date_{StartFall}$) were analyzed in the optimization study to compare the optimal summer period with the traditional custom.

2.3.7. Energy consumption for greenhouse heating and cooling

To maintain the set point air temperatures in the greenhouse at desired levels for the crop, cooling and heating system are needed. These air conditioning systems consume electricity for cooling (e.g. pad and fan cooling system, fog cooling system, and heat pumping system) and resources like natural gas and fuel oil for heating.
The fundamental energy balance for a greenhouse system was defined as:

$$Q_V = Q_{\mathrm{SR}} - (Q_{\mathrm{LH}} + Q_{\mathrm{SH}} + \mathrm{Q_{LW}}) \quad (31)$$

where Q_{SR} (W) was the solar radiation into the greenhouse, Q_{LH} (W) was latent heat from crop, which is mainly given by transpiration, Q_{SH} (W) was sensible heat from conduction and convection through greenhouse covering material (both sidewall and roof), and Q_{LW} (W) was the net thermal longwave radiation through greenhouse covers to the atmosphere. Q_V (W) was the energy controlled by heating or cooling equipment: If Q_V was positive, the same amount of heating energy must be removed (cooling), and if it was negative, the same amount was supposed to be added (heating) by heating system to maintain the greenhouse air temperature at the setpoint values. Each term in the righthand side was calculated based on the given environmental data and constant values and the predefined setpoint temperature.

The Q_{SR} was simply given:

$$Q_{\mathrm{SR}} = I_{\mathrm{plant}} \times S_{GH} \quad (32)$$

where I_{plant} (W m^{-2}) was the solar irradiance to plants, and S_{GH} (m_2) was the greenhouse floor area.

Q_{SH} was expressed as:

$$Q_{\mathrm{SH}} = \mathrm{U}\left(T_{air} - T_{sp}\right) \times \left(S_{roof} + Height_{GH} \times (Width_{GH} + Depth_{GH})\right) \quad (33)$$

where S_{roof} (m^2) was the greenhouse roof area, $Height_{GH}$ (m), $Width_{GH}$ (m), $Depth_{GH}$ (m) were the height, width and depth of the modeled greenhouse. U was the overall heat transfer coefficient (W m^{-2} $°C^{-1}$), which depended on material types, T_{air} was the temperature of outside air, which was hourly data imported from the local weather station (OASIS), and T_{sp} (°C) was the setpoint temperature inside greenhouse. The default value of U was set to be 6.3 referring to Hanan (1998), which is the U value for single layer UV resistant polyethylene film. Since the greenhouse internal air temperature was assumed to be perfectly controlled to the setpoint temperatures, T_{sp} was either U_{Tday}, or U_{Tday} depending on simulation hour.

Q_{LW} was given as (Hodges, 1998):

$$Q_{\mathrm{LW}} = \delta\tau\left(\varepsilon_i T_{sp}^4 - \varepsilon_{sky} T_{sky}^4\right) \times S_{GH} \quad (34)$$

where δ (5.67×10^{-8} W m^{-2} K^{-4}) was Stefan-Boltzman's constant, τ was the transmissivity of thermal radiation of greenhouse covering material, ε_i and ε_{sky} was the thermal emissivity of greenhouse covering material and that of the sky respectively, and T_{sky} (K) was the temperature setpoint of the sky.

The τ was assumed to be 0.8 following Sabeh et al. (2014). The ε_i was assumed to be 0.3 as 100 μmol thermal emissivity of single layer PE film (Okada, Ishige, & Ando, 2016),

The sky temperature was approximated as a function of T_{air} as (Swinbank, 1963):

$$T_{sky} = 0.0552\left(T_{air}\right)^{1.5} \tag{35}$$

ε_{sky} was calculated with the following equation (Idso, 1981):

$$\varepsilon_{sky} = 0.70 \ + \ 5.95 \ \times 10^{-7} \ (e_a) \ \exp(1500/T_{air} \ ) \tag{36}$$

where e_a (Pa) was the ambient vapor pressure, which was obtained by (Cronk laboratory at the Biodiversity Research Centre, University of British Columbia, http://cronklab.wikidot.com/ and National Water Service, https://www.weather.gov/):

$$e_s = 610.7 \times 10^{(7.5\times \, T_{air})/(237.3+T_{air})} \tag{37}$$

$$e_a = \mathrm{RH} \times \ e_s \tag{38}$$

where RH was the relative humidity outside, which was imported from the local weather station.

The model of Q_{LH} was mainly referred from Pollet, Bleyaert, and Lemeur (2000). They constructed the model of evapotranspiration based on Penman-Monteith model, which was given as:

$$Q_{LH} = \left(\frac{s(R_n - F)}{s + \gamma^*} + \frac{\left(\rho \, c_p \, D/r_b\right)}{s + \gamma^*}\right) \times S_{cultivation} \tag{39}$$

where $S_{cultivation}$ (m^2) was the greenhouse cultivation floor area, s (g m^{-3} K^{-1}) was the slope of the saturation vapor pressure-temperature curve, R_n (W m^{-2}) was the net all-wave radiation, F (W m^{-2}) was the soil flux, ρ (1.204 kg.m^{-3}) was the density of the air; c_p (1010 J kg^{-1} K^{-1}) was the specific heat of the air and D was the vapor pressure deficit (g.m^{-3}). In this model F was assumed to be 0 W m^{-2} because soil flux to or from the ground was assumed not to have significant impact to the model for simplicity as mentioned before.

D was given as:

$$D = (1 - RH_{GH}) \times \left(\frac{217.0\, e_s}{T_{SP} + 273.15}\right) \tag{40}$$

where RH_{GH} was the relative humidity inside greenhouse, which was assumed to be 0.65 during daytime and 0.8 during night time, and T_{SP} was the saturated vapor setpoint temperature inside greenhouse.

The following equations were used to determine psychrometric constant and resistances as:

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_b}\right) \tag{41}$$

where γ (g m^{-3} K^{-1}) was the psychrometric constant, r_c (s m^{-1}) was the crop resistance; r_b (s m^{-1}) was the aerodynamic resistance of the crop, and

$$r_c = \frac{r_s}{L}, \quad r_b = \frac{r_a}{2L} \tag{42}$$

where r_s (s m^{-1}) was the stomatal resistance, L was the leaf area index, and r_a (s m^{-1}) was the aerodynamic resistance of the leaf. L was estimated at $c_{lar}(1 - c_\tau)X_{sdw}$ following Van Henten (1994).

$$r_a = 840\sqrt[4]{\frac{d}{|T_l - T_{sp}|}} \tag{43}$$

where T_l (°C) was the leaf temperature, T_{sp} (°C) was greenhouse air temperature assumed to be the constant setpoint values described already, d (assumed 0.14 m) was the characteristic dimension of the leaf, which was the average between the length and the width of free standing leaves. The difference of the air temperature and leaf temperature was assumed to be constant 2 °C.

Psychrometric constant γ and its atmospheric pressure was given by the following equation (Allen, Pereira, Raes, & Smith, 1998).

$$\gamma = \frac{c_p\, P}{\varepsilon\, \lambda} \tag{44}$$

$$\mathrm{P} = 101.3\left(\frac{293 - 0.006z}{293}\right)^{5.26} \tag{45}$$

where P (kPa) was atmospheric pressure, λ (2.45 MJ kg^{-1}) was latent heat of vaporization, c_p (1.013 10^{-3} MJ kg^{-1} C^{-1}) was specific heat at constant pressure, ε (0.622) was the molecular weight ratio of water vapor and dry air, and z (m) was the elevation above sea level. The default value of z was 700 m.

r_s was:

$$r_s = 164\left(\frac{31.029 + I_s}{6.740 + I_s}\right)\left(1 + 1.011(D - 3)^2\right)\left(1 + 0.016\left(T_{sp} - 16.4\right)^2\right) \tag{46}$$

where I_s (W m^{-2}) was the shortwave irradiance inside greenhouse, same as I_{plant}.

s (g m^{-3} K^{-1}) was given by (Zotarelli & Dukes, 2010):

$$s = \frac{4098\left(610.8\exp\left(17.27T_{sp}/\left(T_{sp} + 273.3\right)\right)\right)}{\left(T_{sp} + 273.3\right)^2} \tag{47}$$

R_n (W m^{-2}) was determined using the following equation (Stanghellini, 1987).

$$R_n = 0.86\left(1 - exp(-0.7L)\right)I_s \tag{48}$$

By substituting all these equations and values for Equation 31, Q_V at each hour was finally calculated. In the next step, the economic cost for heating (negative Q_V value) and cooling (positive Q_V values) were calculated assuming the efficiency of heating and cooling equipment.

2.3.8. Lettuce sales

When iterating for crop fresh weight (FW, g m^{-2}) each time period for the whole simulation period, the model harvested lettuce when the fresh weight per head FW_{head} (g head^{-1}) reached at the harvested fresh weight $FW_{headHarvest}$ (200 g head^{-1} by default) within the next 24 hours. After calculating the total $FW_{harvest}$ (kg) at each harvest by multiplying the crop density d_{plant} (assumed 25 head m^{-2}) and $S_{cultivation}$ (m^2) with FW_{head}, the total lettuce sales price for whole simulation period $Sales_{lettuceTotal}$ (USD) was obtained by multiplying lettuce sales price per kg $Sales_{LettucePerKg}$ (USD kg^{-1}) with $FW_{harvest}$ (kg). Thus, $Sales_{lettuceTotal}$ was calculated as:

$$\text{Sales}_{\text{lettuceTotal}} = \text{Sales}_{\text{LettucePerKg}} \sum_{\text{day}=1}^{\text{DAYS}_{\text{simulation}}} \left(FW_{head} \times d_{plants} \times \text{S}_{\text{cultivation}} / 1000\ g\ kg^{-1} \right) \tag{49}$$

When lettuce is sold per head, $\text{Sales}_{\text{headLettuce}}$ (USD head^{-1}) should be used instead of $\text{Sales}_{\text{LettucePerKg}}$. In this case, $\text{Sales}_{\text{lettuceTotal}}$ was:

$$\text{Sales}_{\text{lettuceTotal}} = \text{S}_{\text{cultivation}} \sum_{\text{day}=1}^{\text{DAYS}_{\text{simulation}}} d_{plant} \times \text{Sales}_{\text{headLettuce}} \tag{50}$$

In the model, it was assumed the lettuce was sold per head, and not sold when the head weight was not more than 90 % of $\text{FW}_{\text{headHarvest}}$ by terminating the cultivation dues to the end of simulation and the start of the summer period.

To simulate the sales per head at Arizona in the US, the price per head $\text{S}_{\text{headLettuce}}$ (1.99 USD head^{-1} for "Lettuce, Other, Boston-Greenhouse") was cited from USDA (https://www.ams.usda.gov). $\text{FW}_{\text{headHarvest}}$ was assumed to be 200 g referring to Hannaone.com (https://hannaone.com/Recipe/weightlettuce.html), Biowish Technologies (https://biowishtechnologies.com/) indicating around 5.5 g dry weight for bibb, 6.2 g dry weight for bouquet, and 8 g dry weight for romaine lettuce, and Brechner and Both (1996) mentioning 150 g fresh weight as a marketable head weight in general.

2.3.9. Lettuce cost for labor

The cost for lettuce production highly depends on the market condition of each location (e.g. labor market, financial market, electricity market). The default cost $\text{Cost}_{\text{lettuceTotal}}$ (USD) was calculated as below.

$$\text{Cost}_{\text{lettuceTotal}} = \text{Cost}_{labor} + \text{Cost}_{coolingEle} + \text{Cost}_{NG} \tag{51}$$

where Cost_{labor} (USD) was the labor cost for lettuce cultivation, $\text{Cost}_{coolingEle}$ (USD) was the cost of electricity for running pad and fan cooling system, and Cost_{NG} (USD) was that of natural gas for running heating system in greenhouse. The Cost_{labor} (USD) was calculated with the necessary labor per 10000 kg yield $Labor_{lettuce}$ (0.315 person (10000 kg)$^{-1}$) from Eaves and Eaves (2018) and the hourly wage per person Wage (12.8 USD person^{-1} hour^{-1}) was from "Occupational Employment and Wages in Tucson — May 2017" in United States Department of Labor (https://www.bls.gov/). The working hour per day was assumed to be 8 hours per day.

$$\mathrm{Cost}_{labor} = \sum_{\mathrm{day}=1}^{\mathrm{DAYS_{simulation}}} \mathrm{FW_{harvest}} \times \mathrm{Labor_{lettuce}} \times Wage \times 8 \tag{52}$$

2.3.10. Lettuce cost for heating and cooling

Heating and cooling energy for lettuce cultivation was calculated based on Q_V (heating when Q_V was negative (Q_{VHeat}) and cooling when Q_V was positive (Q_{VCool})), economic energy cost and the efficiency of heating and cooling equipment which was assumed from a general natural gas heating system and pad and fan cooling system. From Amer, Boukhanouf and Ibrahim (2015), the coefficient of performance (COP) of pad and fan cooling system ($COP_{padAndFan}$) was assumed to be 15, and electricity cost ($Cost_{monthlyRetailEle}$) was assumed to be same as the monthly electric sales price ($Sales_{monthlyRetailEle}$). Thus, the equation for cooling cost was:

$$\mathrm{Cost}_{coolingEle} = \sum_{\mathrm{day}=1}^{\mathrm{DAYS_{simulation}}} Cost_{\mathrm{monthlyRetailEle}} \times \sum_{hour=1}^{hour_{end}} \left(Q_{VCool}/COP_{padAndFan}\right) \tag{53}$$

The heating efficiency was assumed to be 0.9 (c_{heater}) from American Gas Association (https://www.aga.org/), which mentioned that top-of-the-line furnaces achieved efficiency levels of more than 90 percent. The price of natural gas delivered to residential consumers at Arizona $Cost_{\mathrm{monthlyGas}}$ (USD ft^{-3}) was cited from U.S. Energy Information Administration (https://www.eia.gov/dnav/ng/hist/n3010az3m.htm), and volumetric energy conversion ratio of natural gas $C_{MJPerm3}$ (38.7 MJ m^{-3}) was from Natural Gas Conversion Guide by International Gas Union (IGU) (http://agnatural.pt). Integrating these numbers, Cost_{NG} was given:

$$\mathrm{Cost}_{NG} = \sum_{\mathrm{day}=1}^{\mathrm{DAYS_{simulation}}} Cost_{\mathrm{monthlyGas}} \times \sum_{hour=1}^{hour_{end}} \left(Q_{VHeat} \times c_{heater}\right) \tag{54}$$

The depreciation of greenhouse land and all equipment (e.g. cooling system, heating system, covering material) and the cost for purchasing plant seed and seedlings were assumed to be zero because these factors completely depends on individual simulation conditions (these may not be significantly large in the whole cost).

2.3.11. Total economic profit and loss

Finally, by summing the result from each sale and cost model of electric energy and lettuce, the total economic profit was obtained by the following equation.

$$\mathrm{Profit_{plant}} = \mathrm{Sales}_{lettuceTotal} - \mathrm{Cost_{lettuceTotal}} \tag{55}$$

$$\mathrm{Profit_{ele}} = \mathrm{Sales_{ele}} - \mathrm{Cost_{ele}} \tag{56}$$

$$\mathrm{Profit_{all}} = \mathrm{Profit_{plant}} + \mathrm{Profit_{ele}} \tag{57}$$

where $\mathrm{Profit_{plnat}}$ (USD) was the profit made by plant yield, $\mathrm{Profit_{ele}}$ (USD) was the profit made by electricity yield, and $\mathrm{Profit_{all}}$ (USD) was the total profit obtained for the whole simulation period.

2.4. Optimization description

The study evaluated the end date of shading curtain deployment in spring ($\mathrm{Date_{endSpring}}$), the start date in fall ($\mathrm{Date_{StartFall}}$) and and OPV coverage ratio (r_{PV}) as parameters for optimization which aimed to maximize $\mathrm{Profit_{all}}$ (USD) per greenhouse floor area S_{GH} (m^{-2}). The summer period when lettuce crop is not cultivated was defined as the period between $\mathrm{Date_{endSpring}}$ and $\mathrm{Date_{startFall}}$ (e.g. if $\mathrm{Date_{endSpring}}$ is April 30 and $\mathrm{Date_{startFall}}$ is September 1st, the summer period starts from May 1st and ends on August 31st). For the convenience in optimization coding, the first two parameters were defined to be the number of days from the simulation start date, January 1st, 2015. For example, if the spring period was defined from March 16th to May 31st, $\mathrm{Date_{endSpring}}$ was 151 (31 days in January, 28 days in February, 31 days in March, 30 days in April, and 31 days in May).
The MIDACO solver (http://www.midaco-solver.com/) was used as a solver for optimization. It can solve mixed integer non-linear programming (MINLP) problem by combining an extended evolutionary Ant Colony Optimization (ACO) algorithm with the Oracle Penalty Method for constrained handling. Since this solver is a meta-heuristic algorithm, it is not guaranteed to converge into the globally optimal solution, but it "can optimize complex real world applications

in a reasonable time to a reasonably good solution." (MIDACO-SOLVER, 2018). All the 13 parameters but FOCUS for the solver were set as the default values. FOCUS was changed between 0 and 20 to let the solver find the optimal solution. The parameter controls the solver's search focus around the current best solution. If it is small (e.g. 10, 100), the solver searches the wider range of parameters from the current best solution. As it becomes large (e.g. 10000, 100000), it searches only close scope from the current solution. The detail of the other parameters is written at its user manual (http://www.midaco-solver.com/index.php/download).
The objective function, constraints and bounds of the problem was shown in Fig. 10. The definition of each symbol was mentioned in the Nomenclature.

3. Results and discussions

3.1. Model validations

3.1.1. Atmospheric transmissivity (p) decision and validation of solar irradiance to tilted PV

As a preparation of the validation, an appropriate p value (atmospheric transmissivity) was determined by comparing the total hourly solar irradiance in 2015 (Table 2).

The horizontal measured irradiance was the raw data from the local weather station. Since the horizontal estimated irradiance became less than that of horizontal measured value ($1.90 \times 10^6 < 2.03 \times 10^6 < 2.21 \times 10^6$) when p value changed from 0.7 to 0.6, a proper value would be between these values, which was calculated to be 0.643 assuming the solar irradiance between p = 0.6 and 0.7 linearly changed.

The model for solar irradiance to tilted PV modules was validated comparing the estimated solar irradiance with measured irradiance obtained from the local weather station. The results were compared for both horizontal surface and tilted surface respectively, with greenhouse tilt angles assumed to be that of modeled greenhouse roof. For tilted surface, the overall solar irradiance was derived by averaging I_T (W m^{-2}) to east and west facing roofs. Fig. 5 showed the correlation of estimated and real solar irradiance to horizontal surface while Fig. 7 showed correlation of the estimated and real solar irradiance to horizontal surface choosing only sunny days per month. Fig. 6 and 8 presents correlation of the estimated and real solar irradiance to tilted surface considering all days and only clear sunny days, picked only one day from each month, respectively. In all cases, the model predictions were reasonably acceptable.

3.1.2. Transmittance through multi-span greenhouse roof

The estimated transmittance through multi-span greenhouse roof are shown in Fig.9 on a 1st days of four months in 2015.Overall, the transmittance ranged from 0.8 to 0.9 during daytime, and 0.2 to 0.7 during a couple of hours at sunrise and sunset. Sabeh, Higgins, Kuack and Millett (2014) reported single PE transmittance 0.85-0.9 while the shape of the transmittance curve presented in Fig. 9 were similar to those reported by Soriano et al. (2004). Therefore, the model prediction accuracy for greenhouse cover transmittance was acceptable.

3.1.3. Lettuce growth model

The estimated lettuce fresh weight per head (FW_{head} (g head^{-1})) was compared with the fresh crop weight measured by Kacira et al. (2017) with five cultivars under the same climatic conditions. The r_{PV} was assumed to be 0.2 to calculate the solar irradiance to lettuce. The data showed that the estimated fresh weight (blue line) was within the one standard deviation from the mean fresh weight of Magenta and Cherokee. However, it was quite higher than the fresh weight of Salanova Red Butterhead, Salanova Red Incised and Rex Green Butterhead. From this result, it could be said that the model estimated significantly precise final fresh weight for large size cultivars, but some further adjustments might be required for the model if medium or small size cultivars are considered for the study.

3.1.4. Energy balance

Fig. 11. through 15 shows the contributions of each heat flux terms in the greenhouse energy balance. January 1st and 30th, April 1st, July 1st and October 1st were chosen to describe how each term could fluctuate depending on plant growth level, season and shading curtain. Following the sign rule at Equation 31, positive Q_V meant cooling the greenhouse and the negative meant the heating, positive Q_{SR} meant adding heat energy as solar irradiance, and positive Q_{LH}, Q_{SH}, Q_{LW},

were removing heat energy out of greenhouse and the negative values were adding heat into greenhouse. The r_{PV} was assumed to be 0.2 to calculate the solar irradiance inside greenhouse. The difference between Fig. 11 and 12 showed how the latent heat by transpiration changed as the crop was growing. When it was just begun to be planted, no cooling by transpiration was observed. However, on two days before the predicted harvest date, the latent heat increased more than 300 W m^{-2} at the peak during the day time (Fig. 12). Shading curtain was deployed from 8:00 to 17:00, for the whole daytime, and 11:00 to 15:00 in Fig. 13,14, and 15 respectively. It was observed that due to shade curtain deployment and OPV coverages, the solar irradiance in the greenhouse (Q_{SR}) for all periods were reasonably decreased to similar average levels. (about 300 to 400 W m_{-2} during daytime). The dynamic changes in the sensible heat (the yellow line) was mainly due to the dynamics of the outside weather conditions relative to the assumed greenhouse climate setpoints and latent heat from the plans. In fact, it was observed that the sensible heat was more positive indicating that heat loses occurred from the greenhouse to outside in the winter season (Fig. 11 and 12) and negative, meaning the greenhouse gains heat due to convection and conduction during the hot season (Fig. 13 to 15).

Overall, the model estimated reasonable energy for cooling and heating for whole simulation period considering all the anticipated factors such as crop transpiration, the seasons, and shading curtain effect.

3.2. Model results and discussion: plant and electric energy yield

The model determined the lettuce crop yield and electricity production based on OPV coverage ratios. The following three cases were simulated (Table 3): Case1, 100% OPV module coverage and no crop production during the summer period (1 June to 15 September), Case2, 50% OPV module coverage during the summer period with crop production, Case3, 100% OPV module coverage during summer with crop production. The coverage ratio during the cultivation period (all days except the summer period) was changed from zero to 100 %. The deployment time of shading curtain each month was updated with each OPV coverage ratio. This result shows the model can also be used for decision making on various OPV coverage ratios, effect on crop yield and energy production when focusing on these yields rather than their economic values.

The resulting crop yield (kg m^{-2}) and electricity production (kWh m^{-2}) per greenhouse floor area

under varying r_{PV} between 0 (not OPV on the roof) and 1.0 (fully covered by OPV film) in the three cases are shown in Fig. 16. The unit of crop yield was changed by multiplying the plant density (25 head m^{-2}) with the harvested lettuce heads and its weight. Case 2 and 3 produces almost same quantity of lettuce per area, which was higher than that of Case 1. The other calculation and parameters followed in the previous equations and Nomenclature.
The generated electricity in Case 1 and 3 were completely same which is because the solar irradiance which OPV film receives does not change whether lettuce is grown in summer or not; The amount electricity was same in Case 1 and 3. The reason why the crop yield in Case 2 and 3 were very close even though the OPV coverage ratio during the summer was different (0.5 and 1.0) would be because this difference did not have enough impact to save time for another cultivation cycle. As mentioned before, following the sales custom of greenhouse lettuce, the crop is sold per head instead of weight (if the final fresh weight is less than 90 % of the pre-defined fresh weight, the yield is abolished). Thus, it is possible the total yield does not change just by the last cultivation period increase a little which is not enough for the final fresh weight exceeds 90%. Another discovery was the total crop yield did not almost change from r_{PV} = 0 to r_{PV} = 1.0. It could highly possible to happen that the number of cycles decrease somewhere between the range and the yield suddenly decreased because the transmittance of the OPV film was assumed to be only 30 %. The reason would be the film's affect was mitigated by shading curtain: as r_{PV} increased, the shading curtain deployment time decreased. If the outer solar irradiance, the target average DLI level (17 mol m^{-2} sec^{-1}) and/or the OPV transmittance were changed, the results could be different.

Based on the preference of yield-electricity balance, growers can simulate a preferable OPV coverage ratio depending on their energy and plant produce yield demand.

3.3. Optimization results and discussion

The optimization results of two scenarios (growing and not growing lettuce in summer) were presented in Tables 3 to 5. The optimization computations were conducted starting from three different initial values – ($Date_{endSpring}$ = 1, $Date_{startSpring}$ = 1, and r_{PV} = 0.0), (183, 183, and 0.5), and (365, 365, and 1.0) to explore the optimal condition where the profit increase by electricity production and the decrease by crop yield delay and reduction were the most balanced. It took around 15 minutes for each optimization to process until the objective function converges (less than 500 iterations depending on the initial parameters). If more detailed optimizations were necessary after analyzing the results, more computations with different initial decision values would be conducted (e.g. (183, 183, and 0.0), (1, 1, and 0.5) and (92, 92, and 0.25)). Each scenario was run several times, and all results except those of not growing summer staring from (183, 183, and 0.5, the first row in Table 4) provided very close outputs for each iteration. The PV module coverage ratio in the summer period was same as that of cultivation season in this optimization simulation. The initial purchase costs of the OPV modules and shading curtains were not considered in this analysis. When assuming not growing lettuce in summer (the second scenario in each table), the parameter $Date_{endSpring}$ and $Date_{startFall}$ can be ignored because the crop is cultivated during the whole year whatever the summer period is.

The results revealed that the scenarios where the initial parameters (($Date_{endSpring}$, $Date_{startSpring}$, and r_{PV})) started from 183, 183, and 0.5 showed the best case (the second scenario in Table 4), maximizing the objective function ($Profit_{All}$ / S_{GH} = 460.5 USD m^{-2}), and the second largest scenario was growing in summer and the initial parameters started from 1, 1, and 0.0 (the second scenario in Table 3).

When running the solver assuming not growing summer starting from (183, 183, and 0.5) (the first case in Table 4), the optimization results varied at each computation. The range of the objective function and r_{PV} were 305.6 to 460.5 and 0.574 to 0.882. The $Date_{endSpring}$ and $Date_{startFall}$ were also highly variable. For instance, the solver sometimes indicated starting shading in March and ending in April and around 100 days summer period in other running. This might be because there could be some or various plateaus, ridges and local maxima around the initial starting points. The important point and objective for the current study was to determine a coverage ratio and production scenario that provided the largest economic profit as the globally optimal solution, which was observed when the initial starting point for the computations were 183, 183, and 0.5, (the second case in Table 4).

Fig. 17 and 18 shows the transitions of $Profit_{All}$ / S_{GH} against r_{PV} when fixing $Date_{endSpring}$ and $Date_{startFall}$ with the derived values at the first column in Table 3 (not growing in summer) and the second column in Table 4 (growing in summer), which supported the optimization results in the tables. Since the summer period was ignored when assuming growing lettuce in summer, Fig. 18 was common in all the cases when growing crops in summer in Table 3 to 5.

Fig. 17 indicated that, as the OPV coverage ratio (r_{PV}) increased, the total economic profit per area

($Profit_{All}$ / S_{GH}) gradually increased whether it was assumed to grow lettuce in summer or not. This was caused by the increase in electricity profit. The reason why the economic profit did not decrease at high coverage ratio due to the reduction of solar irradiance to crops would be because the shading curtain was deployed less frequently as r_{PV} increased, which equalized the overall solar irradiance at any coverage ratio. On the other hand, Fig. 18 exhibited a sudden reduction of the profit when r_{PV} was increasing to around 0.5. This change would have been caused by the reduction of cultivation cycle producing more than 90 % of the defined head weight (final target fresh weight of 200 g was assumed) (Fig. 19). In the simulations, the harvesting rule was implemented that if the fresh head weight before the summer period or the end of simulation was less than 90 % of the required head weight, then the crop was harvested. Decrease in the solar irradiance to lettuce and increase in OPV coverage ratio results in the time increase for the crop to grow to the expected harvest weight. Thus, the immediate reduction would have happened when the last cultivation cycle's fresh weight became less than 90 % of the harvest fresh weight.
It is also important to note that the impact of electricity generation and the revenue generated by its sales is much smaller than the profit generated from lettuce crop sales with the assumed OPV specifications in this study for the total economic profit because of the difference of impact to the total economic profit from the increase in r_{PV} and from the reduction of one cultivation cycle.

Comparing $Profit_{All}$ / S_{GH} along with the r_{PV} when not growing lettuce in summer (Table 3 to 5), the objective function corresponded well with the results presented in Fig. 19. When r_{PV} was less than 0.5 the $Profit_{All}$ / S_{GH} was around 455 to 460 with a small increment and when r_{PV} was more than that, the $Profit_{All}$ / S_{GH} declines to about 415 (the second row in Table 5).
The data presented in Tables 3 and 4 also implied the importance of the initial values selected for the optimization process. With the default parameter settings as discussed earlier, the solver may not return the global solution but concentrate on the local optimal points (e.g. the second row in Table 5) or the computation may take too long time to reach the global optimal solution (e.g. growing in summer in Table 3). Assigning small values to FOCUS (e.g. 10, 100) instead of the default value (i.e. 0, indicating dynamically increasing the parameter as the process proceeds) can be a way to mitigate this problem, but still repetitive try and error with different parameter combinations at the solver and reasonable interpretation are necessary to find an appropriate global solution with confidence.

From Tables 3 and 4, it is highly probable that it would make more profit to cultivate crops in summer even at the semi-arid region (Arizona) because the objective function when growing in summer was always higher than or almost equal to that when not growing in summer, and the optimized summer period when not growing crops was extremely short. To confirm it is better to grow crops in summer and the global solution is the condition of the second row at Table 4 (growing in summer with 58% OPV coverage ratio), other two optimization analyses were conducted. Tables 7 and 8 showed the result when the initial point was (183, 183, 1.0) and (183, 183, 0.0) respectively. FOCUS was set to be 10 to let the solver explore wider range of the parameter combinations. The objective functions in tables were smaller than that of the currently best case, and the optimized summer period was short like the previous conditions. Therefore, it would be reasonable to conclude the second row at Table 4 is the global solution.

4. Further Improvement

The developed simulator is flexible enough to investigate the profitability at various economic and environmental conditions as exemplified at the results and discussions section. However, the following factors can be considered to make the model and optimization more extensible and realistic:

- photoinhibition and tipburn
- Economic value penalization by tipburn
- The influence of shade made by other spans at multi-span roof: If the shade covers PV module, the electricity yield would be reduced.
- Greenhouse air temperature: The cooling efficiency by evaporative pad and fan based cooling system depends on outside climate, and it is possible the system's efficiency for cooling might be limited under hot and humid conditions or not being able to maintain very low setpoint temperatures.
- The characteristics of lettuce cultivar: The plant growth model should be modified depending on what lettuce cultivars the users grow because the mature size and the resistance to the environment can be significantly different.
- Longer simulation period: If longer (more than one year) weather station data without missing data is available, the variability of the weather conditions can be considered by calculating the standard deviation on the same day each year.

- More parameters for optimization: Depending on the user's interest, more parameters can be adopted such as the expected harvest fresh weight, spring start date and fall end date (if the shading curtain was assumed to be deployed only during the spring and fall seasons).

5. Conclusion

A comprehensive simulation model was developed which estimates the overall economic profit of lettuce crop production in a greenhouse integrated with OPV film as part of the greenhouse cover. The model calculated the solar irradiance to a tilted surface, electric energy generated by OPV modules installed on greenhouse roof, transmittance through multi-span greenhouse roof, solar irradiance to lettuce in the greenhouse, the growth of lettuce yield, energy consumed by cooling and heating, cost and sales of electric energy and lettuce respectively, and finally the total economic profit. The model enabled evaluating various organic PV coverage ratios as well as traditional inorganic PV module by changing the model specification.

The model was used for optimization analysis to determine the crop cultivation period and OPV module deployment strategy. Thus, the analysis considered the range of summer cultivation periods and OPV module coverage ratio on the roof for maximizing the overall economic profit. For this analysis, MIDACO solver (http://www.midaco-solver.com/) was used as an optimization solver.

The simulations were performed for one year period considering the 2015 local climate date for Tucson, Arizona. The optimization results revealed that the overall profitability could increase if lettuce crop is continued to be cultivated during summer even considering the cost increase by labor and cooling. At the economically optimal conditions, the coverage ratio on the roof of PV module was at less than 58.0% when its purchase price was assumed to be zero, with 4.3% cell efficiency (Lucera et al, 2017), 30 % visible light transmittance, and 0.02% temperature coefficient, and the selling price of generated electricity was same as the purchase price, which was around 0.11 to 0.12 USD kWh^{-1} in Arizona. In addition to the specification of the given OPV film and the optimized factors, there are various factors that can also be considered such as OPV module body temperature, OPV degradation, depreciation period and method, greenhouse air temperature set points, humidity and CO_2 concentration, lettuce selling price, labor cost.

The results of this study illustrated that Agrivoltaics can potentially improve the profitability in greenhouse-based farming if OPV and shading curtain are strategically implemented and help minimizing competition for land use between power generation and food production while the economic impact of electricity production was still significantly smaller than that of lettuce. However, reasonable assumptions were made in this current study for optimization and modeling. Thurm further study would be necessary to evaluate other factors with different environment and market data.

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Fig. 1 - Physical dimensions (in meters) of the modeled greenhouse per span. A 10-span gutter connected greenhouse was modelled in the study.

Fig. 2 - Overall flow of the integrated model

Fig. 3 - Visual relationship of the solar altitude angle (α)the solar incident angle (γ), the angle between the perpendicular vector component of the solar radiation (red line) and the horizontal axis perpendicular to the greenhouse span (①, the angle E), the incidence angle of E (②, γperpendicular), and the absolute difference of module azimuth angle and solar azimuth angle (③, |ψp – ψs |). The green rectangle place was supposed to be a greenhouse roof.

Fig. 4 - The objective function, constraints and bounds of the problem.

Fig. 5 - Correlation of the model predicted and measured solar irradiance to horizontal surface.

Fig 6 - Correlation of the model predicted and measured solar irradiance to tilted surface.

Fig 7 - Correlation of the model predicted and measured solar irradiance to horizontal surface, choosing only sunny days per month.

Fig 8 - Correlation of the model predicted and measured solar irradiance to tilted surface, choosing only sunny days per month.

Fig 9 - Transmittance through multi-span roof on January (blue), April (orange), July (gray), and October (yellow) 1^{st}.

Fig. 1 - Comparison of the estimated fresh weight with the measured weights by Kacira et al. (2017). The vertical lines indicate standard deviation from the mean fresh weight.

Fig. 11 - Transition of energy balance elements on 1st January 2015, just started cultivating the crop, which makes little transpiration. No shading curtain was deployed.

Fig. 2 - Transition of energy balance elements on 30th January 2015, two days before harvesting the crop. No shading curtain was deployed.

Fig. 13 - Transition of energy balance elements on 1st April 2015. The shading curtain was deployed from 8:00 to 17:00.

Fig. 3 -Transition of energy balance elements on 1^{st} July 2015. The shading curtain was deployed for the whole day time.

Fig. 4 - Transition of energy balance elements on 1^{st} October 2015. The shading deployment time was from 11:00 to 15:00

Fig. 5 - Harvested lettuce fresh weight and electric energy produced by PV module at each PV coverage ratio.

Fig. 6 - The total economic profit per greenhouse floor area against OPV coverage ratio, fixing the summer period from 2^{nd} to 7^{th} January (not growing lettuce in summer in Table 3).

Fig. 7 - The total economic profit per greenhouse floor area against OPV coverage ratio, fixing the

summer period from 5th July to 14th July (growing lettuce in summer in Table 3 to 5).

Fig. 8 - Lettuce fresh weight per head at each simulation day (r_{PV} = 0.5). The blue dots are for the fresh weight per head each day and the orange dots are for the increase of fresh weight during each day.

Table 1 - Advantages and disadvantages of OPV modules

Advantages		Disadvantages	
1	Lower manufacturing cost	1	Small cell efficiency
2	Easy tunability of light absorbing spectrum color schemes and thickness	2	Unstable cell efficiency and (short) lifetime in real environment (almost no measurement has been conducted)
3	Low environmental impact during manufacturing and operations		

Table 2 - Atmospheric transmissivity and solar irradiance to horizontal to tilted surface

P	Solar irradiance (W m$^{-2)}$			
	Horizontal		Tilted	
	Estimated	Measured	Estimated	Measured
0.8	2.53E+06	2.03E+06	2.26E+06	2.40E+06
0.7	2.21E+06	2.03E+06	1.97E+06	2.03E+06
0.6	1.90E+06	2.03E+06	1.68E+06	1.70E+06

Table 3 - Three cases of cultivation and PV module deployment in the summer period (June 1 to September 15)

	coverage ratio (fixed)	grow lettuce?
Case1	1.0	No
Case2	0.5	Yes
Case3	1.0	Yes

Table 4 – Optimization results with two scenarios, growing lettuce in summer or not and sell it per head starting from 1, 1, and 0.0 as initial values.

Grow in summer?	$Profit_{All}$ / S_{GH} (USD m^{-2})	r_{PV}	$Date_{endSpring}$	$Date_{startFall}$
No	421.3	0.986	2 (2nd Jan)	7 (7th Jan)
Yes	458.9	0.230	4 (4th Jan)	6 (6th Jan)

Table 5 - Optimization results with two scenarios, growing lettuce in summer or not and sell it per head starting from 183, 183, and 0.5 as initial values.

Grow in summer?	$Profit_{All}$ / S_{GH} (USD m^{-2})	r_{PV}	$Date_{endSpring}$	$Date_{startFall}$
No	305.6 to 460.5	0.574 to 0.882	Unfixed	Unfixed
Yes	460.5	0.580	186 (5th July)	195 (14th July)

Table 6 - Optimization results with two scenarios, growing lettuce in summer or not and sell it per head starting from 365, 365, and 1.0 as initial values.

Grow in summer?	$Profit_{All}$ / S_{GH} (USD m^{-2})	r_{PV}	$Date_{endSpring}$	$Date_{startFall}$
No	419.9	1.0	362 (28th Dec)	364 (29th Dec)
Yes	418.8	0.992	362 (28th Dec)	364 (29th Dec)

Table 7 - Optimization result when not growing lettuce in summer and sell it per head starting from 183, 183, and 1.0 as initial values (FOCUS = 10).

Grow in summer?	$Profit_{All}$ / S_{GH} (USD m^{-2})	r_{PV}	$Date_{endSpring}$	$Date_{startFall}$
No	420.7	0.99	166 (15th Jun)	176 (25th Jun)

Table 8 - Optimization result when not growing lettuce in summer and sell it per head starting from 183, 183, and 0.0 as initial values (FOCUS = 10).

Grow in summer?	$Profit_{All}$ / S_{GH} (USD m^{-2})	r_{PV}	$Date_{endSpring}$	$Date_{startFall}$
No	418.3	0.059	153 (2nd Jun)	167 (16th Jun)