

ABSTRACT

HOLLINGSWORTH, JOSEPH ARDEN. Environmental and Economic Impacts of Solar Powered Integrated Greenhouses. (Under the direction of Dr. Joseph DeCarolis, Dr. Jeremiah Johnson).

Greenhouse vegetable production plays a vital role in providing year-round fresh vegetables to global markets, achieving higher yields and using less water than open-field systems, but at the expense of increased energy demand. This study examines the life cycle environmental and economic impacts of integrating semi-transparent organic photovoltaics (OPVs) into greenhouse designs. Life cycle assessment (LCA) is used to analyze six environmental impacts associated with producing greenhouse-grown tomatoes in a Solar PoweRed Integrated Greenhouse (SPRING) compared to conventional greenhouses with and without an adjacent solar photovoltaic array, across three distinct locations. The SPRING design produces significant reductions in environmental impacts, particularly in regions with high solar insolation and electricity-intensive energy demands. For example, in Arizona, global warming potential (GWP) values for a conventional, adjacent PV, and SPRING greenhouse are found to be 3.71, 2.38, and 2.36 kg CO₂ eq/kg tomato, respectively. Compared to a conventional greenhouse, the SPRING design may increase life cycle environmental burdens in colder regions because the shading effect of OPV increases heating demands. This analysis shows that SPRING designs must maintain crop yields at levels similar to conventional greenhouses in order to be economically competitive. Assuming consistent crop yields, uncertainty analysis shows average net present cost of production across in Arizona to be \$3.43, \$3.38, and \$3.64 per kg of tomato for the conventional, adjacent PV, and SPRING system, respectively.

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Environmental and Economic Impacts of Solar Powered Integrated Greenhouses

by
Joseph Arden Hollingsworth

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APPROVED BY:

Dr. Joseph F. DeCarolis
Co-Chair of Advisory Committee

Dr. Jeremiah Johnson
Co-Chair of Advisory Committee

Dr. S. Ranji Ranjithan

Dr. Brendan O'Connor

DEDICATION

To my high school AP Biology and AP Chemistry teacher, Dr. Marilyn Stephens, who taught and inspired me for two of my most formative years. If not for your classes, I do not believe I would have sought to continue education in the field of science and engineering. Thank you so much for your incredible courses, advice, and guidance during those years.

BIOGRAPHY

Joe was born in Tuscaloosa, Alabama in 1992 where he was raised, attended high school, and college. He is the youngest between himself and his older sister, Elizabeth Hollingsworth. His parents, Arden and Madelene Hollingsworth, also grew up in Tuscaloosa where they both attended the University of Alabama. During his high school career, Joe enjoyed playing soccer, camping, hunting, and playing music with friends. Many of his summers were spent working alongside his father at a farm in Boligee, AL. He went on to attend the University of Alabama, where he completed his degree in Civil and Environmental Engineering. During his time at UA, he worked as a co-op student for a year at Brasfield & Gorrie general contractors. Additionally, he was the director of the student government associations environmental affairs. During his time with SGA, he worked to develop student groups focused on increasing recycling rates and energy efficiency around the campus.

Between his experiences working as a co-op student at a large coal power plant and studying abroad to see large renewable energy projects, Joe was compelled to further his education in energy systems. He enrolled in NCSU during the fall of 2017, in the environmental engineering department. Along with working on this thesis, Joe has been a part of a team studying life cycle environmental impacts of shared electric scooters. During his time in Raleigh, he has enjoyed the outdoor activities that North Carolina has to offer such as hiking the Pisgah National Forest and visiting the beaches of Wilmington. Highlights of Joe's studies at NCSU include competing in the Civil Engineering Department's three-minute thesis and winning first place in the EWC symposium poster presentation. Upon graduation, Joe is pursuing a career in renewable energy development.

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Dr. Ranjithan played a significant role in my project with his course on linear programming. Although many of the optimization techniques he taught are not used in this analysis, his course deeply improved my understanding of how to analyze results of a model and how to effectively present results to decision makers.

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CHAPTER 1

1. INTRODUCTION

To feed a global population of 9 billion in 2050, the Food and Agriculture Organization estimates food production will need to increase by 70% (WHO 2009). As the demand for food continues to rise and production of greenhouse vegetables continues to increase, the energy demands required for consistent crop yields will subsequently increase (Ntinas et al. 2017; Cook and Calvin 2005). Although greenhouses can produce yields an order of magnitude higher per unit area than field crops, Barbosa et al. (2015) estimate that energy demands for greenhouse heating and cooling are eighty times the energy required for field grown crops. This large energy requirement often results in higher environmental impacts per unit of product than field grown vegetables (Page, Ridoutt, and Bellotti 2012; Ntinas et al. 2017). Tomatoes are used as a reference crop because it is the most commonly grown greenhouse crop in the United States and is used worldwide for both fresh and processed fruit (i.e., preserved in cans and as juices). Additionally, global tomato production has increased from 116.5 million tons in 2002 to 171 million tons in 2014 (Heuvelink 2018).

Regional climate and crop selection have a direct relationship with the energy and water demand of the greenhouse system (Boulard et al. 2011; Khoshnevisan et al. 2013; Ntinas et al. 2017; Dias et al. 2017). Ntinas (2017) examined seven scenarios of crop production, including five greenhouses designs with different heating systems and notes that heating demand is the primary hotspot for environmental burdens, followed by electricity, structures, and the use of fertilizers. In addition, there is a clear trade-off between greenhouses and open field crops in terms of energy and water use (Page, Ridoutt, and Bellotti 2012; Ntinas et al. 2017). Compared with open field crop production, greenhouses can significantly reduce water use with rockwool

growing media and hydroponic irrigation systems. However, thermal regulation of greenhouses requires higher energy demands and subsequently results in much higher greenhouse gas emissions associated with crop production (Barbosa et al. 2015; Ntinis et al. 2017).

Organic photovoltaics (OPVs) offer the possibility to generate electricity using the greenhouse roof area, and represent an attractive option given their potential to be low cost, lightweight, flexible, and, most importantly, semi-transparent (Lizin et al. 2013; Pearsall 2011). Similar to multicrystalline silicon (mc-Si) PV cells, OPVs consist of multiple layers that include an anode, hole transport layer, active layer, electron transport layer, cathode, and encapsulation substrate layers (Lizin et al. 2013; Jungbluth et al. 2012). Certain polymers allow for semitransparent OPVs with tunable band gaps, and have achieved transmissivity of 25% (Luo et al. 2018). Previous LCAs of OPVs have shown significantly lower energy payback times and cumulative energy demands than silicon-based PV technology, suggesting that this may be an environmentally preferable technology (Yue et al. 2012; A. Anctil et al. 2010; Lizin et al. 2013).

Recently, there have been several OPV-related developments in both the electron donating polymer with the introduction of donor-acceptor polymers, and the electron acceptor with the introduction of alternative non-fullerene small molecules. These innovations have led to a large number of demonstrated OPV cells with efficiencies over 10%, including a recent demonstration of 15% for a single active layer (Yuan et al. 2019). There have also been recent advancements in semitransparent device performance (Li et al. 2018), with power conversion efficiencies of 10% and visible transmittance over 34% (Sun et al. 2019; Li et al. 2018). Additionally, new alternative blend films such as PTB7-Th:IEICO-4F (Liu et al. 2019) and FTAZ:ITM (Ye et al. 2018) also demonstrate high efficiencies. Industrially scalable methods on areas of 60cm² have also been demonstrated with P3HT as the donor material in a

semitransparent device with 5% efficiency (Strohm et al. 2018). Although semi-transparent devices have historically had lower efficiencies than 5%, these recent improvements are used as a reference for this analysis.

The estimated cost of OPV modules and balance of system costs vary widely across the published literature due to heterogeneity in assumptions related to manufacturing processes, efficiencies, and OPV materials (Gambhir, Sandwell, and Nelson 2016; Mulligan et al. 2014). Gambhir (2016) used representative pilot-scale processes and a detailed material inventory to estimate module and balance of system costs of $\$0.23\text{-}0.34/W_p$ and $\$0.66/W_p$, respectively, based on Monte Carlo simulations (MCS) of mass-manufactured OPV modules. This near-term projection is highly competitive with mature PV technologies, which show factory gate module costs of $\$0.35/\text{Watt}$ (Fu et al. 2017). Emmot (2015) considered the decreased crop productivity from lower light entering the greenhouse with OPVs applied to the entire roof area, concluding that the photosynthetic active radiation loss in the OPV integrated greenhouses was too high to be economically viable. However, Loik et al. (2017) examined various cultivars of tomatoes under wavelength selective, semi-transparent PVs (WSPVs), which are designed to remove mostly green and some blue wavelengths of light while transmitting red portions associated with high photosynthetic activity, and found that yields for most cultivars did not show any difference. To assess the efficacy of OPV-integrated greenhouses relative to conventional alternatives, environmental life cycle assessment and a detailed economic evaluation are required. While there have been several LCA studies that focus individually on the environmental impacts of greenhouses, greenhouse crop production, and OPVs (Lizin et al. 2013; Boulard et al. 2011; Khoshnevisan et al. 2013; A. Anctil et al. 2010; Yue et al. 2012; Ntinis et al. 2017; Dias et al. 2017), none have examined a regional comparison of both life

cycle cost and environmental implications of OPV-integrated greenhouses. This study couples environmental and economic assessments to offer new insights into an emerging technology.

This study fills a gap in the literature by providing a detailed economic and environmental assessment of OPV-integrated greenhouses compared to conventional alternatives. Environmental impacts are estimated by performing a cradle-to-farmgate life cycle assessment. Three greenhouse designs are considered: a Solar PowerRed Integrated Greenhouse (SPRING) with OPV as well as conventional greenhouses with and without an adjacent solar photovoltaic array. In addition, the performance of these three systems is tested in three distinct climate zones represented by Arizona, North Carolina, and Wisconsin. Both the SPRING and adjacent PV greenhouses are represented as grid-connected PV systems, using the regional grid connection to provide power at night or when there is not enough PV production to meet demand. However, Appendix 2 examines the techno-economic feasibility of off-grid SPRING designs with battery storage.

2. METHODS

This LCA is conducted according to international standards ISO 14040 and 14044 and include the following phases: (1) goal scope and definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. A cradle-to-farmgate approach is used to compare three greenhouse systems and their associated environmental impacts. The three grid-connected greenhouse systems in this comparative study are (1) a Solar Powered INtegrated Greenhouse (SPRING) utilizing OPV technology, (2) a greenhouse with a co-located, silicon PV array, and (3) a conventional greenhouse, with all electricity demand met by the grid. The functional unit is one kilogram of tomato production.

2.1 Goal and Scope

The goal of this study is to perform an attributional life cycle assessment that characterizes the environmental and economic impacts associated with a SPRING greenhouse compared to a conventional greenhouse with and without an adjacent solar PV array. The resultant analysis allows us to compare the relative performance of the three systems, which can be used to inform the development of future SPRING systems. The system boundary of this study, shown in Figure 1, includes production, manufacturing, and installation of the greenhouse structure, multicrystalline silicon (mc-Si) PV systems, and OPV systems. Also included are specific crop production demands (e.g. energy, water, fertilizer, and packaging), and end-of-life

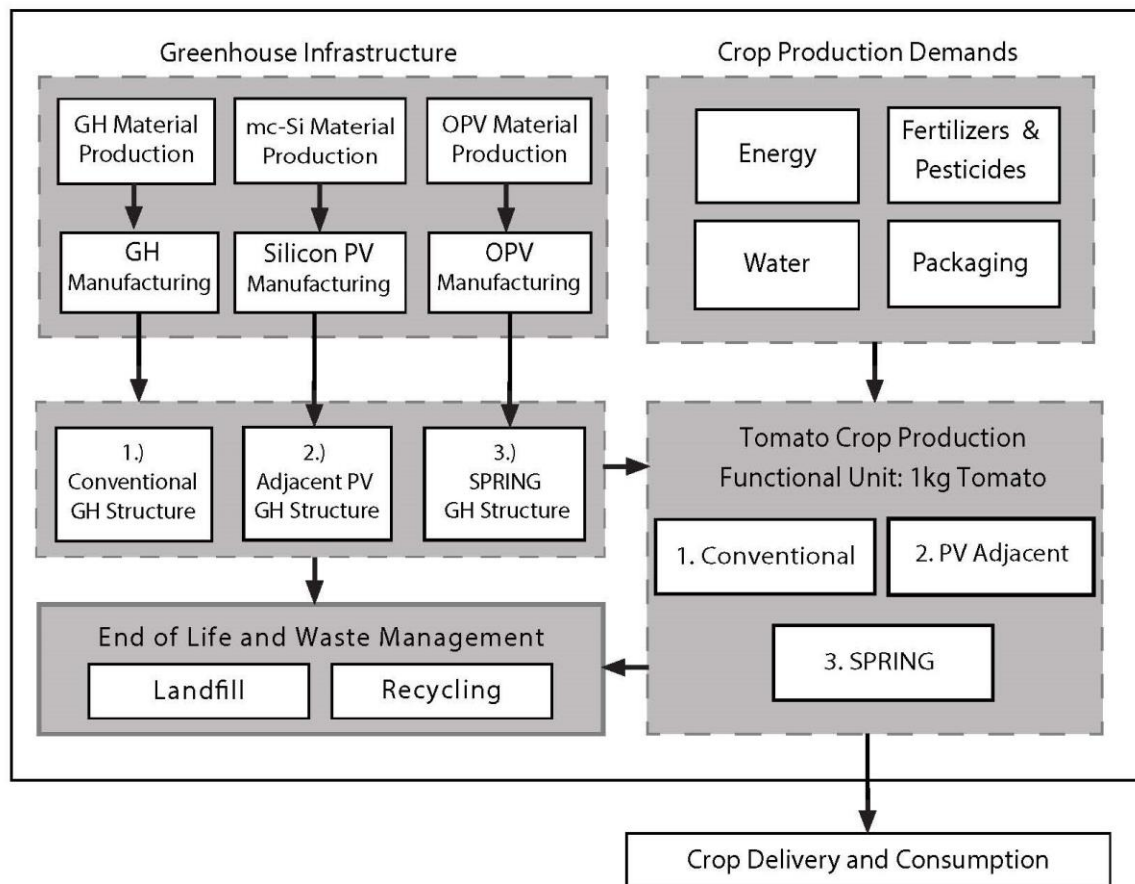


Figure 1 - System boundary for the comparative life cycle assessment of a conventional greenhouse ('Conventional'), mono-silicon adjacent photovoltaic greenhouse ('PV Adjacent'), and Solar PowerRed INtegrated Greenhouse ('SPRING') using organic photovoltaics (OPV)

phases for the greenhouse and PV systems. Transportation to the retailer or wholesaler and end-of-life phase for tomatoes are excluded. Given variations in climate, greenhouses will inevitably have different types of energy demands in various areas of the world. To compare environmental benefits seen from different climates, three locations in the US are examined, consistent with Ravishankar et al. (2019): (1) Phoenix, Arizona (AZ), (2) Raleigh, North Carolina (NC), and (3) Antigo, Wisconsin (WI). AZ represents a hot and dry climate, NC represents a hot and humid climate with mild winters, and WI represents mild summers and extreme cold in the winter. Including each of these locations helps illustrate the importance of climatic diversity when evaluating the environmental benefits from the SPRING system.

2.2 Life Cycle Inventory

Assumed here is a greenhouse area of 214 m², consistent with greenhouse sizes seen in literature specific to greenhouse tomatoes (Snyder, Richard 2016; Marr 1995). Orientation of the arch-roof greenhouse runs north and south with each 27° roof tilt facing east and west. This orientation is typical design practice to avoid uneven sunlight from gutters, trusses, and equipment (Roberts 1998). However, this orientation does not achieve optimal insolation values for the roof-integrated OPV. Compared to a south facing, adjacent PV system, the lower insolation value in the SPRING design requires a higher capacity of OPVs to achieve the same level of generation. Data for the life cycle inventory of the greenhouse structure was drawn from Boulard et al. (2011), starting with the production of materials and ending at the completion of structure assembly. The dataset includes the production of greenhouse structural materials, plastic coverings, and a concrete foundation. The greenhouse infrastructure also includes a heating system (natural gas boiler), a fume condenser, and a fertigation system. Transportation burdens are found to have small impacts when using regional suppliers of greenhouses and materials.

Regional suppliers are assumed since they are accessible in each region, although this could be an overestimate of transport if growers used a more local supplier. For each location, a consistent value of 600 km transport distance is assumed for greenhouse materials and 50 km for concrete transport to represent a local concrete supplier, for a total of 7400 ton-kilometers of freight using a truck for land transportation.

Cost and environmental performance of greenhouse-grown tomatoes are modeled since they account for the majority of greenhouse vegetable sales (USDA 2012), and are consistent with energy demands of Ravishankar and O'Connor (2019). The USDA notes that US and Canadian greenhouse production can reach 500 metric tons per hectare, while the average yield for US field tomatoes is around 34-36 metric tons per hectare (Cook and Calvin 2005). Although open-field tomatoes dominate production for products like sauces, canned tomatoes, and juices, greenhouses are emerging as a competitor to field-grown tomatoes, especially for fresh produce given their ability to produce year-round, high quality product (Launack, 2016). In 2016, 25% of all tomatoes in the United States came from greenhouses, including imports from Mexico and Canada; this is significant, particularly compared to negligible amounts from greenhouses in the 1990s (Launack 2016; Cook and Calvin 2005).

The functional unit used is 1 kg of tomato is used and two crop cycles per year are assumed. This analysis assumes the greenhouse is operational year-round, although growers may choose to avoid certain extreme climate months with large heating and cooling demand. Snyder (2016) notes that for a 214 m² greenhouse, about 460 to 576 plants can be grown. Thus, two crop cycles are assumed with a conservative estimate of 450 plants per cycle, for a total of 900 plants per year. Crop yields are calculated on a per plant basis, with a yield of 4.1 kg/plant for each greenhouse system, also a conservative estimate compared values of 3.5 - 5.8 kg/plant, estimated

by Marr (1995). The assumed greenhouse structure and crop yields are used in the three greenhouse systems: conventional, adjacent PV, and SPRING systems. The base case analysis in Arizona does not consider decreases in crop yields from OPV integration in the SPRING design. However, an uncertainty analysis is used to determine the effect of crop productivity on cost and environmental impacts.

Given the novelty and wide range of OPV materials, a specific OPV design is selected to assemble material flows based on existing literature. Although there are a variety of polymers that could be effectively used in the active layer of OPVs, environmental assessments have been heavily focused on the poly(3-hexylthiophene)/[6,6]-phenyl-61 butyric acid methyl ester or a P3HT/PC₆₀BM blend (Lizin et al. 2013). The process by which OPVs are manufactured can also vary. However, each process follows general steps in constructing OPVs as described by Lizin (2013), Frischknecht (2012), and Anctil (2012). The OPV module production process uses the data and approach described in (Tsang, Sonnemann, and Bassani 2016), who studied the life cycle assessment of an OPV with poly(3-hexylthiophene) (P3HT) as the donor material and phenyl-C₆₁-butyric acid methyl ester (PCBM) as the acceptor materials in the OPV cell. (Tsang, Sonnemann, and Bassani 2016) developed life-cycle inventory data for prospective OPV module production and disposal, while using unit processes available in ecoinvent for the balance of system components such as inverters, wiring, and structural components. Polyethylene terephthalate (PET) is used as a flexible encapsulation substrate, molybdenum trioxide is used for the hole transport layer, and the back electrode is aluminum with a layer of lithium fluoride to enhance efficient operation.

Integrating OPVs onto the roof of a greenhouse will affect the heating and cooling demands require to maintain set temperatures (Ravishankar and O'Connor 2019). This analysis

utilizes methods described in Ravishankar and O'Connor (2019) to determine energy demands as they vary with increasing roof coverage of OPVs (Figure SI 6). Each grid-connected PV system is sized specifically to produce electrical energy equivalent to the annual electricity demand for each respective greenhouse. Thus, PVs may overproduce during the day, and the greenhouse will be grid-dependent during the night, but total demand and generation balances across the year.

Equation (1) describes the sizing calculation for each PV system based on the demand:

$$P_{DC} = \frac{E_A}{DR * I_A} \quad \text{Eq (1)}$$

where P_{DC} is the dc capacity (kW) of the modules, E_A is the annual greenhouse electricity demand (kWh), DR is the derating factor (which accounts for losses due to inverters, shading, temperature, and system efficiencies), and I_A is the annual insolation in hours of peak sun per year (Masters 2013). A grid-connected PV system is used for both SPRING and adjacent PV greenhouses to effectively compare each greenhouse in terms of environmental impacts. Further investigation is used in Appendix 2 to understand the feasibility of off-grid SPRING designs with battery storage. To compare the environmental impact of each PV system, this analysis present each PV system's global warming potential (GWP), energy payback time (EPBT), and energy return on investment (EROI). EBPT and EROI are calculated in Equations 2 and 3 based on direct electricity output and the methods described in Raugei et al. (2016).

$$EROI_{el} = \frac{Out_{el}}{Inv} \quad \text{Eq (2)}$$

$$EPBT = \frac{T}{EROI_{el}} \quad \text{Eq (3)}$$

The energy investment (Inv) is the sum of the energy needed to produce, manufacture, and dispose of the PV system. This cumulative energy demand is calculated using the methods described in Frischknecht et al. (2015). Equation 4 describes the calculation for the output of electricity (Out_{el}), where (η_{PV}) is the cell's conversion efficiency.

$$Out_{el} = I_A * \eta_{PV} * PR \quad \text{Eq (4)}$$

The modeling assumption used here is also used in Raugi et al. (2016) for a rooftop PV, where the performance ratio (PR) of 75% includes age-related degradation, inverter losses, and temperature performance losses. Based on recent OPV performance and industry goals, the sensitivity analysis uses a lifetime of 5-10 years for both cost and environmental impact, and an assumed 5% device efficiency.

Modules are oriented equally to each of the east and west slants of the roof in each location, which results in different, often inferior, angles of incidence when compared to the mc-Si system which is southern facing, latitude-equivalent fixed tilt. Rather than assume degradation in electricity production over time, additional installments of PVs and OPVs are used depending on their expected useful life and use a performance ratio factor to account for average degradation. In the base case for Arizona, OPV module lifetime is assumed to be 10 years, requiring 3 installments over the lifetime of the greenhouse system. Theecoinvent processes for inverters and electronic installations are used along with the OPV module. Insolation values for each location are drawn from the National Solar Radiation Database for a typical meteorological year (TMY3) and are shown in Table SI 1 (Wilcox and Marion 2008).

Ecoinvent 3.3 data is used for photovoltaic panel production, multi-Si wafer, for the multi-crystalline silicon PV module, balance of system, and ground mounting system. The photovoltaic panel (multi-Si wafer), inverter (2.5 kW), and photovoltaic mounting system (open ground module) are considered part of the PV system. As previously mentioned, the adjacent PV greenhouse system allows for comparison of the SPRING system with a mature PV technology, installed adjacent to the greenhouse. Each modeled mc-Si PV is fixed tilt, south facing, with the

tilt equal to the latitude of the location. The additional land needed for the ground mounted mc-Si PV systems assumes ground cover ratios for each location to result in a shading derate factor of 0.975 (Table SI 2).

The annual crop materials inventory is adopted from theecoinvent activity: tomato production, fresh grade in heated greenhouse. Fertilizers, pesticides, growing media, and emissions are accounted for in this process and each input is based on 1 kg of tomato production in this specific activity. As described below, a range for certain inputs are considered, including electricity demand, heating demand, and irrigation.

Energy demand of the greenhouse using a transient energy model that simulates year-round heating and cooling demands, fully described in Ravishankar et al. (2019). Their study compares energy demands associated with tomato crop production in AZ, NC, and WI for a Venlo-type greenhouse, consisting of vertical sidewalls and an A-frame roof. The greenhouse is constructed of glass walls and roof, with OPVs integrated across the entire roof area. The OPVs include both the top and bottom electrodes made of semi-transparent Indium Tin Oxide (ITO) with PEDOT:PSS serving as the hole transport layer and a 100nm active layer blend of P3HT:PCBM. The authors note that the net transmittance of light entering the greenhouse (with

Table 1 – Annual energy demands for each greenhouse design and location

Appliance	Phoenix, Arizona			Raleigh, North Carolina			Antigo, Wisconsin			Unit
	SPRING	PV		SPRING	PV		SPRING	PV		
		Adj	Conv		Adj	Conv		Adj	Conv	
Cooling Fans	8,823	9,028	9,028	6,414	6,656	6,656	3,481	3,617	3,617	kWh
Water Pumps	1,625	1,668	1,668	623	625	625	480	480	480	kWh
Heat Exchanger Motor	267	266	266	373	368	368	467	461	461	kWh
Heating	96	96	96	209	205	205	310	304	304	MMBtu

the roof fully covered by OPV), drops by around 40% when compared to a conventional greenhouse in each location. All greenhouse systems include typical shading mechanisms to reduce cooling loads and thermal stress to the plants during summer. Energy demands for each greenhouse location and design are compared and can be seen in Table 1. In each location, the conventional and adjacent PV greenhouse designs are assumed to have equivalent energy demands, while the SPRING design will have different energy demands due to partial shading from OPV. Using methods described in Ravishankar (2019), this study analyzes how electricity demands are affected by increasing roof coverage of OPV, allowing us to match the OPV capacity to meet average annual electricity demand (Figure SI 5). Table 1 shows the effect shading has on the greenhouse in terms of heating and cooling. Although the SPRING design results in lower summer cooling demands, it also produces slightly higher heating values in colder regions, where the shading affect during the winter results in higher heating demands than the conventional greenhouse.

Water use is divided into two categories: irrigation water use, WU_i , and evaporative cooling water use from a pad-and-fan system, WU_{pf} . WU_i is highly variant (0.4-5.6 $L \text{ plant}^{-1} \text{ day}^{-1}$) and dependent on the stage of growth and season (Peet and Welles 2005). WU_i is estimated by plant type according to the two crop cycles previously noted. Representative stages of growth and water requirements are taken from Peet and Welles (2005), who note seedling, transplant, harvest, and full harvest demand of 0.2, 0.3, 1.5, and 2.5 $L \text{ plant}^{-1} \text{ day}^{-1}$, respectively. WU_{pf} is calculated based on the evaporation rate calculation from Al-Helal (2007) and Franco et al. (2010). The water uptake rate in the evaporative pad, via air passing through the wetting pad is a function of the ventilation rate and humidity of air

entering and leaving the greenhouse. Equation (5) shows the calculation for evaporation rate, \dot{m}_e , as seen in Al-Helal (2007):

$$\dot{m}_e = \frac{Q_a \rho (W_{in} - W_{out})}{A_f} \quad \text{Eq (5)}$$

where W_{in} is the humidity ratio $\left(\frac{\text{kg}_{\text{water}}}{\text{kg}_{\text{dry air}}}\right)$ of air leaving the pad inside the greenhouse, W_{out} is the humidity ratio of the outside air entering the greenhouse, ρ is the air density (kg m^{-3}), Q_a is the volume flow rate of air (m^3h^{-1}), and A_f is the floor area (m^2). This model assumes an 80% efficient fan pad cooling system for all purposes, consistent with ASHRAE (2003).

2.3 Life Cycle Impact Assessment

This study uses the Tools for Reduction and Assessment of Chemical and other environmental Impacts (TRACI) method to convert the life cycle inventory to midpoint indicators of environmental impact (Bare 2011). Environmental impact categories addressed in this study include global warming, acidification, eutrophication, resource depletion, ozone depletion, and photochemical ozone formation. Omitted from this study are carcinogenic and ecotoxicity impact categories due to uncertainty and data availability. Additionally, quantified here are land and water demands per functional unit to compare the three greenhouse systems.

OpenLCA software is used to determine the drivers of environmental impacts and to address the uncertainty associated with these results. Additionally, Monte Carlo simulations (MCS) are used to quantify the uncertainty associated with environmental impacts of each greenhouse system in each location. Historical heating and cooling degree days are used from NOAA (2018), which were found to be normal distributions for heating and cooling using a Jarque-Bara test for normality in each location. For all other parameters related to pesticides, fertilizers, operational materials, greenhouse structure, water use, and PV systems, a uniform

distribution ($\pm 20\%$) is used, which represents a plausible amount of variation in key parameters and is large enough to produce observable effects on overall costs and environmental impacts.

2.4 Economic Analysis

For each greenhouse system, costs are compared using net present value and the levelized cost of tomato production. Levelized cost is used to compare each greenhouse systems cost associated with producing one kilogram of tomato. Each greenhouse system includes capital costs of a new greenhouse and photovoltaics (when applicable), operations and maintenance, and revenue from crop production. The net present value of each greenhouse system is calculated as shown in Equations (6-9) and uses variables outlined in Table 2. The net present value is calculated using the annual net revenue streams (R_t) and a discount rate of 10%. R_t is inclusive of annual income (I_A), annualized cost of loan payments (P_L), and annual variable cost (C_V), as shown in equation (6).

$$R_t = I_A - P_L - C_V \quad \text{Eq (6)}$$

I_A is the product of market value (V_M), crop production (Y_C), and plant density (D_P), shown in equation (7).

$$I_A = V_M * Y_C * D_P \quad \text{Eq (7)}$$

Equation (8) shows P_L , which represents the annualized investment cost (loan payment), which includes the PV system (OPV_C), land (C_L), and greenhouse structure (C_{GH}), each calculated using a capital recovery factor (CRF) specific to the lifetime of that investment.

$$P_L = OPV_U * OPV_C * CRF_{OPV} + C_L * A_{GH} * CRF_{GH} + C_{GH} * A_{GH} * CRF_{GH} \quad \text{Eq (8)}$$

C_V includes annual electricity costs ($D_E C_E$), annual heating costs ($D_H C_H$), and annual fertilizer, water, and labor costs ($C_{OM} A_{GH}$).

$$C_V = D_E C_E + D_H C_H + C_{OM} A_{GH} \quad \text{Eq (9)}$$

Table 2 – Greenhouse System Costs for Monte Carlo Analysis

Eq (7-9 Variables)	MCS Variables	Min	Max	References
OPV _U	OPV Cost (\$/W) ^c	0.77	4.11	Azzopardi (2011) , Gambhir (2016)
T _{OPV}	OPV Lifetime (yr)	5	10	Gambhir (2016)
D _E	SPRING Electric Demand (kWh/yr) ^d	8,600	13,000	Ravishankar (2019)
	Conv/PV Adj Elec Demand (kWh/yr)	8,800	13,000	Ravishankar (2019)
D _H	SPRING Heating Demand (MMBtu/yr) ^d	77	116	Ravishankar (2019)
	Conv/PV Adj Heating Demand(MMBtu/yr)	77	115	Ravishankar (2019)
C _E	Cost of Electricity (\$/kWh) ^{a,d}	0.07	0.13	EIA (2018)
C _H	Cost of Natural Gas (\$/MMBtu) ^{a,d}	6.2	12	EIA (2018)
C _L	Cost of Land (\$/acre) ^c	17,000	31,000	USDA (2015)
Y _C	Crop Yields (kg/plant)	3.3	4.9	Rutledge (1998)
Constant Variables		Value		
C _{GH}	Greenhouse Cost (\$/m ²) ^c	269		ATLAS Greenhouses
V _M	Market Value (\$/kg) ^e	4.4		Raleigh Greenhouses
D _P	Plant Density (Plant/greenhouse-yr)	900		Snyder (2016)
C _{OM}	Annual Materials and Labor (\$/m ²)	25		Hood (2013)
A _{GH}	Greenhouse Area (m ²)	214		Snyder (2016)
PV _U	m-Si PV Cost	2.13		Fu et al. (2017)
T _{PV}	m-Si PV Lifetime (yr)	30		Fu et al. (2017)
T _{GH}	Greenhouse Lifetime (yr)	30		Boulard (2011)

^a denotes annual increases in cost at 1%

^c Personal communication with ATLAS Greenhouse Co. Includes cost estimations of a multi-bay, gutter connected, 8mm poly-carbonate greenhouse.

^e represents investment costs amortized into loan payments (P_L)

^d represents variable costs (C_V) or demands incurred annually

Note that for a SPRING and adjacent PV design, P_L would include annual payments for the respective PV system (Table SI 1) but would not incur electricity costs seen in C_V (Eq 9), since the PV systems are sized to meet the annual demands of the greenhouse. This scenario represents a net metered system that credits each unit of PV-generated electricity fed back to the grid at retail prices. Likewise, the conventional greenhouse does not incur the loan payments of a PV system (Eq 8) but does incur electricity costs (Eq 9). A 10% discount rate and a 30-year

greenhouse lifetime is used to represent a typical greenhouse useful life (Boulard et al. 2011). Additionally, a consistent investment tax credit of 30% is used throughout the analysis for each PV system. Although this federal incentive is stepping down in coming years, uncertainty in investment costs are addressed by including a uniform distribution of PV unit prices.

As an emerging technology, the achievable costs and lifetimes of OPV modules are uncertain. Although some projections within the literature have shown OPV module cost to be as low as $\$7.85/\text{m}^2$, which equates to $\$0.16/\text{W}$ at standard test conditions and a 5% efficiency, the realized and expected costs of OPVs within the photovoltaic industry are not as readily available as the costs of mc-Si PVs (Mulligan et al. 2014). Within the MCS, the OPV investment cost varies between $\$0.77$ and $\$4.11/\text{Watt}$. Additionally, greenhouse energy demands can vary depending on the specific climate, energy management strategies, and greenhouse structure (Shen, Wei, and Xu 2018).

To better understand the impact of these uncertainties, another MCS is conducted focused on greenhouse economics. Stepwise regression analysis is used to determine which input variables (shown in Table 2) have the largest effect on the net present value. The economic MCS focuses on parameters that will vary with each greenhouse design such as energy demands, PV investment costs, land use, and crop production. Varying these specific parameters allows us to quantify how NPV is affected by different designs. Greenhouse capital and operational costs (fertilizers, insecticide, labor) are not used as variable inputs and are assumed to have equal cost impact on each system. The market value of tomatoes is also kept constant and assumed to be independent of the greenhouse design. Excluded from the net present value calculations are overhead expenses such as sales and real estate taxes, marketing, and transportation. Key cost and performance assumptions are given in Table 2.

Abatement cost per metric ton of CO₂ are calculated by:

$$Abatement\ Cost = \frac{\sum_{i=0}^t \frac{C_{PV} - C_{grid}}{(1+d)^t}}{\sum_{i=0}^t \frac{E_{grid} - E_{PV}}{(1+d)^t}} \quad Eq\ (10)$$

where C is the levelized cost of electricity (\$ kWh⁻¹), and E the emission factor (kg-CO₂ kWh⁻¹), each of which is discounted for the 30-year greenhouse lifetime (see SI for table of all inputs used for abatement costs). Emission factors are drawn from ecoinvent for each state's respective North American Electric Reliability Corporation (NERC) region, and the price of electricity is taken from EPA (2016) for each specific state (Table SI 1).

3. RESULTS

Presented first are the life cycle energy and GWP impacts associated with both the OPV and mc-Si solar PV systems, followed by an assessment of environmental impacts in Arizona for the three greenhouse designs. Also presented are the the environmental impacts returned from the Monte Carlo simulation (MCS) across all three greenhouse scenarios in Arizona, North Carolina, and Wisconsin. Results also specifically address land and water use, and sensitivity of crop productivity to the presence of rooftop OPV. Finally, the greenhouse cost comparison summarizes findings from the MCS focused on net present value and abatement costs associated with the SPRING system.

3.1 Energy and GWP impacts from solar PV

Before considering the environmental impacts of the greenhouse systems, first considered are the energy and GWP impacts from the OPV and mc-Si solar arrays in isolation. Figure 2 shows the GWP and EROI impacts associated with the two PV systems in Arizona, which has climatic conditions most favorable to solar powered greenhouses. GWP tracks greenhouse gas emissions,

which are largely derived from energy consumption associated with solar panel production (SI Figure 5). In terms of GWP, even at lower lifetimes of 5 years, OPV outperforms the mc-Si PV system. However, EROI shows that these low lifetimes may not yield the same returns on energy at a 5-year lifetime. Because EROI looks at the overall energy performance over the lifetime of a PV technology, significant differences are seen in Figure 2. Alternatively, EPBT only measures how quickly the energy investment is returned through electricity production. Using the methods of Raugei et al. (2016), results show that the range of OPV lifetimes has negligible effects on

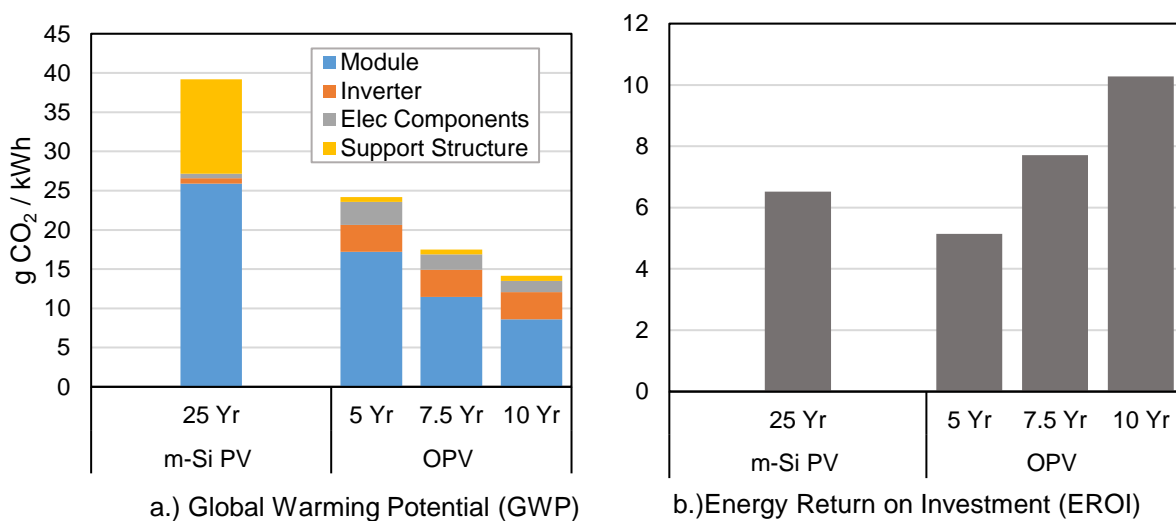


Figure 2 –Impacts of mc-Si PV and OPV integrated with a greenhouse in Arizona. Figure includes (a) global warming potential, and (b) energy return on investment. OPV lifetimes of 5, 7.5, and 10 years are shown to represent uncertainty modeled throughout this analysis.

EPBT. OPVs are estimated to have an EPBT of 0.97 years and mc-Si show 3.8 years, respectively.

3.2 LCA of Arizona Greenhouse Systems

Among the three locations considered, Arizona represents a best-case scenario with high insolation and high electricity demands. Figure 3 shows process-specific environmental impacts for each greenhouse system in Arizona. For each impact category, the conventional greenhouse system shows larger environmental burdens per kg of tomato than either greenhouse system with

photovoltaic technologies. Additionally, the largest driver for each impact category is operational energy demand, followed by the greenhouse structure. Results for the conventional greenhouse are comparable to Boulard, et al. (2011) who analyzed greenhouse tomato production in France and estimates a GWP of 2 kg CO₂-eq/kg tomato. Page, Ridoutt, and Bellotti (2012) estimate 2.03 and 2.28 kg CO₂-eq/kg tomato for a medium and high-tech greenhouse, respectively. As mentioned in the methods section, the Adjacent PV and SPRING systems are grid-connected and assumed to produce an amount of electricity equivalent to the annual electricity demand. In the analysis up to this point, the assumption has been that solar-generated electricity offsets grid electricity with an emissions rate equal to an annual average value that remains constant

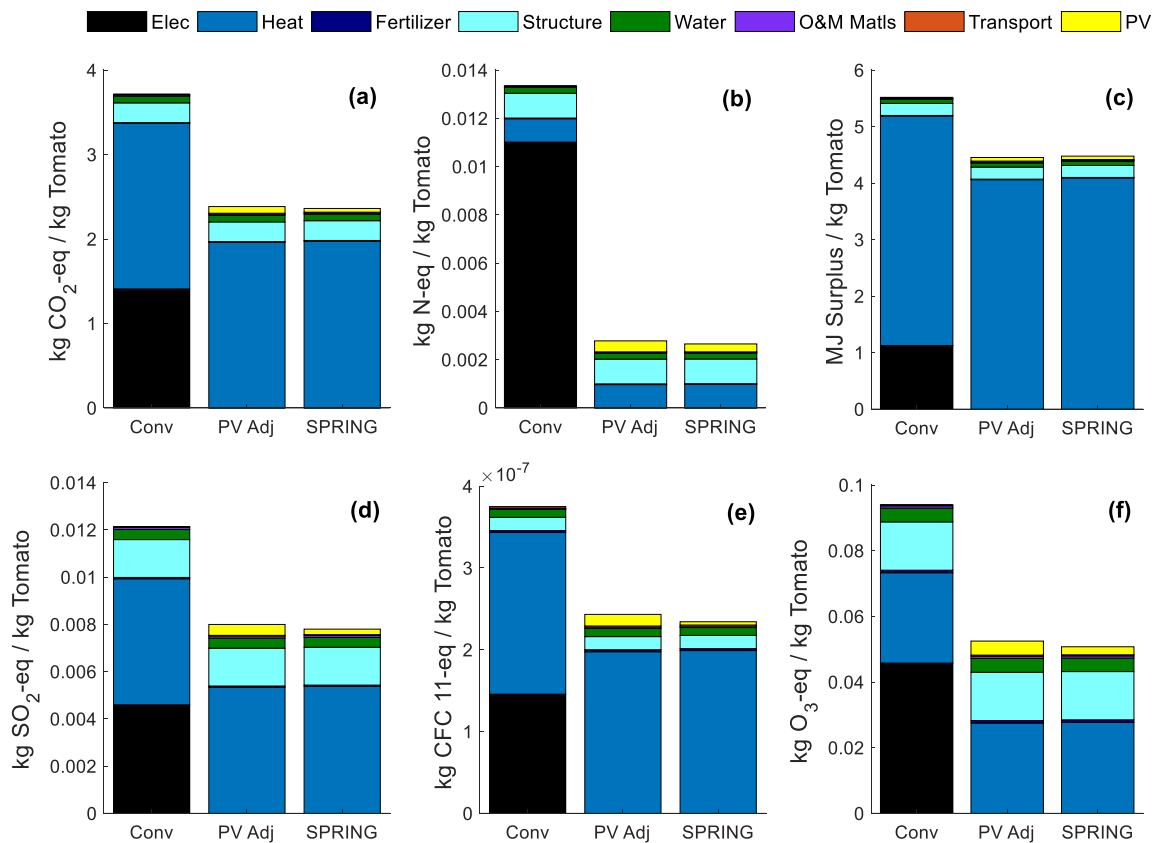


Figure 3 – Life cycle environmental impacts from tomato production in Arizona using a conventional greenhouse (Conv), a conventional greenhouse with co-located solar photovoltaics (PV Adj), and a Solar PowerRed Integrated Greenhouse (SPRING: (a) global warming potential, (b) eutrophication, (c) acidification, (d) resource depletion, (e) ozone depletion, and (f) photochemical ozone formation.

throughout the year. However, this simplified assumption is addressed in the following section using marginal emission factors to account for seasonal and hourly variability of solar generation relative to electricity demand.

Reductions among each environmental impact associated with the SPRING design range from 19% to 81% compared to the conventional greenhouse, and 0% to 7% when compared with an adjacent PV design. Dominant processes producing environmental impact include electricity, heating, and the greenhouse structure. For the conventional greenhouse, energy demands account for 78%-94% of each impact category's environmental burdens, compared with 35-91% for the PV Adjacent system and 38-92% for the SPRING design. Although impacts related to energy demand are dominant in this analysis, there may be some slight variance in real greenhouses which may schedule crop production to avoid high energy demanding months.

3.3 Regional LCA

Environmental impact results are shown in Figure 4 for all three locations. In Arizona, GWP results show averages of 3.71, 2.38, and 2.36 kg CO₂-eq/kg tomato for the conventional, adjacent PV, and SPRING greenhouses, respectively. Although there are comparatively large environmental benefits across all impact categories in Arizona from a SPRING design, this effect is not consistent across all three locations. Environmental burdens are driven by much higher heating demands in the colder locations. For the SPRING design, heating demands alone drive 54-96% and 70-98% of the environmental burdens in North Carolina and Wisconsin, respectively. Figure 4 shows that, in North Carolina, SPRING greenhouses continue to see reduced environmental impacts, but this reduction becomes less apparent in Wisconsin. Consistent with Figure 3, eutrophication is shown to be most sensitive to grid powered electricity and shows the largest reductions in impacts when a PV system is used to meet electricity

demands. Also consistent with Figure 3, resource depletion appears to be the most sensitive to heating demands, explaining why a SPRING design has the highest average impact in Wisconsin. Integration of OPVs onto the roof of a greenhouse introduces a year-round shading effect, which increases winter heating demands, and therefore increased use of natural gas.

Rather than rely solely on annual average emissions factors, marginal emission factors are also utilized with rates from Azevedo et al. (2017), which utilize a method described in Siler-Evans, et al. (2012) to determine if avoided emissions associated with PV electricity production are disproportionately larger in certain seasons and times of day. Marginal emission factors allow us to estimate emissions associated with the incremental system load imposed by the greenhouse at a specific hour. However, this temporal variation in emissions rate has minimal impact from

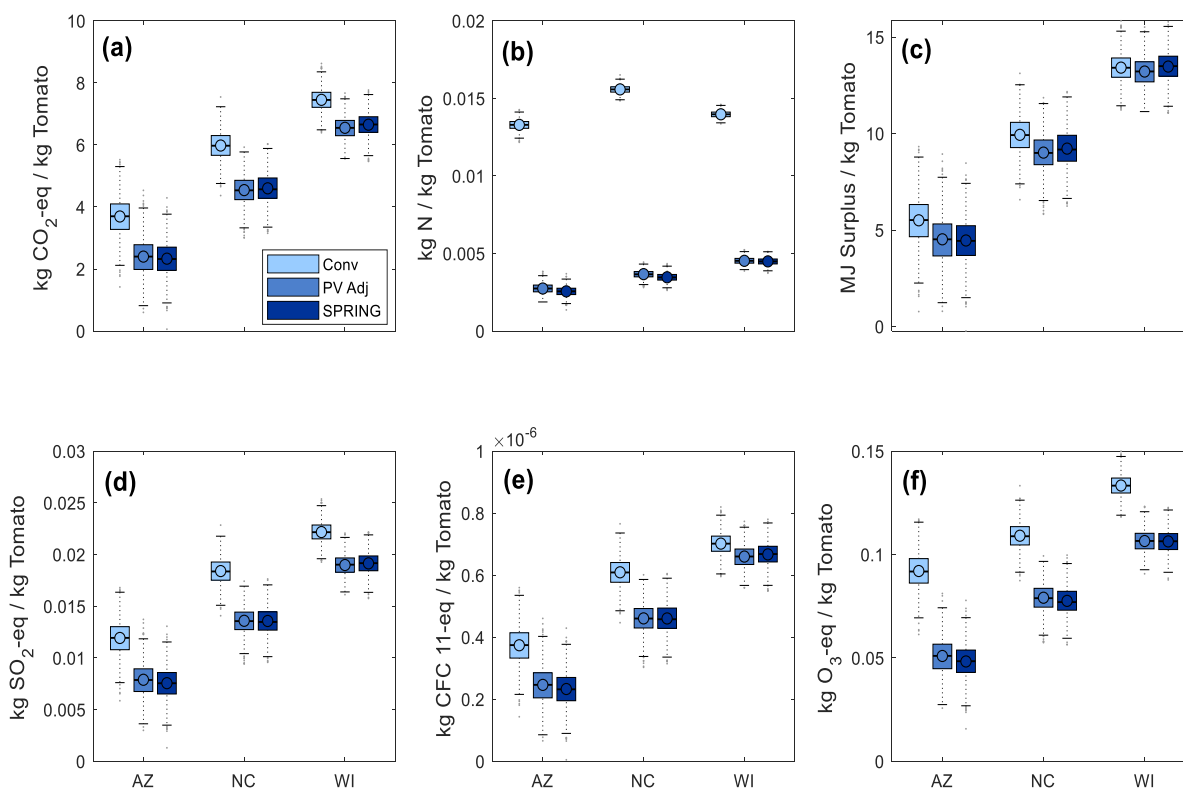


Figure 4 – Uncertainty analysis of each greenhouse system and location for impact categories (a) global warming potential, (b) eutrophication, (c) resource depletion, (d) acidification, (e) ozone depletion, and (f) photochemical ozone formation. Box and whisker plots display the median (center line), average (circle), quartiles (boxes), and 95th and 5th percentiles (whiskers).

initial results. Specifically, the use of marginal emissions factors would only change the net reduction in emissions from the power sector by approximately 1-2% relative to the completely grid dependent greenhouse. Although this analysis assumes a constant annual average grid emissions rate in the SPRING design, minimal differences are observed when accounting for temporal variability in grid emissions.

3.4 Land and Water Use

Air conditioning and cooling systems come with high installation and operating costs in greenhouses; the most common cooling systems in greenhouses are pad-and-fan designs (Bucklin et al. 2016). Pad-and-fan systems use evaporative cooling methods to reduce air temperature by converting sensible heat energy into latent heat by evaporation (Kubota, Sabeh, and Giacomelli 2006). Although greenhouses can significantly reduce irrigation demands compared to field crops, Sabeh et al. (2011) notes that studies tracking water use by evaporative cooling systems is limited, finding a peak water use of $11 \frac{L}{m^2 \cdot d}$ during summer months. Since evaporative cooling is included throughout night and slightly higher pad efficiencies than Sabeh et al. (2011), findings show the peak summer water use to be $16.5 \frac{L}{m^2 \cdot d}$. Total annual water use in Arizona (pad-and-fan plus irrigation) is 144 L/kg tomato for a SPRING system, and 148 L/kg tomato for the PV Adjacent and Conventional greenhouse systems. Slightly less water is consumed by the SPRING design due to lower cooling loads and fewer air changes needed. Significantly less water is used in North Carolina and Wisconsin, mainly due to lower cooling demands. Additionally, the higher level of humidity in Raleigh, NC and Antigo, WI means less water is able to evaporate from the pad into the air, therefore slightly less water is used by the pad because of ambient humidity (Figure SI 3).

AZ, NC, and WI require 33%, 33%, and 28% more land area to accommodate a co-located, mc-Si PV technology to cover electricity demands. An adjacent PV greenhouse would produce 12.9, 12.9, and 13.4 kg tomato $\text{m}^{-2} \text{yr}^{-1}$ in AZ, NC, and WI; SPRING designs would produce 17.2 kg tomato $\text{m}^{-2} \text{yr}^{-1}$ in each location since no additional land is required (Table SI 2).

3.5 Crop Production Sensitivity

Each greenhouse system consists of an equivalent structure, but different electricity sources. For the SPRING design, energy demands are affected by the capture of incident light through the roof of the greenhouse. Potentially the most uncertain parameter presented in this study is crop production yields in the SPRING design due to losses in incoming light. For all previous results, a crop production of 4.1 kg per plant is assumed, which is considered a conservative estimate compared to Rutledge (1998), who provides common values of commercial greenhouse crop yields at 5.4-6.8 kg/plant in the spring season and 4.5 kg/plant in the fall (Rutledge 1998). Results from Loik et al. (2017) show that the average mass of tomatoes decreases by approximately 17% under wavelength selective photovoltaics. To reach environmental burdens equivalent of the conventional greenhouse, the SPRING design in Arizona would have to decrease tomato yields by 37% for GWP, 36% for acidification, 81% for eutrophication, 19% for resource depletion, 38% for ozone depletion, and 48% for photochemical ozone formation.

3.6 Greenhouse Cost Comparison

Differing regional climates along with uncertain energy demands, fuel costs, and investment costs can have a significant impact on the cost-effectiveness of different greenhouse configurations. MCS is performed to address the uncertainty in the net present value and present cost of the greenhouse systems. The stepwise regression analysis shows that the net present value

of the SPRING design is most sensitive to crop production, followed by OPV cost, OPV lifetime, and the price of natural gas (each resulting in p -values < 0.05).

Average net present values for a conventional, Adjacent PV, and SPRING system are \$36,000, \$38,000 and \$29,000 (Figure SI 2). Figure 5 shows the MCS net present value results for a SPRING design in Arizona. The MCS results shown in Figure 5 include variation in all uncertain input parameters, but highlights the sensitivity to crop production, OPV prices, and OPV lifetime. By visual inspection, OPV cost (\$/W) has a larger impact on net present value than OPV lifetime.

The average present cost per kilogram of tomato for a conventional, adjacent PV, and

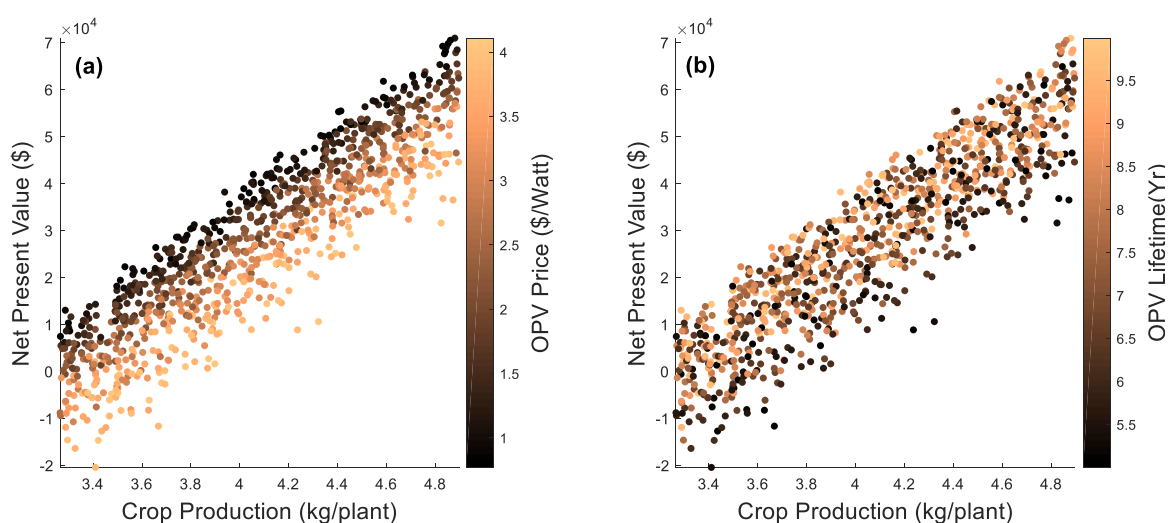


Figure 5 – SPRING net present values based on Monte Carlo simulation. Panel (a) shows results of crop production sensitivity comparison with a gradient of OPV prices. Panel (b) shows the same results as (a), with a gradient of OPV lifetime.

SPRING system is \$3.43/kg, \$3.38/kg, and \$3.64/kg. Higher average costs for the SPRING system can be attributed to the higher costs and lower lifetime of OPVs. Although the average is higher for a SPRING system, MCS results show the SPRING design is more cost effective than the conventional or adjacent PV design when the investment costs (\$/W) are low, and lifetimes of OPV are high.

Figure 6 shows the abatement cost, for a range of lifetimes and unit prices, in dollars per metric ton of CO₂ equivalent in each region for the SPRING system. Regional variance in abatement are costs due to differing regional emission factors, insolation values, and electricity prices (Table SI 1). For reference, Figure 6 includes EPA's social cost of carbon (\$55/ton CO₂ in 2030 at a 3% discount rate), which represents the estimated cost of CO₂ damages (EPA, 2010). As the lifetime of OPVs increases, and unit costs fall to the projections estimated by Gambhir

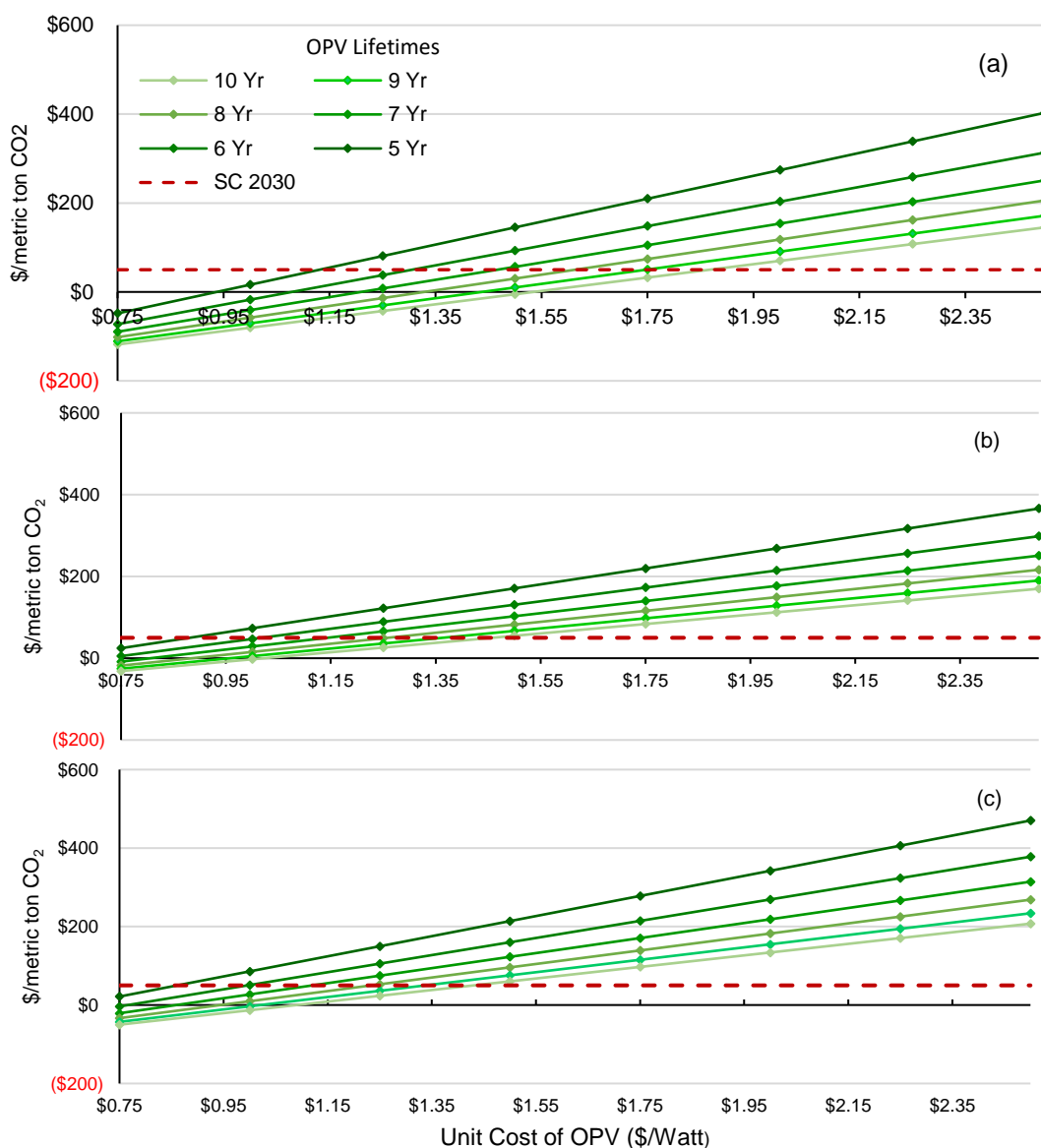


Figure 6 – Abatement cost of the SPRING system compared with the conventional greenhouse in (a) Arizona, (b) North Carolina, and (c) Wisconsin. Dashed red line represents social cost of carbon at a 3% discount rate in

(2016) and Mulligan et al. (2013), OPVs yield abatement costs lower than the social cost of carbon.

4. DISCUSSION AND CONCLUSION

Results from this study suggest that SPRING greenhouses can produce lower environmental burdens compared to conventional systems in warm climates with high solar insolation. The SPRING design is more desirable in warmer climates because it reduces environmental burdens associated with greenhouse cooling. Greenhouses in colder climates show environmental impacts dominated by the use of natural gas for heating. Results are consistent with Dias et al. (2017), who studied the environmental impacts of greenhouse tomato production in Ontario, Canada, noting that heating from fossil fuels in Ontario makes up 50-85% of the burdens for each environmental impact category.

Although the SPRING system may result in lower environmental impacts, OPV light absorptivity introduces uncertainty in crop production levels. Emmott et al. (2015) performed a techno-economic evaluation of OPV integrated greenhouses, concluding that currently available materials absorb too much light within the photosynthetically active region to be competitive with conventional greenhouses. Additionally, a challenge of OPV design is the trade-off between increasing cell efficiency for higher energy production, which requires increasing the thickness and light absorption, and lowering the cell efficiency to increase crop production (Emmott et al. 2015). However, more recent developments in WSPVs show that crop yields may not be affected if the correct wavelengths are transmitted through the PV system (Loik et al. 2017). Although SPRING designs can be cost-effective, particularly as OPV cost decreases and lifetime increases, crop yields must be maintained to be competitive with prevailing greenhouse design. Future

work should investigate crop yields based on various roof coverages and patterns of OPV installment.

In the face of uncertain climate and increasing land constraints, greenhouses have the potential to produce consistent supplies of food. However, energy demands – essential for thermal regulation and reliably high yields – can be an order of magnitude higher than field grown crops. Emerging OPV technology has potential for greenhouse integration due to its lightweight, semi-transparent characteristics. In areas with high insolation values and high electricity demands, OPV integrated greenhouses can reduce environmental burdens without requiring additional land. SPRING greenhouses in Arizona show reductions in environmental burdens ranging from 19% to 81%. In colder regions, the SPRING design can result in higher heating demands and subsequently higher environment burdens than the conventional greenhouse. Co-located PV systems consistently show lower environmental burdens than the conventional greenhouse, but at the expense of additional land use.

This analysis uses grid connected PV systems for a SPRING and adjacent PV design to compare environmental impacts. However, Appendix 2 extends this analysis to understand the feasibility of off-grid applications could be used in areas with little access to infrastructure or electricity. An optimization model is used to minimize cost based on Arizona electricity demands and solar resource for a SPRING design. This is particularly relevant for OPVs as an emerging technology that has great potential for low cost designs and as Li-ion battery costs continue to decline (Wilson 2018). Findings show that least cost solutions can be further reduced through reducing peak summer demands, reducing nighttime demands, and increasing efficiencies of the OPVs.

Although this analysis takes the perspective of a small-scale greenhouse business integrating OPVs, SPRING designs could provide value to utility companies and independent power producers wanting to conserve land and reduce their environmental impacts. With over 30,000 acres of greenhouses in the US, SPRING designs could conserve land needed for both food and energy production (USDA 2012). In addition to drastically reducing the environmental burden associated with food production, integrating renewables to heat greenhouses could add significant value to food systems in remote communities, with little access to existing electrical infrastructure. Although this LCA is limited to a single data source on OPV production (Tsang, Sonnemann, and Bassani 2016), findings show that energy consumption for thermally regulating greenhouses in the use phase is what drives environmental impacts in crop production for each region examined. Thus, manufacturing OPVs and greenhouse materials in areas of the world with higher grid emissions would not have a significant impact on the regional greenhouses examined here. Future work on semi-transparent OPV should also include detailed data collection of materials and energy needed for different designs. Further investigation of SPRING designs could consider the extent to which OPVs can power electric heating systems, which are currently powered by on-site fossil fuels, and whether battery storage systems can be used for off-grid, self-sustaining food systems.

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APPENDICES

Appendix 1.0 – Supplementary tables and figures for manuscript

Table S1 –SPRING and adjacent PV location specific characteristics used in Figure 3 and Figure 6

PV Tech	State	Insolation (kWh m ² /year) ¹	PV Lifetime (Yr)	PV PCE	Tilt (deg)	Annual Electric Demand (kWh)	PV Capacity (kW)	Module Area (m ²)	Grid Elec Price ² (\$/kWh)	Regional Emission Factor (kg CO ₂ /kWh) ³
OPV	AZ	2,209	10	5%	27	10,714	6.47	129.3	0.104	0.470
Module (SPRING)	NC	1,766	10	5%	27	7,410	5.60	111.9	0.086	0.760
	WI	1,525	10	5%	27	4,464	3.90	78.1	0.107	0.707
m-Si	AZ	2,388	30	19%	33.4	10,962	6.12	32.2	0.104	0.470
Module (PV Adjacent)	NC	1,942	30	19%	35.7	8,692	5.97	31.4	0.086	0.760
	WI	1,705	30	19%	45.1	5,775	4.52	23.8	0.107	0.707

1 - Insolation Values from NSRDB TMY3

2 - EIA (2016) Electric Power Annual

3 - Regional Emission factors for respective regions of the North American Electric Reliability Corporation

Table S2 - Adjacent PV area specifications

	Latitude (deg)	Ground Cover Ratio	Capacity (kW)	Co-located m-Si area required (m ²)	Additional land area needed	Annual crop density (kg m ⁻² yr ⁻¹)
AZ	33.5	0.46	6.12	70.0	33%	12.9
NC	35.8	0.45	5.97	69.8	33%	12.9
WI	45.1	0.40	4.52	59.5	28%	13.4

*assumes m-Si PV PCE of 19%

*GCRs estimated for each latitude to avoid self-shading (Masters 2013)

*Greenhouse footprint is 214 m²

Where area required for the co-located m-Si PV system is calculated as seen in Masters (2013):

$$\text{PV Area Required (m}^2\text{)} = \frac{\text{Capacity (kW)}}{\text{PCE} * \left(1 \frac{\text{kW}}{\text{m}^2}\right) * \text{GCR}}$$

Table S3 - Life cycle environmental impact summary per functional unit

Location	Greenhouse System	GWP (kg CO ₂ -eq/kg Tomato)	Acidification (kg SO ₂ -eq/kg Tomato)	Eutrophication (kg N-eq/kg Tomato)	Resource Depletion (MJ Surplus/kg Tomato)	Ozone Depletion (kg CFC 11-eq/kg Tomato)	Photochemical Ozone Formation (kg O ₃ -eq/kg Tomato)
AZ	Conventional	3.72	1.21E-02	1.33E-02	5.52	3.75E-07	0.094
	PV Adj	2.39	8.00E-03	2.78E-03	4.45	2.43E-07	0.052
	SPRING	2.35	7.74E-03	2.57E-03	4.45	2.33E-07	0.049
NC	Conventional	5.02	1.59E-02	1.52E-02	7.92	5.11E-07	0.097
	PV Adj	3.61	1.12E-02	3.19E-03	7.07	3.64E-07	0.067
	SPRING	3.61	1.10E-02	3.02E-03	7.13	3.58E-07	0.065
WI	Conventional	7.46	2.23E-02	1.40E-02	13.41	7.02E-07	0.135
	PV Adj	6.57	1.91E-02	4.53E-03	13.23	6.62E-07	0.107
	SPRING	6.65	1.92E-02	4.45E-03	13.46	6.67E-07	0.107

Table S4- Annual emissions of a SPRING and Conventional greenhouse (kg CO₂) using different emission factor methods

	Net Electric Grid Demands (kWh)	Emissions using constant EF from ecoinvent (kg CO ₂) ^a	Emissions using seasonal-hourly MEFs (kg-CO ₂) ^b	MEF Emissions Reduction Change
AZ -Conv	10,962	5,152	5,866	-0.6%
AZ -SPRING	0	0	-33	
NC - Conv	7,649	5,408	4,878	1.3%
NC - SPRING	0	0	64	
WI - Conv	4,558	3,472	3,516	-1.9%
WI - SPRING	0	0	-69	

^a annual emissions using a constant emission factors for all hours as seen in ecoinvent 3.0

^b annual emissions using marginal emission factors for each season and hour of day, using approach from Siler-Evans, Azevedo, and Morgan (2012)

^c each location uses the respective NERC region for emission factors, i.e. AZ – WECC, NC – SERC, WI - MRO.

Table S5 – Production of OPV solar cell as used in our study and drawn from Tsang, Sonnemann, and Bassani (2016).

organic solar cell, at plant (Area: 1 m ²)	Reference Flow Amount: 1 m ²	
Inventory Item	Amount	Units
Aluminum, primary, at plant, RER	0.001	kg
Annealing, process	1	number of items
FTO substrate, sputtered, at plant	1	m ²
Gravure printing	1	number of items
Lamination flexible solar module, at plant	1	m ²
Lithium fluoride, layer, application	1	number of items
Molybdenum(VI) oxide, at plant	0.00024	kg
Monochlorobenzene, at plant, RER	0.0076	kg
poly(3-hexylthiophene-2,5-diyl), at plant	0.00024	kg
PCBM, purified 99%, at plant	0.00021	kg
Transport, freight, rail, RER	0.005	t*km
Transport, lorry 16-32t, EURO3, RER	0.00018	t*km
Water, ultrapure, at plant, GLO	0.16	kg

*The amounts of materials used per layer were estimated using well-documented descriptions used in the scientific literature Anctil et al. (2012), Gacia-Valverde and Cherni (2010), and Espinosa et al (2012).

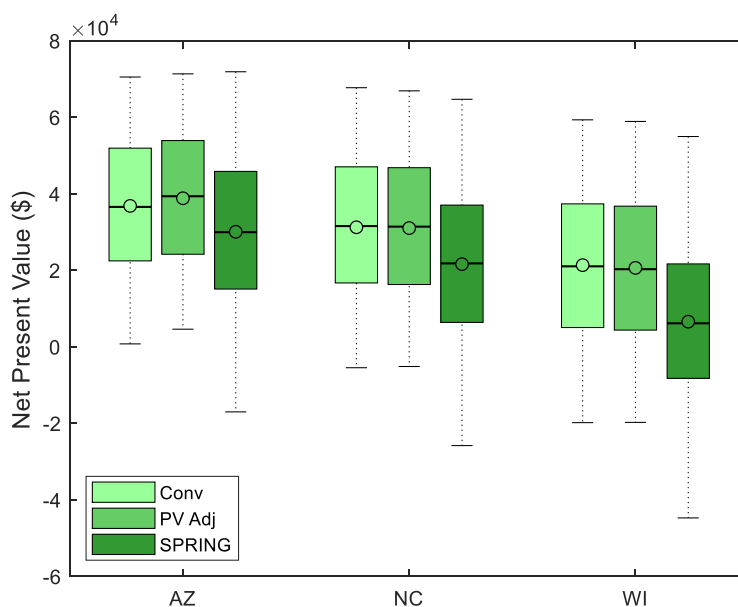


Figure S1 – Net present value results for MCS in Arizona, North Carolina, and Wisconsin for a conventional, PV adjacent, and SPRING design.

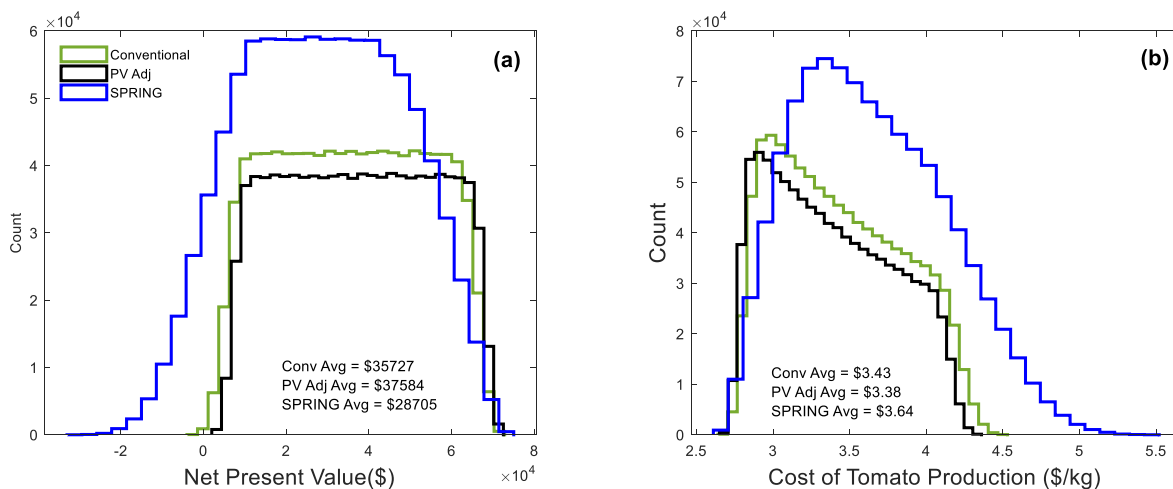


Figure S2 – MCS results for each greenhouse system in Arizona in terms of (a) levelized cost of tomato production and (b) net present value.

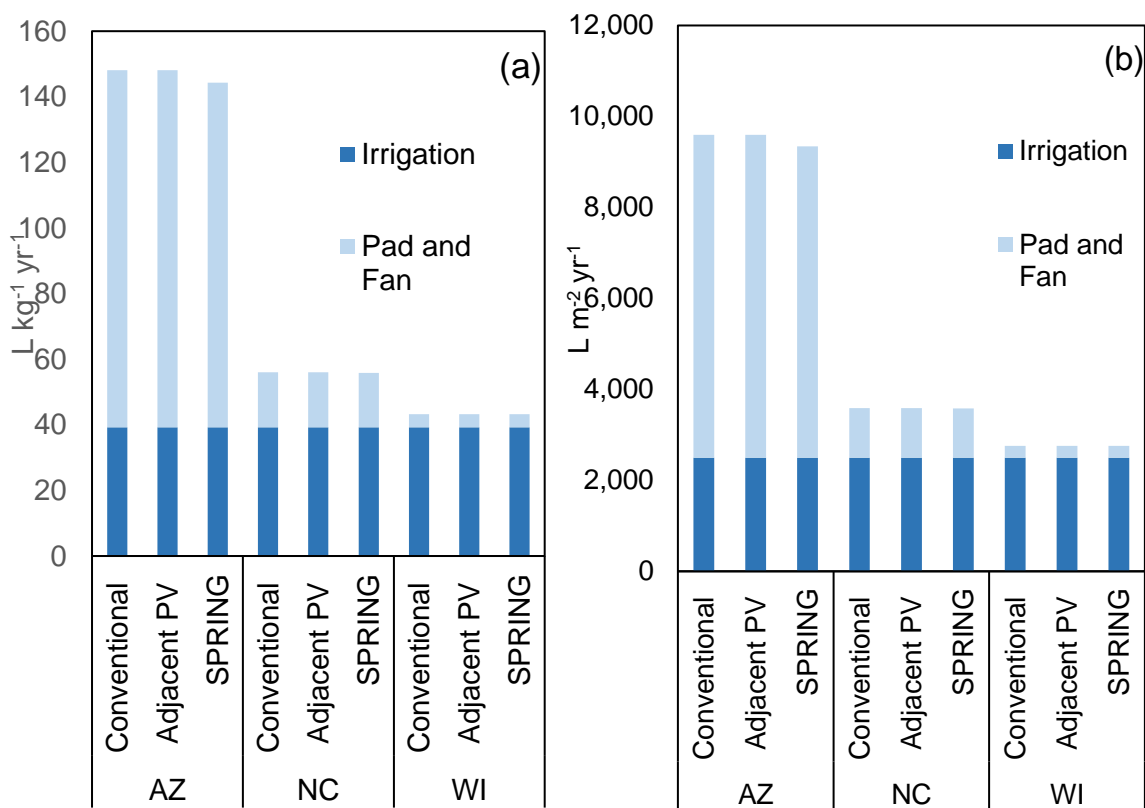


Figure S3 - Water use for cooling (pad-and-fan system) and irrigation in terms of (a) annual liters per kg of tomato and (b) annual liters per square meter. Larger water consumption is seen in Arizona due to a dryer climate, overall higher cooling demands, and subsequently more air changes needed. We assume irrigation demands to be constant since each greenhouse is being regulated to equivalent set temperatures. The SPRING design shows slightly lower water demands for pad-and-fan cooling due to overall lower air changes needed to cool the greenhouse.

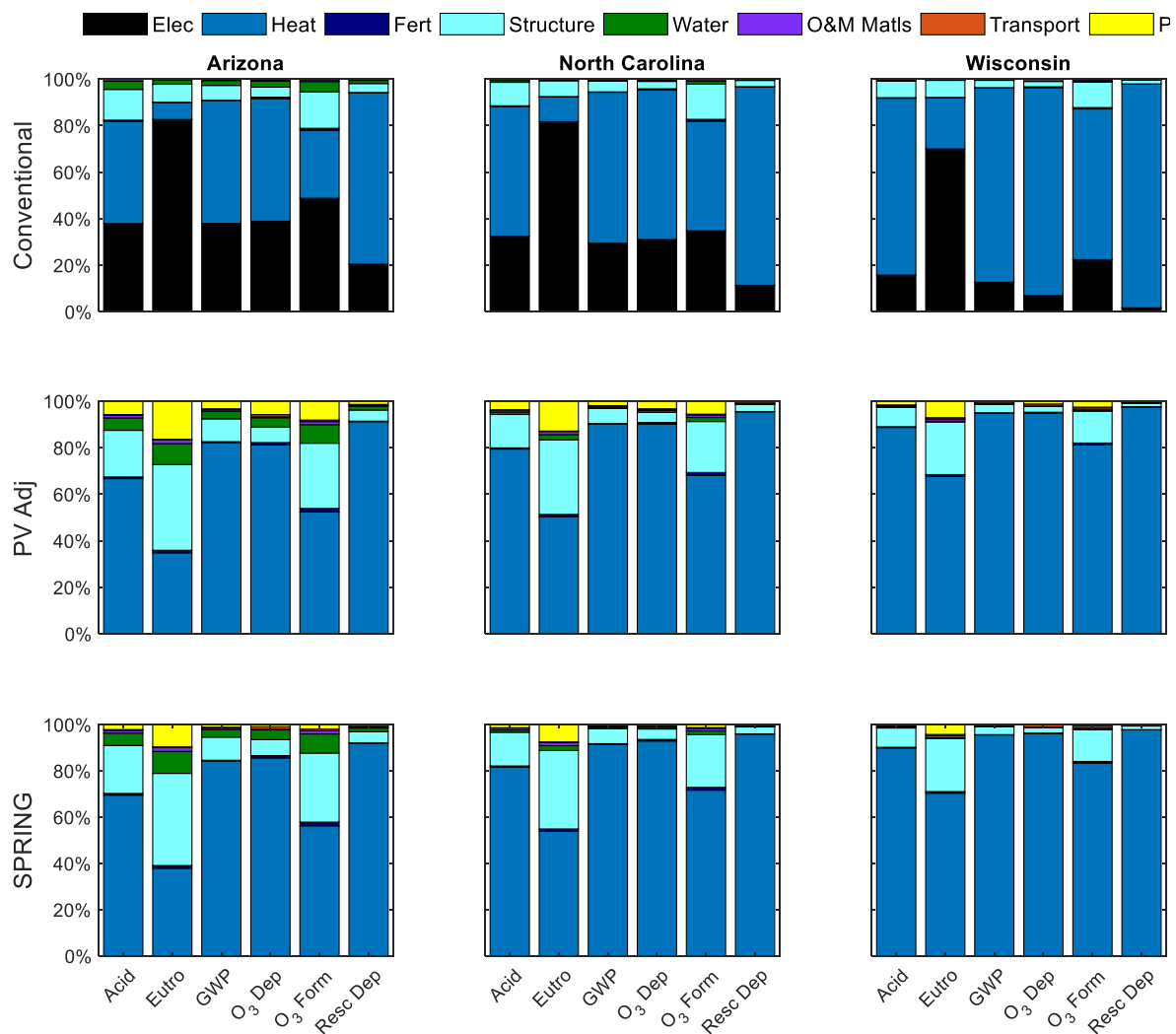


Figure S4 – Normalized life cycle impacts for a conventional, adjacent PV, and SPRING design in Arizona, North Carolina, and Wisconsin. Impact categories include acidification, eutrophication, global warming potential, ozone depletion, photochemical ozone formation, and resource depletion. All impact categories are largely affected by the heating and electricity demands. When renewable energy sources are used for electricity (PV Adj and SPRING designs), heating demand becomes a more dominant driver across impacts. Heating demand is also a more dominant driver in colder regions.

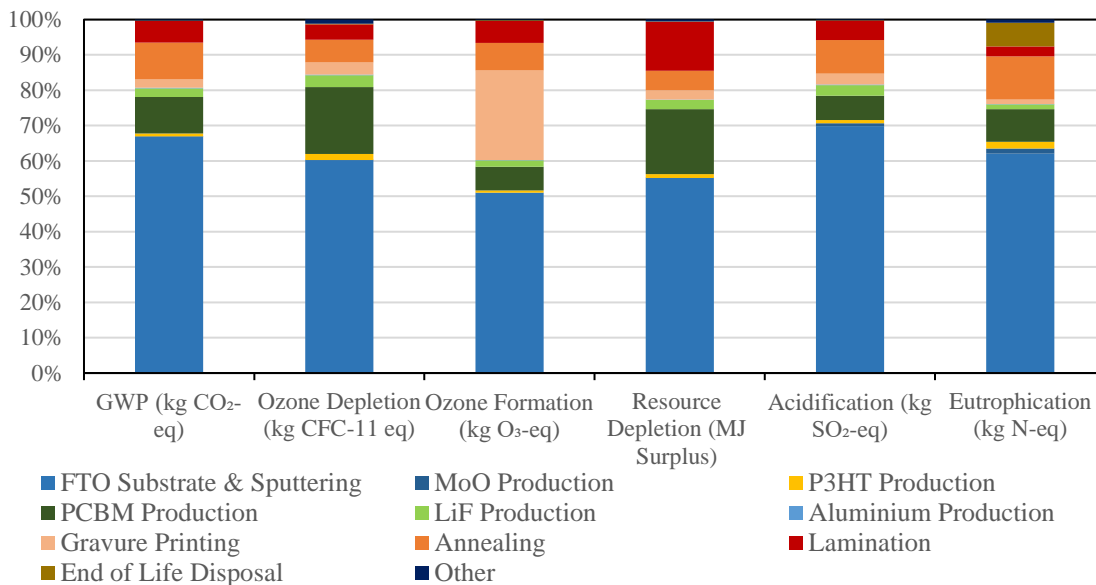


Figure S5 – Life cycle impacts of 1 m² of OPV, based on the methods and data from Tsang, Sonnemann, and Bassani (2016).

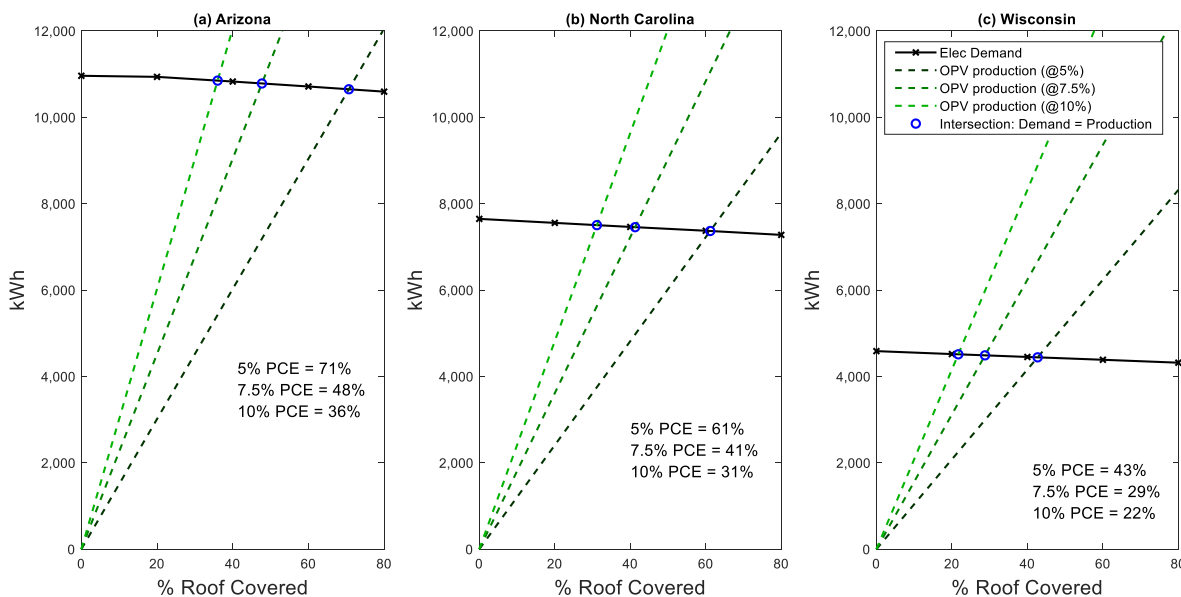


Figure S6 – Regional electricity demands and OPV production (at 5%, 7.5%, and 10% PCE) at various greenhouse roof coverage. A Conventional and PV Adjacent greenhouse would have demands of at zero percent roof coverage. Electricity demands of a SPRING design vary with increasing roof coverage of OPV. Blue circles indicate where roof coverage of OPV will result in equivalent annual electricity demands of the greenhouse.

Appendix 2.0 - Least Cost Solutions to Solar Powered Integrated Greenhouses for Off-Grid Applications

A 2.1 Introduction

Many areas of the world suffer from food insecurity associated with limited land and water availability. Additionally, climate change has negative impacts on many areas of the world where large populations are most vulnerable to food insecurity. Off-grid greenhouses could provide value in areas of the world where there is little access to existing infrastructure and electricity. While the main purpose of the thesis is to quantify the environmental and economic impacts associated with grid-connected SPRING designs, this appendix expands on the analysis to examine potential off-grid applications. This analysis uses linear programming methods to find least cost solutions for OPV plus storage systems applied to off-grid greenhouses. Reducing demands through better greenhouse materials and improving OPV efficiencies can produce significant cost reductions in off-grid greenhouse applications.

Compared with open field crop production, greenhouses can significantly reduce water requirements with rockwool growing media and hydroponic irrigation systems. However, thermal regulation of greenhouses entails significantly higher energy demands than open field systems and results in much higher greenhouse gas emissions associated with crop production (Barbosa et al. 2015; Ntinis et al. 2017). Al-Ibrahim and Al-Abbadi (2006) modeled and studied off-grid greenhouses in Saudi Arabia, noting a strong correlation between summer electricity demands required for cooling and the daily irradiance profile of the sun. They studied the growth of cucumber and tomatoes in off grid greenhouses, concluding that solar PV is a viable option for supplying electrical power to greenhouses in remote areas.

Climate-related events are known to increase food insecurity, threatening the livelihoods of communities and individual households alike (FAO 2017). Furthermore, FAO (2017) notes that adopting sustainable and resilient agriculture practices should be promoted to help future communities most vulnerable to food insecurity.

Organic photovoltaics (OPVs) offer the possibility to generate electricity using the greenhouse roof area, and represent an attractive alternative given their potential to be low cost, lightweight, flexible, and, most importantly, semi-transparent (Lizin et al. 2013; Pearsall 2011). Similar to multicrystalline silicon (mc-Si) PV cells, OPVs consist of multiple layers that include an anode, hole transport layer, active layer, electron transport layer, cathode, and encapsulation substrate layers (Lizin et al. 2013; Jungbluth et al. 2012). Certain polymers allow for semitransparent OPVs with tunable band gaps, and have achieved transmissivity of 25% (Luo et al. 2018). The cost of mobile battery storage technologies has declined significantly in recent years and is projected to continue declining in the coming years. Wilson (2018) notes that lithium-ion, vanadium, and zinc bromide batteries are expected to decline by 28%, 38%, and 45%, respectively, over the next 5 years.

This study models cost optimal solar PV and battery storage systems, with a specific focus on OPV technology, which has the potential to reduce land use through integration into the roof area of the greenhouse. Additionally, this study is used to show how rapidly decreasing investment costs for modular battery storage systems can decrease the net present cost of an off-grid greenhouse. The following sections describe the relevant input data and development of the cost optimization model. Section 2.2 reviews the objective function, constraints, decision variables, and input parameters of the solar plus storage model.

A 2.2 – Optimization model input data

Before introducing the objective function and constraints, there are important characteristics of the model to note. Input electricity demand (kWh) and insolation ($W * m^{-2}$) is used on an hourly basis over one year to determine the least cost combination of installed solar and storage capacity. The formulation is implemented in a way that a finer temporal resolution could be used if data were available for both demand and insolation values. Hourly demand values are taken from Ravishankar and O'Connor (2019), who developed a transient energy model for OPV integrated greenhouses. Their model estimates heating and cooling loads of a Venlo style, A-frame greenhouse in Phoenix, AZ, Raleigh, NC, and Antigo, WI. Their transient energy model includes a greenhouse with OPV integrated onto the roof of the greenhouse, allowing for a comprehensive understanding of how the design affects energy demands. Hourly insolation values are drawn from the National Solar Radiation Database for a typical meteorological year (TMY) (Wilcox and Marion 2008).

The investment cost of lithium-ion batteries is drawn from (Wilson 2018), who estimated commercial scale battery cost for PV plus storage to be in the range of \$409-\$572/kWh for energy storage modules and balance of system. The power conversion system costs (inverter, protection, and energy management system) show a range of \$191-\$292/kW. The distinction between cost of energy storage modules (\$/kWh) and power conversion costs (\$/kW) is important in this model because the total investment cost of a battery is inclusive of both. However, in this model, the required energy capacity (kWh) of the battery is a decision variable, but the required power (kW) is an input parameter, calculated as the largest difference in OPV generation and demand. Modeling battery power in this way insures that the battery can meet peak demand at any given hour. Input values for OPV cost are taken from Mulligan et al. (2014), who estimate future cost of

OPVs, based on current pilot scale manufacturing techniques and projections of advanced OPV production plants with increased economies of scale. Gambhir, Sandwell, and Nelson (2016) and Mulligan et al. (2014) estimate OPV module costs ranges of \$0.11/W - \$0.34/W and balance of system cost to be \$0.66/W to \$1.22/W.

A 2.3 – Optimization model formulation

The model formulation is linear with a continuous set of variables, resulting in values of OPV capacity (kW) and battery capacity (kWh). Equation 1 describes the objective function with the main decision variables to minimize cost:

Minimize:

$$\text{Total Cost} = x_{opv}C_{opv} + x_bC_b + (E_{charge,t} * CE_t + E_{discharge,t} * CE_t) \quad \text{Eq (1)}$$

Where x_{opv} is the capacity of OPVs (kW), x_b is the energy storage capacity of Li-ion battery (kWh), and C_{opv} and C_b are unit prices of the OPV and battery, respectively. The model's objective also requires the terms in parentheses, which represents the additional cost of cycling the battery at each hour, where CE_t is an increasing hourly price of battery cycling (charging or discharging). The model has perfect foresight, so each hourly store or dispatch decision is optimized simultaneously over the year. To make the model more realistic and focus on near-term dispatch decisions, a small cycling cost that increases with time is added to the objective function. This cycling cost incentivizes the model to use the battery more regularly rather than solely based on perfect knowledge of the future. It is also noteworthy that CE_t must be a very small value (10^{-5}) to avoid affecting the optimal OPV and battery sizes. For example, if CE_t is too expensive, then the model will decide to oversize the battery and OPV to avoid the added cost of cycling.

Equation 2 represents the hourly output of electricity, in kWh, from the OPV.

$$P_{opv,t} = x_{opv} * I_t * DR \quad \text{Eq (2)}$$

Where x_{opv} is the capacity (kW), as seen in the objective function from equation 1, I_t is the hourly insolation (W/m^2), and DR is the scalar de-rate factor, which accounts for losses due to temperature, shading, and degradation over the lifetime of the OPV. The following Table A1 and set of equations (3-11) include load satisfaction, power balance, state of charge, and roof area constraints, which consist of hourly decision variables (E_t) for OPV production, battery charging and discharging (E_{charge} , $E_{discharge}$), curtailment of OPV ($E_{curtail}$), and unmet load (E_{unmet}). Each of these are subscripted by t , to indicate there is a decision variable for each hour. Additionally, SoC_t represents the hourly state of charge of the battery, in kWh and DoD is

Table A1 - Model Formulation Nomenclature

Set		Notes
t		Model is used across all hours (8760) of the year
Decision Variables	Units	Notes
x_b	kWh	Energy storage capacity of the battery
x_{opv}	kW	Capacity of OPVs
E_{load}	kWh	Electrical energy demand of the greenhouse
$E_{unmet,t}$	kWh	Energy load that is unmet
$E_{charge,t}$	kWh	Battery charging
$E_{discharge,t}$	kWh	Battery discharging
$E_{curtail,t}$	kWh	Curtailment due to over production of PV & full battery
$E_{slack,t}$	kWh	Slack variable to represent either curtailment or unmet load
SoC_t	kWh	Battery state of charge at time
Input Parameters	Units	Notes
	hrs "peak	
I_t	sun"	Insolation values (i.e., solar resource)
ρ	%	Annual percent load coverage requirement
DoD	%	Battery depth of discharge
DR	%	Derate factor for OPVs
CE_t	\$	Charging price
η	%	Roundtrip efficiency of the battery

the depth of discharge (or minimum percent state of charge) the battery must maintain. The roundtrip efficiency of the battery is denoted by η_{rt} . Similarly, η_{opv} represents the performance efficiency of the OPV, which can make the available roof area (GH_{roof}) a binding constraint for least cost solutions. The term ρ describes the percent of annual load that must be covered throughout the year. The model optimizes the installed battery and OPV capacity at different values of ρ .

Load Satisfaction Constraint

$$\sum_t P_{load,t} - \sum_t P_{unmet,t} \geq \rho \sum_t P_{load,t} \quad \text{Eq (3)}$$

Power Balance Constraint

$$P_{opv,t} - P_{load,t} = P_{charge,t} - P_{discharge,t} + P_{slack,t} \quad \text{Eq (4)}$$

$$P_{unmet,t} = P_{curtail,t} - P_{slack,t} \quad \text{Eq (5)}$$

State of Charge Constraints

$$SoC_t = SoC_{t-1} + \eta * P_{charge,t} - P_{discharge,t} \quad \text{Eq (6)}$$

$$SoC_0 = x_b \quad \text{Eq (7)}$$

$$(1 - DoD) * SoC_0 \leq SoC_t \leq SoC_0 \quad \text{Eq (8)}$$

Charging Constraints (kWh)

$$P_{discharge,t} \leq x_b \quad \text{Eq (9)}$$

$$P_{charge,t} \leq x_b \quad \text{Eq (10)}$$

OPV Sizing (Roof Area) Constraint

$$x_{opv} \leq GH_{roof} * \eta_{opv} \quad \text{Eq (11)}$$

Table A2 – Base case mode input parameters

<i>Battery specific inputs</i>	
Depth of Discharge (%)	0.8
Roundtrip Efficiency (%)	0.90
Cost (\$/kWh)	491
Cost (\$/kW)	242
Lifetime (years)	7
<i>OPV specific inputs</i>	
Efficiency (%)	0.05
Cost (\$/W)	1.5
De-rate Factor (%)	0.75
Lifetime (years)	10

The described model formulation is used to analyze cost optimal solutions to off-grid greenhouses in Phoenix, AZ, as the representative location for the greenhouse. Techno-economic input parameters used for the base case scenario are shown in Table A2. This analysis demonstrates how costs, OPV capacity, and battery capacity are affected by (1) the percent annual load coverage, (2) cell efficiencies, (3) crop schedules, and (4) changes in nighttime demands. For the purposes of this study, each cost value is calculated in terms of annualized costs, since OPV and battery lifetimes are shorter than the expected 30-year life of the greenhouse itself. Although annual degradation of OPVs and battery storage is not accounted for in the analysis, OPVs are modeled with a 10-year life expectancy and batteries are modeled at a 7-year life expectancy. The following sections include results and discussion for the off-grid greenhouse applications.

A 2.4 – Model results

Greenhouse electricity demands in Arizona are highest in the summer months. Although this corresponds with the highest seasonal insolation values, these extreme climatic months are still what drive cost when trying to cover a higher percentage of annual load with off-grid systems.

Figure A1 shows the total monthly electricity demands, stacked by met and unmet load, when the annual load coverage constraint is at 95%. This figure shows that May through October have some electricity load that goes unmet. However, completely off-grid greenhouses may want to require a higher percentage of their load to be covered (i.e., provide more consistent thermal regulation) to ensure consistent crop productivity. A range of annual load coverage constraints (95%-100%) are used to see how cost is affected. Figure A2 shows how cost becomes significantly more expensive as the system must cover the last few percentages of load. These results are consistent with Masters (2013), who notes that off-grid PV systems are commonly backed up with diesel or gasoline generators, which are used when the last few percent of load cannot be covered or for extended periods without sunshine. Figure A2 also shows a range of OPV efficiencies to display how a higher efficiency can help reduce system cost. A range of OPV cost is drawn from Azzopardi and Emmott (2011) and Gambhir, Sandwell, and Nelson (2016), who note that OPVs often have much lower efficiencies than silicon-based PV cells, which have conversion efficiencies of 20%-25%. The cost of the entire solar plus storage system

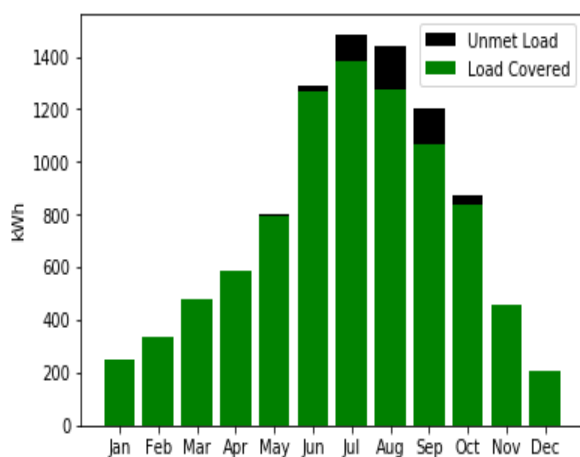


Figure A1 – Monthly greenhouse electricity loads in Phoenix, AZ, constrained to 95% load coverage ($\rho = 0.95$). Stacked bars represent total demands for each month, broken into the load covered and unmet by the OPV + Li-Ion battery storage system.

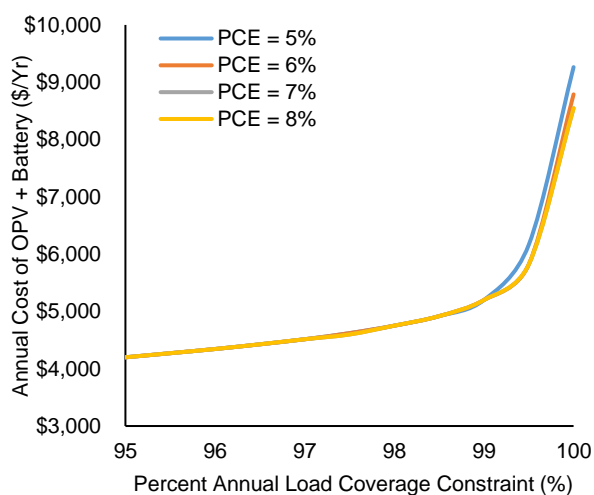


Figure A2 – Annualized cost of OPV plus storage system at varying constraints of percent annual load covered. Each line shows how cost optimal solutions vary with different OPV power conversion efficiencies (PCE), which is the rated efficiency of the modules.

shown in Figure A2 is equal for all efficiencies until the load coverage constraint exceeds 97%. At this point, lower efficiencies make the greenhouse roof area constraint binding, which requires a larger battery. However, at higher OPV efficiencies (8-9%), this constraint is not binding and results in a lower cost since a larger battery is not required. The optimal installed OPV and battery capacities are explicitly shown in Figure A3 at a given OPV cell efficiency. In Figures 3a-c, as the percent load coverage increases, the constraint on roof area becomes binding and the only option is to increase battery size.

Although greenhouses allow for extended growing seasons and more reliable crop yields, field grown crops are commonly more cost competitive (Rutledge 1998). Additionally, during

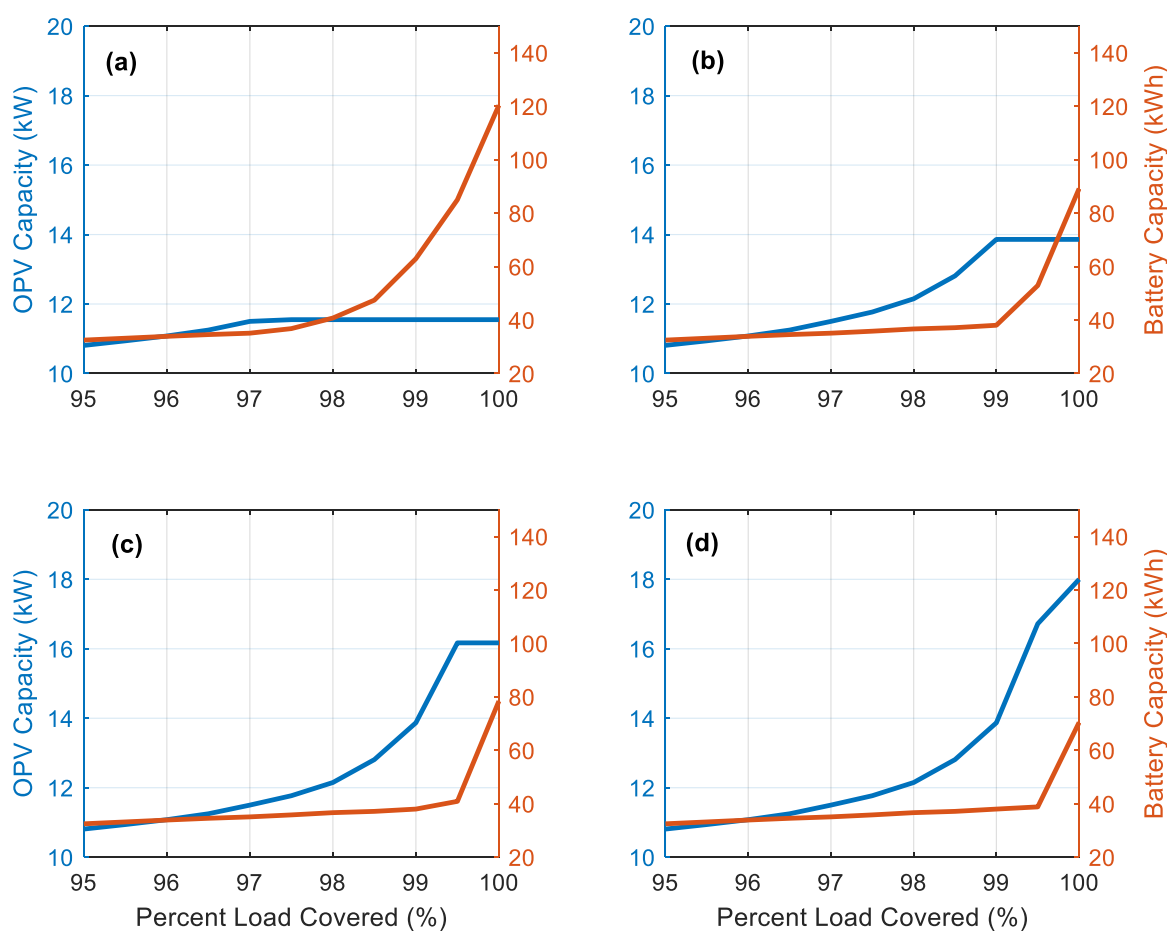


Figure A3 – Optimal OPV capacity and battery capacity at varying percent annual load coverage constraints. Plots a, b, c, d represent OPV efficiencies of 5%, 6%, 7%, and 8%, respectively.

warmer months, some greenhouse vegetable growers avoid production for clean-up and maintenance of the greenhouse (Marr 1995) . The optimization model is used to estimate the reduction in cost when July and August are excluded from the load coverage constraint. Excluding these months can reduce the OPV plus battery system cost by 11% under base case assumptions. Met and unmet load for each month when excluding July and August are shown in Figure A4. During these two months, the only time the load is being covered is when there is

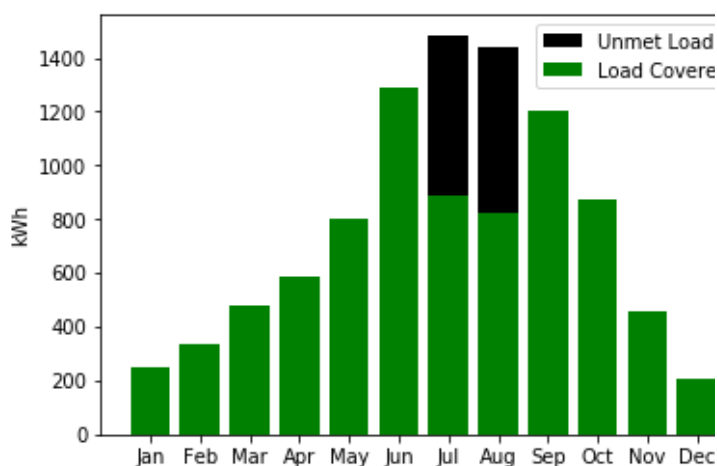


Figure A4 – Monthly greenhouse electricity loads in Phoenix, AZ, constrained to meeting all loads except for July and August.

OPV production. The battery storage system is not utilized during these months since there is no crop production and therefore no incentive to cover the load. The effects of changes in lithium-ion storage and OPV investment costs are shown in Figure A5. As previously mentioned, the cost of lithium-ion battery technology is projected to decrease significantly in the short term. Wilson (2018) estimates that Li-ion battery costs could decrease by 28% over the next five years. Figure A5 shows how the annualized system cost could change with changes in investment costs. Though not shown, results indicate that the underlying decision variables for OPV and battery capacity do not change under the base case assumptions seen shown previously in Table 2. Thus,

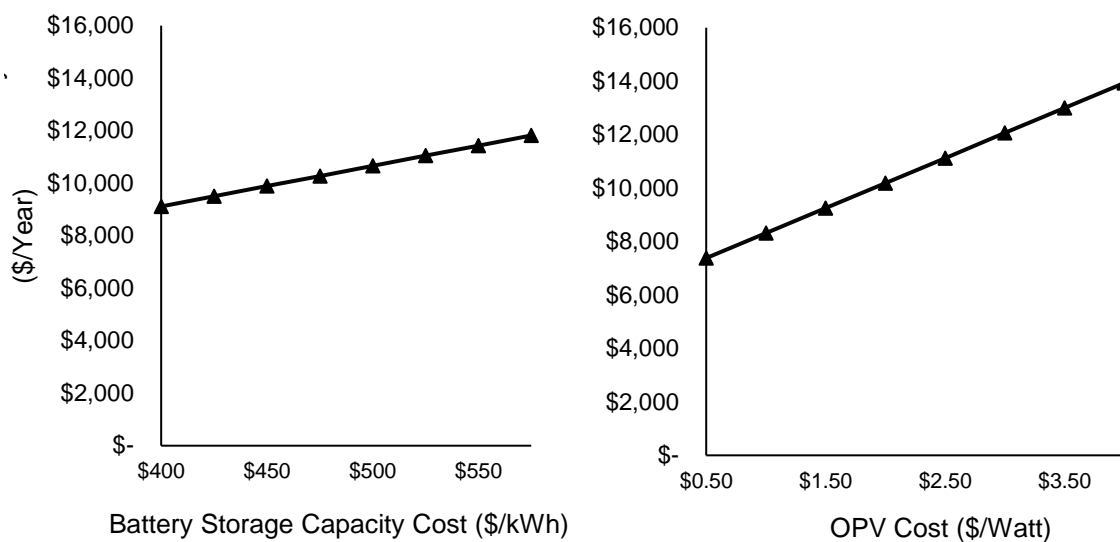


Figure A5 – Annualized cost of solar plus storage systems with respect to a change in OPV and battery costs.

results shown in Figure A5 only have decreasing costs because the unit cost of investment (i.e. \$/W for OPV and \$/kWh for battery) is lower.

The cost given by the objective function is ultimately driven by the greenhouse energy demand. Battery storage is needed to meet demand during the nighttime when there is no sun

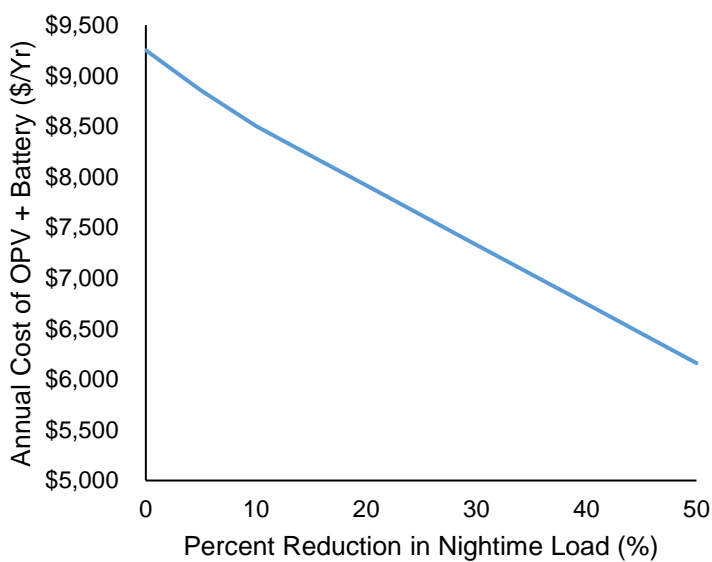


Figure A6 – Optimal solar plus storage solutions based on decreases in nighttime electricity demands.

available to generate electricity. Figure A6 shows how reduction in nighttime demand (defined as 7pm-7am) can reduce the overall costs of the solar plus storage system. These nighttime reductions could be achieved by raising the set temperature, so that large cooling demands are not required at night. Additionally, reductions in demand can be achieved with higher quality greenhouse materials with better insulation.

A 2.5 - Conclusion

This analysis uses linear programming methods to develop least cost solutions that include OPV plus storage applications for off-grid greenhouses. This analysis suggests that improvements in OPV efficiencies and investing in higher quality greenhouse materials that can reduce demands will ultimately reduce the cost of OPV and storage. In addition, significant reductions in system cost can be realized if the greenhouse is not used during the hottest months of the year when electrical load is highest. Today, many areas of the world are faced with food insecurity, that is often heightened by climate change. OPV integrated greenhouses could allow for a controlled agriculture environment powered by solar energy, without requiring additional land or access to electrical infrastructure.