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RESEARCH AND ANALYSIS

Environmental and economic impacts of solar-powered integrated greenhouses

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Abstract

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 semitransparent organic photovoltaics (OPVs) into greenhouse designs. We employ life cycle assessment 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 values for a conventional, adjacent PV and SPRING greenhouse are found to be 3.71, 2.38, and 2.36 kg CO_2 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. Our 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 Arizona to be \$3.43, \$3.38, and \$3.64 per kg of tomato for the conventional, adjacent PV and SPRING system, respectively.

KEYWORDS

food systems, greenhouse, industrial ecology, life cycle assessment (LCA), organic solar cells, sustainable agriculture

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 (Cook & Calvin, 2005; Ntinas, Neumair, Tsadilas, & Meyer, 2017). 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 80 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 (Ntinas et al., 2017; Page, Ridoutt, & Bellotti, 2012). Our analysis uses tomatoes 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 metric tons in 2002 to 171 million metric 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; Dias et al., 2017; Khoshnevisan, Rafiee, Omid, Mousazadeh, & Clark, 2013; Ntinas 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 (Ntinas et al., 2017; Page et al., 2012). 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; Ntinas 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, semitransparent (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 (Jungbluth, Stucki, Flury, Frischknecht, & Büsser, 2012; Lizin et al., 2013). Certain polymers allow for semitransparent OPVs with tunable band gaps and have achieved transmissivity of 25% (Luo et al., 2018). Previous life cycle assessment (LCA)s of OPVs have shown significantly lower energy payback times (EPBTs) and cumulative energy demands than silicon-based PV technology, suggesting that this may be an environmentally preferable technology (Anctil, Babbitt, Landi, & Raffaelle, 2010; Lizin et al., 2013; Yue, Khatav, You, & Darling, 2012).

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 nonfullerene 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, Xu, Cui, & Li, 2018), with power conversion efficiencies of 10% and visible transmittance over 34% (Li et al., 2018; Sun et al., 2019). 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 60 cm^2 have also been demonstrated with P3HT as the donor material in a semitransparent device with 5% efficiency (Strohm et al., 2018). Although semitransparent devices have historically had lower efficiencies than 5%, we use these recent improvements as a reference for our 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, & Nelson, 2016; Mulligan et al., 2014). Gambhir, Sandwell, & Nelson (2016) used representative pilot-scale processes and a detailed material inventory to estimate module and balance of system costs of \$0.23–0.34/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/W (Fu, Feldman, Margolis, Woodhouse, & Ardani, 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, semitransparent 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 LCA 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 (Anctil et al., 2010; Boulard et al., 2011; Dias et al., 2017; Khoshnevisan et al., 2013; Lizin et al., 2013; Ntinas et al., 2017; Yue et al., 2012), none have examined a regional comparison of both life cycle cost and environmental implications of OPV-integrated greenhouses. Our 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. We consider three greenhouse designs: a Solar PoweRed INtegrated Greenhouse (SPRING) with OPV as well as conventional greenhouses with and without an adjacent solar photovoltaic array. In addition, we test the performance of these three systems in three distinct climate zones represented by Arizona, North Carolina, and Wisconsin.

2 | METHODS

We conduct this LCA 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 1 kg of tomato production.

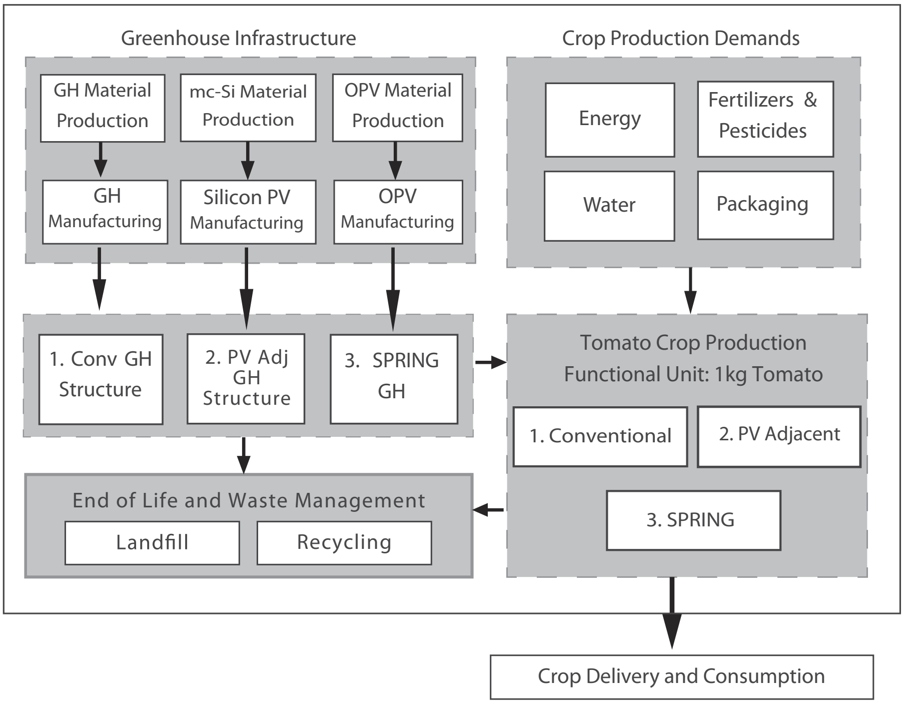

FIGURE 1 System boundary for the comparative life cycle assessment of a conventional greenhouse ("Conventional"), mono-silicon adjacent photovoltaic greenhouse ("PV Adjacent"), and Solar PoweRed INtegrated Greenhouse ("SPRING") using organic photovoltaics (OPV)

2.1 | Goal and scope

Our goal is to perform an attributional LCA 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 phases for the greenhouse and PV systems. We exclude transportation to the retailer or wholesaler and end-of-life phase for tomatoes. 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, we examine three locations in the United States, consistent with Ravishankar & O'Connor (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

For each location considered, we assume a greenhouse area of 214 m^2, consistent with greenhouse sizes seen in literature specific to greenhouse tomatoes (Marr, 1995; Snyder, 2016). Orientation of the arch-roof greenhouse runs north and south with each 27° roof tilt facing east and west. This orientation is a 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, we assume a consistent value of 600 km transport distance for greenhouse materials and 50 km for concrete transportation to represent a local concrete supplier, for a total of 7400 ton-km of freight using a truck for land transportation.

We choose to model the cost and environmental performance of greenhouse-grown tomatoes since they account for the majority of greenhouse vegetable sales (USDA, 2012) and are consistent with energy demands of Ravishankar & O'Connor (2019). The USDA notes that U.S. and Canadian greenhouse production can reach 500 metric tons per hectare, while the average yield for U.S. field tomatoes is around 34–36 metric tons per hectare (Cook & 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 (Launeck, 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 (Cook & Calvin, 2005; Launeck, 2016).

Our functional unit is 1 kg of tomato and two crop cycles per year are assumed. Our 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 m^2 greenhouse, about 460 to 576 plants can be grown. Thus, we assume two crop cycles 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 to 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. Our base case analysis in Arizona does not consider decreases in crop yields from OPV integration in the SPRING design. Although the energy demands in each location represent maintaining specific set temperatures for greenhouse tomato production, crop yields may vary between regions depending on the solar resource. However, we perform uncertainty analysis to determine the effect of crop productivity on cost and environmental impacts.

Given the novelty and wide range of OPV materials, we selected an OPV design 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/PC_{60}BM 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 et al. (2013), Frischknecht, Wyss, Knopfel, & Baloutski (2015), and Anctil (2012). The OPV module production process uses the data and approach described in (Tsang, Sonnemann, & Bassani, 2016), who studied the life cycle assessment of an OPV with poly(3-hexylthiophene) (P3HT) as the donor material and phyenyl-C_{61}-butyric acid methyl ester (PCBM) as the acceptor materials in the OPV cell. Tsang et al. (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 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 required to maintain set temperatures (Ravishankar & O'Connor, 2019). We utilize methods described in Ravishankar & O'Connor (2019) to determine energy demands as they vary with increasing roof coverage of OPVs (see Figure S6). 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

$$P_{DC} = \frac{E_A}{DR * I_A} \tag{1}$$

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). To compare the environmental impact of each PV system, we calculate each PV system's global warming potential (GWP), 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, Frischknecht, Olson, Sinha, and Heath (2016).

$$\mathrm{EROI_{el}} = \frac{\mathrm{Out_{el}}}{\mathrm{Inv}} \tag{2}$$

$$\mathrm{EPBT} = \frac{\mathrm{T}}{\mathrm{EROI_{el}}} \tag{3}$$

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, Wyss, Knöpfel, S., and Balouktsi (2015). Equation (4) describes the calculation for the output of electricity ($\mathrm{Out_{el}}$), where (η_{PV}) is the cell's conversion efficiency.

$$\mathrm{Out_{el}} = I_A * \eta_{PV} * \mathrm{PR} \tag{4}$$

TABLE 1 Annual energy demands for each greenhouse design and location

	Phoenix, Arizona			Raleigh, North Carolina			Antigo, Wisconsin			
Appliance	**SPRING**	**PV Adj**	**Conv**	**SPRING**	**PV Adj**	**Conv**	**SPRING**	**PV Adj**	**Conv**	**Unit**
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

We use the modeling assumption used in Raugei 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, our 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, we include additional installments of PVs and OPVs 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 three installments over the 30-year lifetime of the greenhouse system. The ecoinvent 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 S.1 in Supporting Information S1 (Wilcox & Marion, 2008).

We use ecoinvent 3.3 data, 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 factovvxr of 0.975 (see Table S.2 in Supporting Information S1).

The annual crop materials inventory for each location is adopted from the ecoinvent 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, we consider a range for certain inputs, including electricity demand, heating demand, and irrigation.

We determine the energy demand of the greenhouse using a transient energy model that simulates year-round heating and cooling demands, fully described in Ravishankar & O'Connor (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 semitransparent indium tin oxide with PEDOT:PSS serving as the hole transport layer and a 100-nm active layer blend of P3HT:PCBM. The authors note that the net transmittance of light entering the greenhouse (with 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 & O'Connor (2019), we analyze how electricity demands are affected by increasing roof coverage of OPV, allowing us to match the OPV capacity to meet average annual electricity demand (see Figure S5). 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 plant^{-1} day^{-1}) and dependent on the stage of growth and season (Peet & Welles, 2005). WU_i is estimated by plant type according to the two crop cycles previously noted and is assumed to be consistent for each greenhouse location given that temperature set points are the same (see Figure S3). 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 plant^{-1} day^{-1}, respectively. WU_{pf} is calculated specific to each location 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).

$$\dot{m}_e = \frac{Q_a \rho \left(W_{in} - W_{out}\right)}{A_f} \tag{5}$$

TABLE 2 Greenhouse inputs for Monte Carlo simulations

(a) MCS variable ranges				
Equations (6)–(9) Variables	**MCS variables**	**Min**	**Max**	**References**
OPV_U	OPV cost ($/W)[a]	0.77	4.11	Azzopardi & Emmott (2011), Gambhir, Sandwell, & Nelson (2016)
T_{OPV}	OPV lifetime (year)	5	10	Gambhir, Sandwell, & Nelson (2016)
D_E	SPRING electric demand (kWh/year)[b]	4,500	8,500	Ravishankar & O'Connor (2019)
	Conv/PV Adj (kWh/year)	5,900	9,000	Ravishankar & O'Connor (2019)
D_H	SPRING heating demand (MMBtu/year)[b]	25	46	Ravishankar & O'Connor (2019)
	Conv/PV Adj (MMBtu/year)	25	46	Ravishankar & O'Connor (2019)
C_E	Cost of electricity ($/kWh)[b,c]	0.07	0.13	EIA (2018)
C_H	Cost of natural gas ($/MMBtu)[b,c]	6.2	12	EIA (2018)
C_L	Cost of land ($/acre)[a]	17,000	31,000	USDA (2015)
Y_C	Crop yields (kg/plant)	3.3	4.9	Rutledge (1998)
(b) Constant inputs for greenhouse costs and revenue				
	Constant variables	Value		
C_{GH}	Greenhouse cost ($/S.F.)[a,d]	25	ATLAS greenhouses	
V_M	Market value ($/kg)[e]	4.4	Raleigh greenhouses	
D_P	Plant density (plant/greenhouse-year)	900	Snyder (2016)	
C_{OM}	Annual materials and labor ($/S.F.)	2.3	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 (year)	30	Fu et al. (2017)	
t_{GH}	Greenhouse lifetime (year)	30	Boulard et al. (2011)	

[a] Represents investment costs (C_i) amortized into loan payments.
[b] Represents variable costs (C_v) or demands incurred annually.
[c] Denotes annual increases in cost at 1%.
[d] Communications with ATLAS Greenhouse Co. include cost estimations of a multi-bay, gutter connected, 8 mm polycarbonate greenhouse.
[e] Communications with local greenhouse growers in Raleigh, NC.

where W_{in} is the humidity ratio ($\frac{kg_{water}}{kg_{dry\ air}}$) 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. We omitted carcinogenic and ecotoxicity impact categories due to uncertainty and data availability. Additionally, we quantify land and water demands per functional unit to compare the three greenhouse systems.

We use open LCA software to determine the drivers of environmental impacts and to address the uncertainty associated with our results. We conduct an MCS to quantify the uncertainty associated with environmental impacts of each greenhouse system in each location. We analyzed historical heating and cooling degree days from NOAA (2018), which were found to be normal distributions for heating and cooling using a Jarque–Bera test for normality in each location. For all other parameters related to pesticides, fertilizers, operational materials, greenhouse structure, water use, and PV systems, we assume a uniform distribution (±20%), 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, we compare costs using net present value and the levelized cost of tomato production. Levelized cost is used to compare each greenhouse system's cost associated with producing 1 kg 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).

$$R_t = I_A - P_L - C_V \tag{6}$$

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

$$I_A = V_M \times Y_C \times D_P \tag{7}$$

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.

$$P_L = OPV_U \times OPV_C \times CRF_{OPV} + C_L * A_{GH} \times CRF_{GH} + C_{GH} \times A_{GH} \times CRF_{GH} \tag{8}$$

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

$$C_V = D_E\, C_E + D_H C_H + C_{OM} A_{GH} \tag{9}$$

Note that for a SPRING and adjacent PV design, P_L would include annual payments for the respective PV system (see Table S.1 in Supporting Information S1) but would not incur electricity costs seen in C_V (Equation (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 (Equation (8)) but does incur electricity costs (Equation (9)). We use a 10% discount rate and a 30-year greenhouse lifetime to represent a typical greenhouse useful life (Boulard et al., 2011). Additionally, we assume a consistent investment tax credit of 30% throughout the analysis for each PV system. Although this federal incentive is stepping down in coming years, we recognize uncertainty in investment costs 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 costs to be as low as \$7.85/m^2 , which equates to \$0.16/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, we allow the OPV investment cost to vary between \$0.77/W and \$4.11/W. Additionally, greenhouse energy demands can vary depending on the specific climate, energy management strategies, and greenhouse structure (Shen, Wei, & Xu, 2018).

To better understand the impact of these uncertainties, we conduct another MCS focused on greenhouse economics. We also use stepwise regression analysis 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 and location. 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.

We also estimate abatement cost per metric ton of CO_2

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

where C is the levelized cost of electricity (\$ kWh^{-1}), and E the emission factor (kg-CO_2 kWh^{-1}), each of which is discounted for the 30-year greenhouse lifetime (see Supporting Information S1 for a table of all inputs used for abatement costs). Emission factors are drawn from ecoinvent for each state's respective North American Electric Reliability Corporation region, and the price of electricity is taken from EPA (2016) for each specific state (see Table S.1 of Supporting Information S1).

3 | RESULTS

We first present 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. We also present the environmental impacts returned from the MCS across

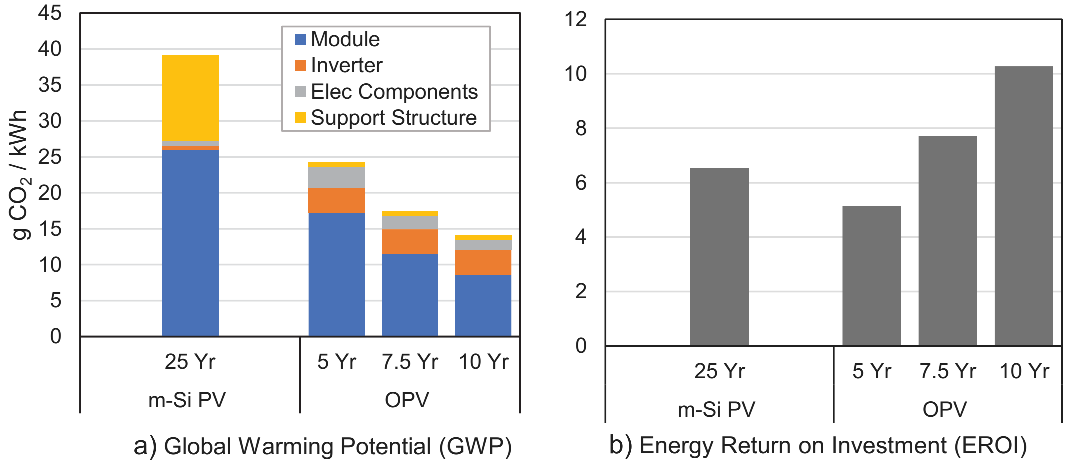

FIGURE 2 Impacts of mc-Si PV and OPV integrated with a greenhouse in Arizona. Figure includes (a) global warming potential and (b) energy return on investment. OPV lifetimes of 5, 7.5, and 10 years are shown to represent uncertainty modeled throughout this analysis (see underlying data in Supporting Information S2)

all three greenhouse scenarios in Arizona, North Carolina, and Wisconsin. Our 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, we first consider 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 (see Figure S5). 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), we find that the range of OPV lifetimes has negligible effects on EPBT. OPVs are estimated to have an EPBT of 0.97 years and mc-Si shows 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 kilogram 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 estimate a GWP of 2 kg CO_2-eq/kg tomato. Page et al. (2012) estimate 2.03 and 2.28 kg CO_2-eq/kg tomato for a medium and a 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, we assume that solar-generated electricity offsets grid electricity with an emissions rate equal to an annual average value that remains constant throughout the year. However, we address this simplified assumption 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 our analysis, there may be some slight variance in real greenhouses which may schedule crop production to avoid high energy demanding months.

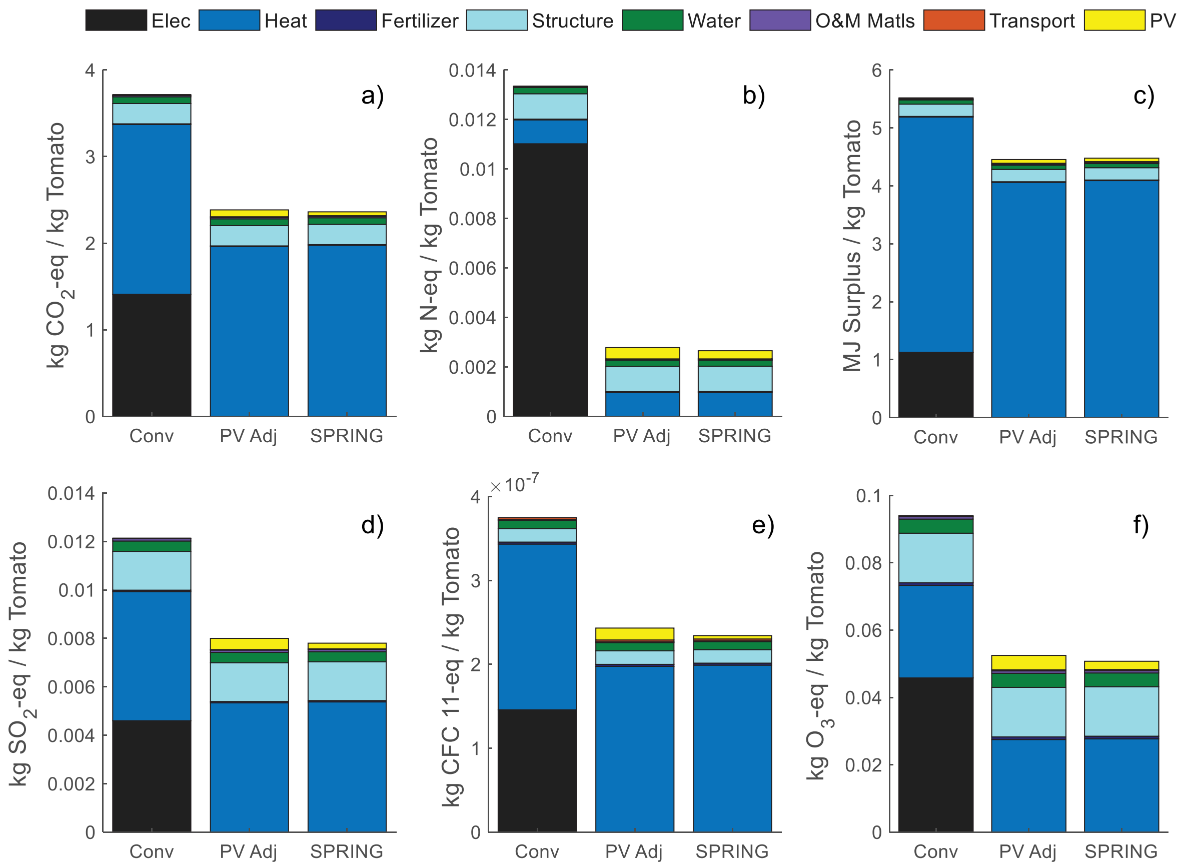

FIGURE 3 Life cycle environmental impacts from tomato production in Arizona using a conventional greenhouse (Conv), a conventional greenhouse with co-located solar photovoltiacs (PV Adj), and a Solar PoweRed INtegrated Greenhouse (SPRING): (a) global warming potential, (b) eutrophication, (c) acidification, (d) resource depletion, (e) ozone depletion, and (f) photochemical ozone formation (see underlying data in Supporting Information S2)

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 CO_2-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 relying solely on annual average emissions factors, we also utilized marginal emissions rates from Azevedo, Horner, Siler-Evans, and Vaishnav (2017), which utilize a method described in Siler-Evans, Azevedo, and Morgan (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. We found, however, that this temporal variation in emissions rate has minimal impact on our 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. While we assume 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, Leary, McConnell, & Wilkerson, 2016). Pad-and-fan systems use evaporative cooling methods to reduce

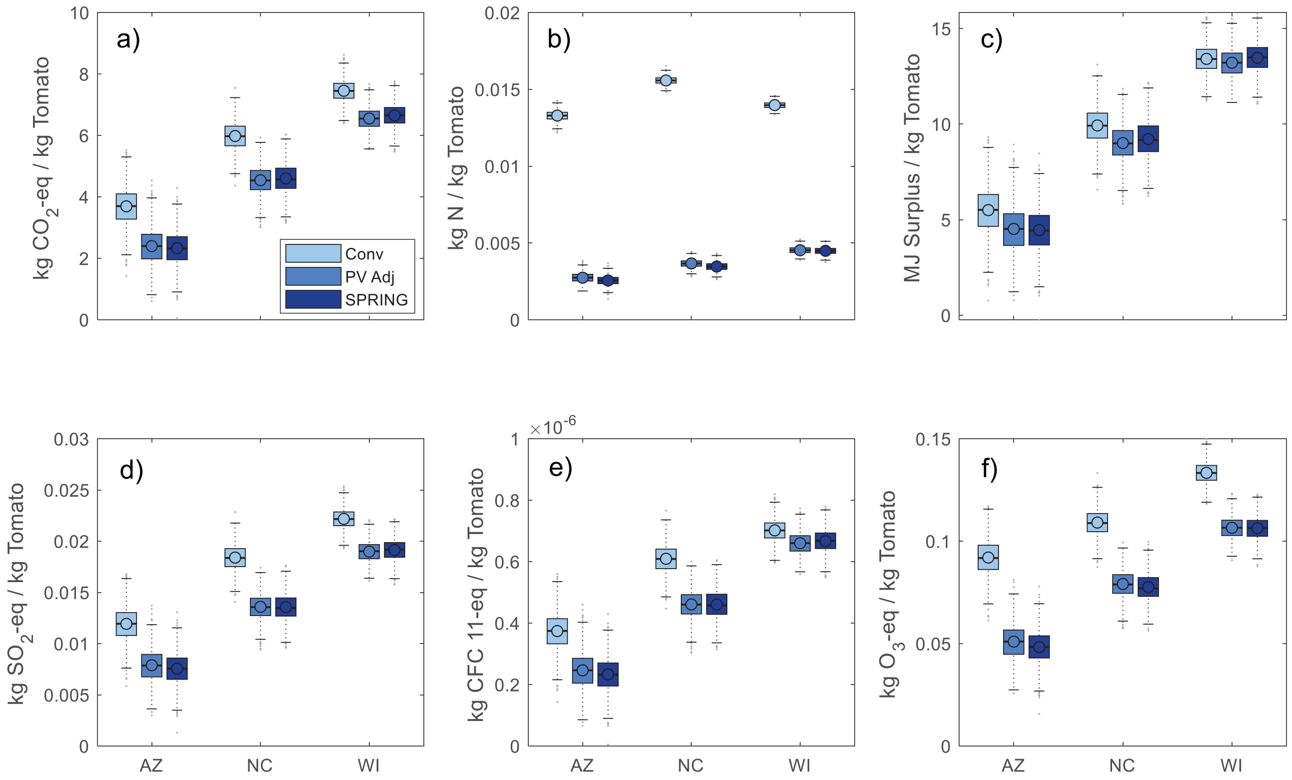

FIGURE 4 Uncertainty analysis of each greenhouse system and location for impact categories: (a) global warming potential, (b) eutrophication, (c) resource depletion, (d) acidification, (e) ozone depletion, and (f) photochemical ozone formation. Box and whisker plots display the median (center line), average (circle), quartiles (boxes), and 95th and 5th percentiles (whiskers) (see underlying data in Supporting Information S2)

air temperature by converting sensible heat energy into latent heat by evaporation (Kubota, Sabeh, & 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 we include evaporative cooling throughout night and slightly higher pad efficiencies than Sabeh et al. (2011), we find 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, due to lower cooling demands and higher levels of outside humidity (see Figure S3).

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 m^{-2} $year^{-1}$ in AZ, NC, and WI; SPRING designs would produce 17.2 kg tomato m^{-2} $year^{-1}$ in each location since no additional land is required (see Table S.2 of Supporting Information S1).

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/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. We perform an MCS to address the uncertainty in the net present value and present cost

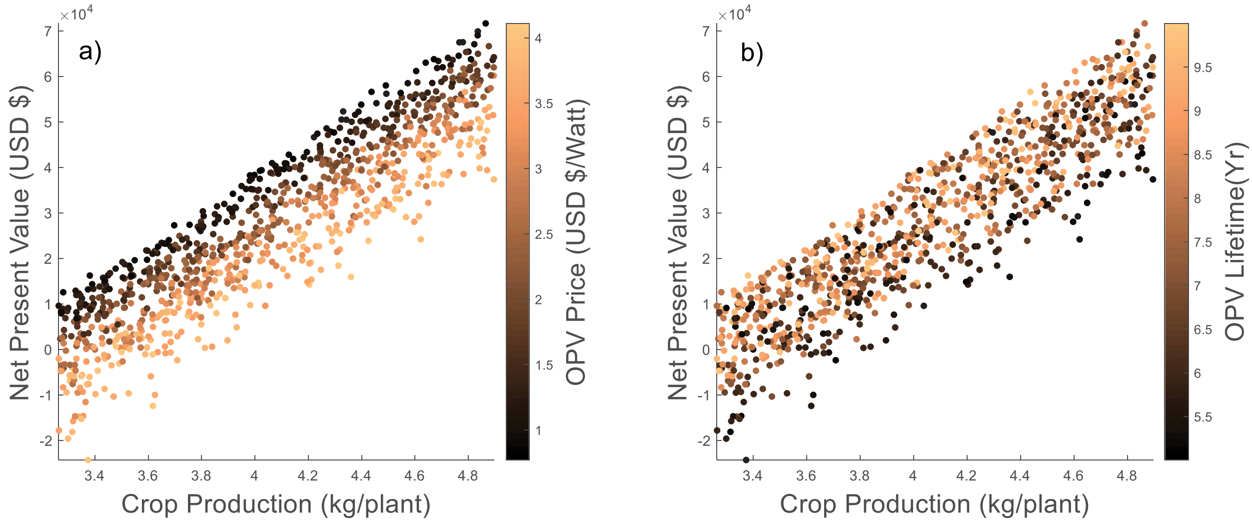

FIGURE 5 SPRING net present values based on Monte Carlo simulation. Panel (a) shows results of crop production sensitivity comparison with a gradient of OPV prices. Panel (b) shows the same results as (a), with a gradient of OPV lifetime (see underlying data in Supporting Information S2)

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 $29,000 (see Figure S2). Figure 5 shows the MCS net present value results for a SPRING design in Arizona. The MCS results shown in Figure 5 include variation in all uncertain input parameters, but we highlight the sensitivity to crop production, OPV prices, and OPV lifetime. By visual inspection, OPV cost ($/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 SPRING system is $3.43 per kilogram, $3.38 per kilogram, and $3.64 per kilogram. Higher average costs for the SPRING system can be attributed to the higher costs and lower lifetime of OPVs. Although the average is higher for a SPRING system, MCS results show the SPRING design is more cost-effective than the conventional or adjacent PV design when the investment costs ($/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 CO_2 equivalent in each region for the SPRING system. Regional variances in abatement are costs due to differing regional emission factors, insolation values, and electricity prices (see Table S.1 of Supporting Information S1). For reference, Figure 6 includes EPA's social cost of carbon ($55 per ton CO_2 in 2030 at a 3% discount rate), which represents the estimated cost of CO_2 damages (EPA, 2010). As the lifetime of OPVs increases and unit costs fall to the projections estimated by Gambhir, Sandwell, & Nelson (2016) and Mulligan et al. (2014), OPVs yield abatement costs lower than the social cost of carbon.

4 | DISCUSSION

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. Our 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.

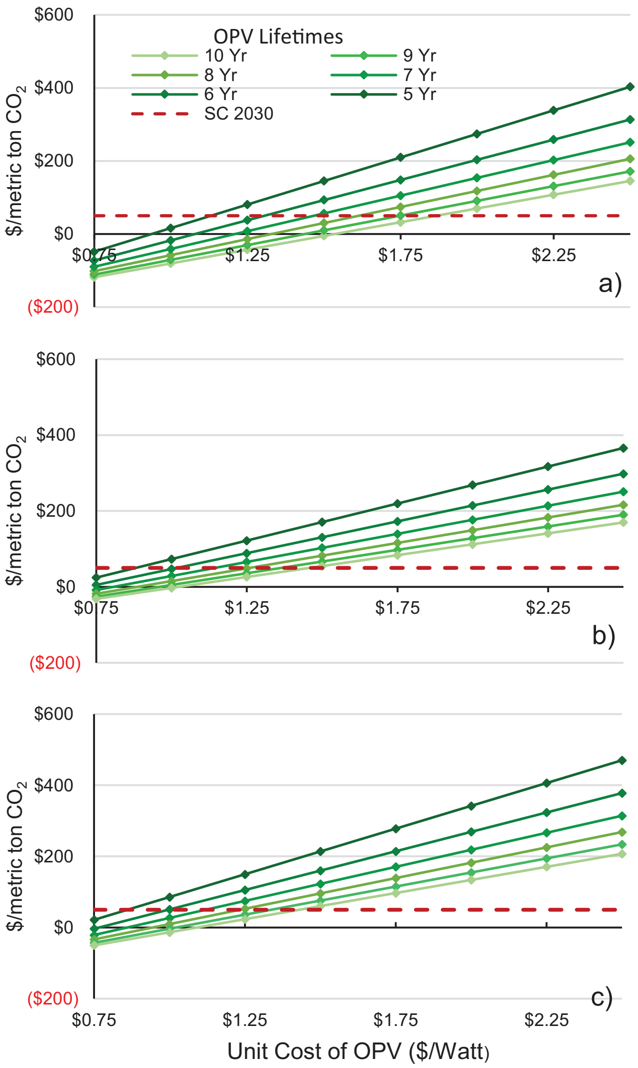

FIGURE 6 Abatement cost of the SPRING system compared with the conventional greenhouse in (a) Arizona, (b) North Carolina, and (c) Wisconsin. Dashed red line represents social cost of carbon at a 3% discount rate in 2030 (SC 2030) reported by EPA (2010) (see underlying data in Supporting Information S2)

Emerging OPV technology has potential for greenhouse integration due to its lightweight, semitransparent 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.

Although our 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 United States, 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 et al., 2016), we find that energy consumption for thermally regulating greenhouses in the use phase is what drives environmental impacts in crop production for each region we 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 we examined. Future work on semitransparent 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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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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