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Luminescent Solar Concentrator Greenhouses for Concurrent Energy Generation and Lettuce Production in the United States

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Abstract. Meeting the needs for both renewable energy production and increased food supply to sustain growing communities remains a global challenge. Agrivoltaic greenhouses can meet these dual needs in one plot of land, mitigating land competition. Luminescent solar concentrators (LSCs) benefit these systems by providing additional design flexibility for crop-specific spectrum modification while allowing sufficient light transmission for crop growth. Silicon quantum dots (Si QDs) have received growing interest as a material candidate for LSC greenhouses as well. We present an investigation into the impact of Si QD film concentration on the energy demands of an LSC greenhouse in Phoenix, Arizona through a comprehensive modelling framework. We then expand upon one Si QD concentration and simulate LSC greenhouses in 48 locations across the United States. We demonstrate LSC greenhouses can supply their annual energy demands in warm climates, where greenhouse heating demands remain low. LSC greenhouses can also be as profitable as the conventional glass greenhouse if the crop yield remains comparable or if the greenhouse can benefit from net metering.

Keywords: Luminescent Solar Concentrators, Greenhouses, Techno-Economic Analysis

1. Introduction

As the global population is projected to increase to 10 billion people by 2050, sustainable food systems must concurrently expand to meet this rising food demand [1]. In addition, global electricity demands are expected to increase, with as much as two-thirds of global electricity generation coming from renewables and nuclear [2]. To meet both of these needs, agrivoltaic systems promote dual land use by strategically combining photovoltaics (PV) and agriculture for both renewable energy and crop production [3], [4]. These systems typically involve either PV installations over open fields or strategic placement of PV cells on agricultural buildings [5]. Alternatively, agrivoltaic greenhouses present a promising opportunity due to the closed environment, where crops are protected from adverse environmental conditions. Furthermore, the controlled growing conditions, such as light, temperature, and humidity, allow for year-round crop growth. However, to supply the significant amounts of energy needed to maintain these conditions, greenhouses are often powered by non-renewable energy sources, leading to more greenhouse gas emissions and expensive operation [6]. The power supplied by intentionally designed PV glazing on agrivoltaic greenhouses can address this problem.

There remains a design challenge for PV glazing on agrivoltaic greenhouses. Fully opaque PVs generate electricity at the expense of light transmission, thereby inhibiting crop photosynthesis [7]. Semi-transparent or transparent PV cells transmit more light to the crops, but suffer from low power conversion efficiencies (PCEs) [8]. Luminescent solar concentrators (LSCs) have received growing interest in the agrivoltaics community as their higher transparency and spectral shaping of transmitted light can benefit crop yield while concentrating light onto small-area PV cells [9], [10], [11], [12]. An additional advantage of LSCs is their ability to absorb both diffuse and direct light, eliminating the need for solar tracking [13]. Our LSC roof design shown in Figure 1 consists of a polymer film embedded with a luminescent nanomaterial surrounded by small-area PV cells on a glass pane. The luminescent film partially absorbs and downshifts incident sunlight to a longer wavelength, guiding the reemitted light to surrounding small-area solar cells *via* total internal reflection.

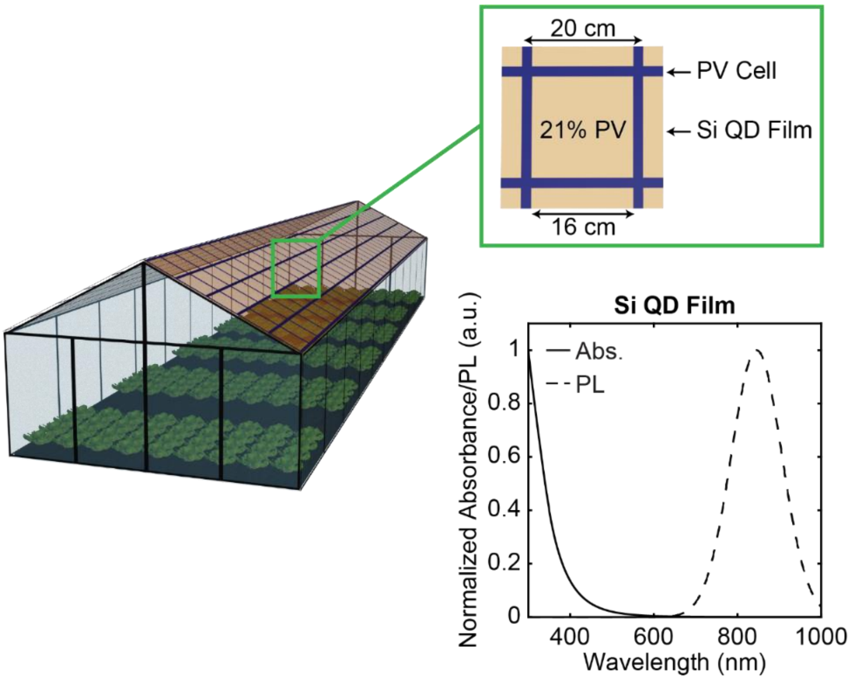

Figure 1. *Schematic of LSC greenhouse with inset showing LSC geometry. The Si QD film absorbs primarily UV light and has NIR photoluminescence.*

The broad LSC design space, including color, transparency, and size, provides ample opportunity for exploration in the context of agrivoltaics. Our previous work on an LSC greenhouse that used a 5 percent by weight (wt%) silicon quantum dot (Si QD) film as the luminescent material showed that the LSC roof could provide all of the renewable electricity needed to run a greenhouse in Arizona for a year [9]. Si QDs are an attractive material candidate for LSCs due to their nontoxicity, broad absorption spectrum, and minimal overlap between their absorption and emission spectra [14]. However, this study was limited to one film size (8 cm x 8 cm) and one film concentration.

In this paper, we present a computational investigation of Si QD LSC greenhouses with differing concentrations from both an energy and an economic perspective. These greenhouses use a 16 cm x 16 cm film size to better match the PV coverage ratio (21%) to the amount of light blocked by greenhouse framing (20%). To understand the impact of film concentration on the operation of the greenhouse, we varied the Si QD loading from 0.1 to 1.5 wt% in steps of 0.1 wt% for LSC greenhouses in Phoenix, Arizona. This lower film loading range was chosen to avoid scattering at higher concentrations, which impacts power generation [15]. We then modelled LSC greenhouses with one film concentration in dozens of locations across the continental United States to determine their potential as net zero energy (NZE) greenhouses and their economic viability relative to that of a conventional glass greenhouse.

2. Simulation Approach

Our modelling framework combines solar resources [9], heat and energy [16], power generation [17], lettuce (cv. Rex) crop yield [18], and economic [19] models to analyze the greenhouse from all aspects of its operation. All simulated greenhouses included shade cloths at gutter height and diffuser films to reflect growing best practices [20], [21].

First, we retrieved downward and diffuse irradiance data from the National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resource (POWER) Database for 48 locations in the conterminous United States [22]. Using this data, we determined hourly sunlight transmitted and absorbed through the roof and walls of the greenhouse both with and without the LSC roof structure. Through optical modelling, we also determined transmitted color fractions depending on the concentration of the Si QD film. As Si QDs absorb ultraviolet (UV) light and emit near infrared (NIR) light, shown in the absorption and photoluminescence (PL) spectra in Figure 1, higher Si QD loadings reduced transmitted blue light. Furthermore, we employed an hourly shading algorithm developed by Albright et al. to control the daily light integral (DLI) [23]. The transmittance of the shade cloth was manually selected to mitigate the light absorbed by the Si QDs in the extended photosynthetically active radiation (ePAR) range of 400 – 750 nm. With increasing concentration, the shade cloth transmittance increased as well to meet a target average annual extended DLI (eDLI) of 19.18 mol/m^2/day. This value represents the typical target DLI of 17 mol/m^2/day for growing lettuce but includes far-red light in the range of 700 – 750 nm [23], [24].

Based on the amount of light absorbed by the luminescent film and the PV cells from the optical model, we used a power generation model to calculate hourly electricity generation. Using the amount of light transmitted through the roof and the walls calculated with the optical model, we then used an environmental model to determine hourly greenhouse temperatures. We retrieved Typical Meteorological Year 3 (TMY3) climate data from the National Renewable Energy Laboratory (NREL) to consider ambient conditions [25]. To maintain temperature setpoints of 21–28 °C during the day and 17–18 °C at night, the heating and cooling demands were also calculated. The shade cloths used during the day to maintain a target eDLI were also used at night for temperature regulation. With the transmitted color fractions determined from the optical model and the hourly crop temperature determined from the environmental model, the spectrum-, eDLI-, and temperature-dependent dry mass growth of Bibb lettuce was determined. We used the model by Abedi et al. [18] as it incorporates the effects of NIR light on crop growth.

Lastly, we computed the net present value (NPV) assuming an interest rate of 10% and a lifetime of 30 years for each greenhouse to determine profitability. Considering greenhouse construction costs, LSC material costs, heating and electricity costs, crop revenue, and potential revenue from net metering, the NPV provides a figure of merit to balance the competing priorities of crop growth and energy generation for LSC greenhouses. As the lifetime of the LSC film was assumed to be similar to those for luminophore films on the market, the LSC film needed to be repurchased every five years [26]. For calculating crop revenue, we assumed a lettuce selling price of $2/kg and that any heads of lettuce smaller than a marketable size were sold as chopped baby lettuce leaves at the same price [27]. If the LSC greenhouse produced excess electricity than it demanded, we assumed the surplus electricity was sold back to an electric grid at $0.13/kWh, which is the average net metering price across the United States [28]. The cost of electricity was also location dependent [29]. The NPV for LSC greenhouses was calculated with respect to that for the conventional greenhouse in the same location. Conventional greenhouses are constructed in the same manner, but only have glass panes as the roofing material.

3. Results

As Arizona is colloquially known as the winter lettuce capital in the United States [30], we simulated Si QD LSC greenhouses with varying Si QD film concentrations in Phoenix, Arizona. Figure 2 illustrates the annual energy demand and supply depending on Si QD loading. The total energy demand is the sum of the heating and cooling demand. Figure 2(a) shows that with increasing Si QD concentration, the heating demand continuously increases while the cooling demand increases slightly but remains relatively constant. Increasing the concentration of the Si QDs inside the film decreases transmission, which affects the heating and cooling demands. However, since the shade cloth transmittance is adjusted for each concentration to meet a target eDLI, and the shade cloths also modify the heat retained in the greenhouse, this significantly changes the effect of concentration on heating and cooling demands. As the concentration increases, the shade cloth transmittance increases, which in turn decreases the amount of heat retained in the greenhouse at night and increases the heating demand.

The cooling demand increases slightly as well due to the increase in shade cloth transmittance. The employed shade cloth algorithm depends on a target eDLI, but the shade cloth is non-spectrally selective. The increase in shade cloth transmittance allows more light outside of the ePAR range to enter the greenhouse as well. As greenhouse temperature increases with increasing insolation, there is a higher cooling demand to lower the greenhouse temperature to its daytime setpoint. However, the shade cloth transmittance for the lowest and highest Si QD concentrations studied only differed by about 5% transmittance. This resulted in all LSC greenhouses transmitting around 30% of incident light to meet eDLI requirements. Therefore, the cooling demand did not change significantly.

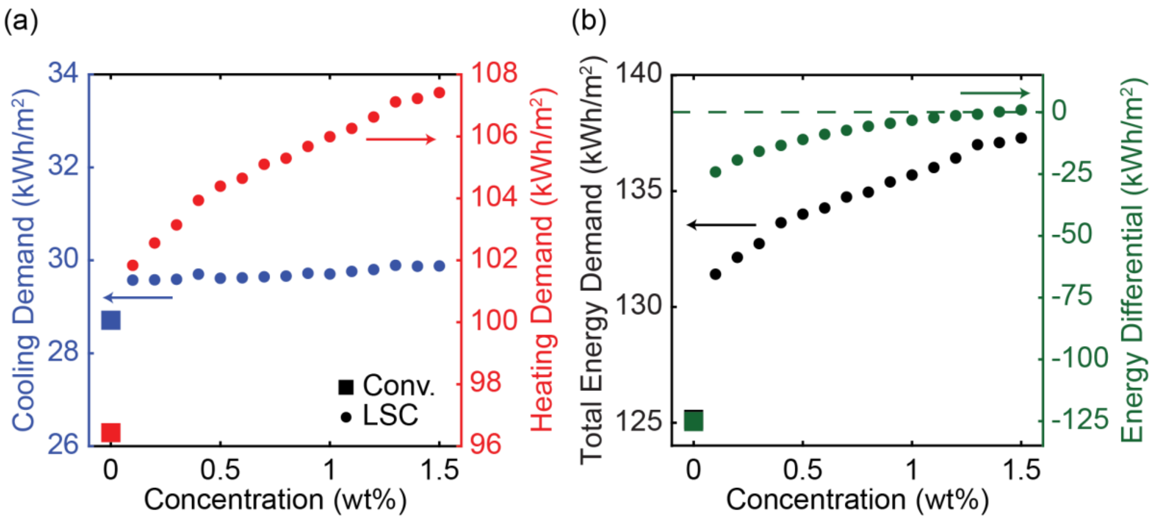

Figure 2. *(a) Annual heating and cooling demands and (b) annual total energy demands and energy differential as a function of Si QD film concentration for LSC greenhouses in Phoenix, Arizona. An energy differential above zero indicates a net zero energy (NZE) greenhouse. The demands for the conventional greenhouse are plotted at 0 wt% as a reference point.*

A NZE greenhouse is one that produces as much energy as it consumes. All LSC greenhouses had higher total energy demands than the conventional glass greenhouse, as shown in Figure 2(b). Due to the continuous increase in heating demand with increasing concentration, the total energy demand for LSC greenhouses increases with Si QD concentration. However, the power generation also increases with increasing concentration, as more photons are concentrated toward the nearby PV cells. The energy differential is defined as the energy demand subtracted from the energy generated, such that a positive energy differential indicates the LSC roof supplied more electricity than was demanded in a year. A negative energy differential indicates electricity must be purchased to sustain the greenhouse. Despite the increase in the total energy demand, Si QD LSC greenhouses with 1.4 wt% and 1.5 wt% Si QD films have a zero or positive energy differential. These greenhouses are therefore NZE, as they can renewably supply the energy they demand. These findings indicate that from an energy perspective, there is an optimum concentration for LSC films in agrivoltaic greenhouses. The optimum concentration is one that can balance the increase in the energy demand from the installation of an LSC film by increasing the power generated to meet this demand.

To further expand our understanding of the potential for LSC greenhouses in the United States, we simulated 1.5 wt% Si QD LSC greenhouses in 48 locations across the country. This concentration was chosen as it led to an NZE greenhouse in Phoenix, Arizona. At this concentration, the LSC greenhouse roofs transmitted 30% – 40% of incident light, with greenhouses at northern latitudes transmitting more light due to a lack of shade cloths. Figure 3(a) depicts the energy differentials for 1.5 wt% Si QD LSC greenhouses. In some southern states, namely Arizona and Florida, the LSC greenhouses are NZE or produce more energy than they require. The other southern states have colder winters, with some days of the year reaching below freezing temperatures. The colder winters result in higher heating demands that cannot be met by the 21% PV coverage. Moreover, as the latitude increases, the colder climates increase heating demands, resulting in further negative energy differentials. The energy differentials are the most negative in the northernmost states due to significant heating requirements; the PV cells in these locations could only provide around one-tenth of the energy demand. In states with energy differentials from -400 to -200 kWh/m^2, the PV cells could still provide 25% to 50% of the energy required to operate the greenhouse. For greenhouses with energy differentials greater than -200 kWh/m^2, the PV cells could provide 40% to 80% of the annual energy demand. The energy demands for the conventional greenhouses were on the same order of magnitude as those for the LSC greenhouse in each location but require 100% purchased electricity or heating.

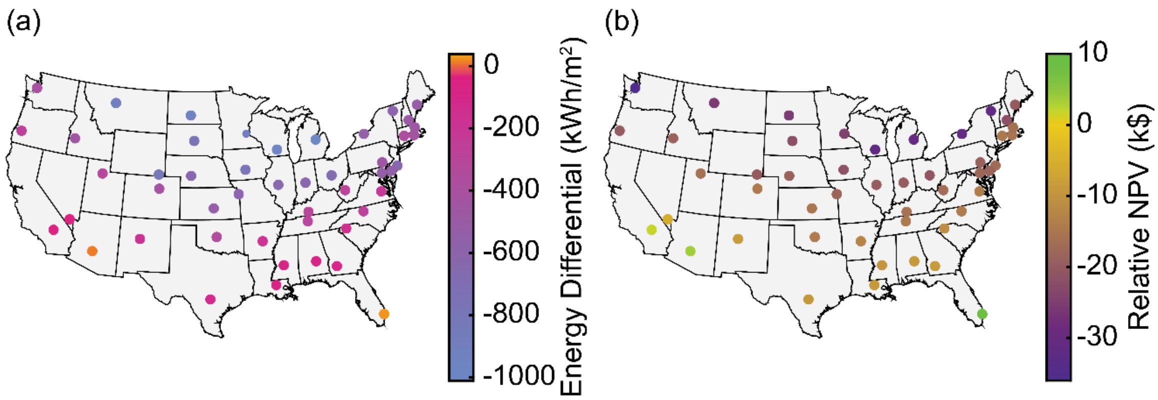

Figure 3. *(a) Annual energy differentials for LSC greenhouses with a 1.5 wt% Si QD film and (b) net present values (NPVs) of 1.5 wt% Si QD LSC greenhouses relative to that of the conventional greenhouse in 48 representative locations across the United States.*

Whether or not the greenhouse is economically viable, however, depends on the yield of the crops grown within the greenhouse and their selling price. We calculated the NPV for LSC greenhouses and conventional glass greenhouses in these locations. The relative NPV is the NPV of the LSC greenhouse subtracted from the NPV of the conventional greenhouse. Figure 3(b) shows that only LSC greenhouses in Arizona, Florida, and California are more profitable than the conventional glass greenhouse. Despite the negative energy differential for the greenhouse in California, the NPV was driven by crop production [31]. The LSC greenhouse in California was the only greenhouse that had comparable crop yield to that of the conventional greenhouse. As latitude increases, the crop yield in LSC greenhouses decreases by up to 25%. This resulted in more negative relative NPVs by up to $35,000 over the 30-year lifetime. Positive energy differentials for greenhouses in Arizona and Florida increased the relative NPV through net metering, where surplus electricity was sold back to an electrical grid at a profit. The benefit through net metering mitigated the loss in profit from lower crop yields relative to that of the conventional greenhouse in these states. Therefore, LSC greenhouses can be economically viable either through minimal losses in crop yield or through additional profit in net metering.

4. Conclusion

This work demonstrates the relation between luminophore concentration and greenhouse operation for 16 cm x 16 cm Si QD LSC greenhouses. For LSC greenhouses in Arizona, increasing Si QD concentration results in increasing heating demands; however, at higher concentrations, the LSC roof structure can provide enough electricity to meet these increased demands. Taking the highest concentration studied and simulating Si QD LSC greenhouses across the conterminous United States, we show that LSC greenhouses in some warm climates can supply their annual energy demands. As the latitude increases, the heating demand increases and becomes too significant for the LSC glazing to meet the energy consumption. From an economic perspective, LSC greenhouses that achieve comparable crop yield can be as profitable as the conventional glass greenhouse. Reductions in crop yield negatively impact the NPV but can be compensated for if the LSC greenhouse generates more energy than it needs. This work points to the need for further research on LSC greenhouses to better understand strategies for bringing this technology closer to fruition.

Data availability statement

The data supporting the results of this work can be accessed at https://doi.org/10.13020/193c-d598.

Author contributions

K.Q.L.: Conceptualization, Methodology, Investigation, Software, Writing – original draft. K.H.: Methodology, Writing – review & editing. N.J.E.: Methodology, Writing – review & editing. U.R.K.: Conceptualization, Methodology, Supervision, Funding Acquisition, Writing – review & editing. V.E.F.: Conceptualization, Methodology, Supervision, Funding Acquisition, Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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