International Journal of Science and Engineering Applications
Volume 13-Issue 05, 28 - 32, 2024, ISSN:- 2319 - 7560
DOI:10.7753/IJSEA1305.1005

Design of a Sustainable PV System to Achieve Net-Zero Energy in Greenhouses

Majid Majidi
Department of Electrical Engineering
University of Bologna
Bologna, Italy

Abdolreza Mehin Ghaffari Nia
Department of Biosystem Engineering
University of Urmia
Urmia, Iran

Majid Ghasemi
Department of Electrical and Computer Engineering
University of Texas
Dallas, USA

Abstract: This study addresses the critical challenges faced by the agricultural sector, particularly in greenhouse operations, by integrating renewable energy sources to achieve net-zero energy consumption. It explored the feasibility, design considerations, and impacts of implementing a sustainable grid-connected photovoltaic (PV) system in greenhouses, using a case study located in Mashhad, Iran. This location was chosen due to its high solar radiation levels, making it an ideal setting for our research. Through simulations and analysis using HOMER software, an optimized PV system was designed that not only meets the energy demands of the greenhouse but also allows for the exchange of surplus energy with the grid, promoting energy efficiency and sustainability. Net-zero energy has been achieved in the greenhouse by using the PV system and the net metering method. The findings highlight the potential for significant reductions in greenhouse gas emissions and fossil fuel dependence, underscoring the economic and environmental benefits of incorporating solar energy into greenhouse agriculture.

Keywords: Sustainable Agriculture; Photovoltaic Systems; Greenhouses; Solar Energy; Net-Zero Energy; Renewable Energy Integration

1. INTRODUCTION

The global agricultural sector is at a critical juncture, where the dual challenges of ensuring food security and mitigating environmental impacts converge. Greenhouses have revolutionized the agricultural landscape by providing a controlled environment that allows for year-round, high-quality produce despite limited agricultural land, rising living standards, and environmental variabilities. This advancement has made it possible to produce a variety of crops throughout the year, regardless of geographical and climatic limitations [1]. However, the energy required to maintain optimal growing conditions within these structures has become a critical issue. The quest for sustainable energy solutions in agriculture has led to extensive research into efficient internal environment control, energy consumption, and the integration of smart, renewable energy sources [2].

Designing a sustainable, grid-connected photovoltaic (PV) system to achieve net-zero energy in greenhouses represents a necessary step towards integrating renewable energy sources within agricultural practices, thereby reducing the carbon footprint of food production [3]. The concept of net-zero energy implies that the total amount of energy used by the greenhouse on an annual basis is roughly equal to the amount of renewable energy generated on-site. In this context, a sustainable grid-connected PV system offers a promising solution by not only providing a renewable source of energy to power greenhouses but also allowing for the exchange of surplus energy with the grid. This enhances the overall efficiency and sustainability of the energy system [4].

The integration of PV systems in greenhouses presents unique challenges and opportunities. The design of such systems must consider the specific energy needs of greenhouses, such as lighting for plant growth, temperature control, and ventilation, and must be optimized for efficiency. Factors such as the geographic location of the greenhouse, the local climate, and the orientation and transparency of the greenhouse cover materials must be considered to maximize solar gain. Furthermore, the grid-connected aspect of the system necessitates the implementation of smart energy management strategies to ensure that the greenhouse operates on a net-zero energy basis throughout the year [5].

This research paper aims to explore the feasibility, design considerations, and potential impacts of implementing a PV system tailored to meet the energy demands of greenhouses while achieving net-zero energy status, using a case study in Iran. Iran is identified as having a desirable condition for using solar energy, making it an ideal location for this study [6]. A commercial greenhouse in Mashhad, a city in Khorasan province known for its relatively high amount of solar radiation, has been selected as the sample for this study. All assumptions regarding load consumption have been based on the annual energy demand of the selected greenhouse.

For achieving the optimal Renewable Energy System (RES) design, different companies have developed computer software for modeling and analyzing the proposed systems in terms of electrical and economical aspects. HOMER software is one such tool used by renewable energy planners to obtain the ideal system among different feasibility study solutions. In this paper, a grid-connected PV system has been simulated and examined from technical and economic aspects by HOMER software [7-9].

Ultimately, this study contributes to the broader discourse on sustainable agriculture and renewable energy, offering insights and practical solutions for advancing towards a more sustainable and resilient food production system.

2. SUSTAINABLE SOLAR GREENHOUSE

Solar energy, recognized as the most widely used renewable energy source, plays a crucial role in advancing greenhouse agriculture towards sustainability and energy independence. Solar-powered greenhouses, blending photovoltaic (PV) panels and solar thermal technologies, harness sunlight to generate electricity and heat, essential for plant growth and operational needs within the greenhouse [10-11]. These innovative structures can be categorized into passive and active systems; passive greenhouses maximize solar energy capture through specialized designs, while active greenhouses integrate solar collecting units such as PV, PVT (Photovoltaic Thermal), or solar thermal collectors. Although passive solar greenhouses tend to have simpler structures with lower initial and operating costs, active systems offer enhanced control over internal conditions, potentially increasing profitability through higher thermal performance and energy efficiency [12].

The deployment of renewable energy sources in greenhouses, including solar collectors and concentrators, can significantly reduce reliance on fossil fuels, leading to up to a 40% decrease in greenhouse gas (GHG) emissions. This shift not only addresses the environmental impacts and depletion risks associated with fossil fuels but also mitigates the economic uncertainties due to fluctuating fuel prices [13]. However, challenges such as energy loss due to defective insulation, mainly in the greenhouse envelope, highlight the need for improvements in construction materials and designs to minimize heat demand in winter and excessive solar heat gains in summer. The concept of "Net-zero energy" greenhouses (nZEGs) emerges as a pioneering criterion in this context, aiming for a balance where the amount of renewable energy produced matches the energy consumed within a year, considering seasonal variations. This approach encourages the integration of on-site renewable energy sources and utility grid, aiming to offset non-renewable energy usage and achieve sustainable cultivation systems [14]. By focusing on renewable energy integration and enhancing insulation and material efficiency, solar-powered greenhouses are paving the way for a sustainable, net-zero energy future in agriculture, promising not only environmental benefits but also economic viability through reduced operating costs and increased energy security.

3. ELECTRICAL IMPLEMENTATIONS

Mohammadzadeh et al. [15] investigated the feasibility of a microgrid architecture targeted at attaining net zero energy which used a PV system to satisfy energy requirements. Their findings indicate that photovoltaic systems may greatly improve energy efficiency and lower building energy expenditures. Given the greenhouse's proximity to the utility grid, the analysis recommends net metering, which eliminates the requirement for energy storage alternatives. The study was carried out using the HOMER program [16], with a 25-year project duration. The research found ideal configurations that strike a balance between technical excellence and budgetary viability.

3.1 Net metering approach with gird-tie inverter

Under a billing arrangement known as net metering, consumers are encouraged to export excess power generated by solar panels back to the electrical grid on days with plenty of sunlight, while also being able to draw power from the grid when solar panels are insufficient due to cloudy weather. This design requires a special type of power converter, the grid-tie inverter, which is fundamental to the system's operation. It investigated how these inverters perform in solar microgrids [17]. These grid-tie inverters convert DC to AC, allowing for the safe and efficient transmission of surplus energy back to the grid while assuring accurate alignment with the grid's AC voltage and phase [18-20]. This research focuses on the utilization of a grid tie.

3.2. Solar irradiation

The potential electricity generation from PV panels is influenced by the solar irradiation at the selected location, along with the type and temperature of the PV cells used [21]. The geographical coordinates for the greenhouse in Mashhad are at 36.3′N latitude and 59.52′E longitude. A depiction of Mashhad's monthly average solar radiation and its clearness index is provided in Figure 2, based on data sourced from NASA's surface meteorology reports [22]. The clearness index represents the proportion of solar radiation that reaches a specific point on Earth's surface, serving as a measure of atmospheric clarity. The peak radiation occurs in June, with an average daily solar radiation of 6.940 kWh/m²/day, while December experiences the lowest solar radiation, at 2.300 kWh/m²/day. The mean annual solar radiation is calculated to be 4.67 kWh/m²/day.

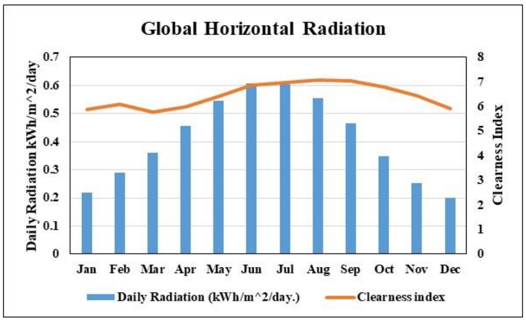

Figure 2. Solar Resource.

3.3 Load Profile

In agricultural greenhouses, significant electrical loads are primarily attributed to systems essential for ensuring optimal plant growth conditions. Primary among these is the Heating, Ventilation, and Air Conditioning (HVAC) system, which consumes considerable energy to regulate temperature and humidity, especially in extreme weather conditions. Artificial lighting stands as another substantial energy consumer, providing essential light for photosynthesis during periods of low natural sunlight, with the choice between LED and high-pressure sodium (HPS) lamps impacting energy use. Automated irrigation systems, crucial for efficient water and nutrient delivery, also contribute to the energy load through the operation of pumps and related equipment. Additionally, CO_2 enrichment systems, which increase atmospheric CO_2 concentration to boost photosynthesis, further elevate energy demands. Control systems that automate environmental conditions integrate sensors, actuators, and data processing units, adding to the greenhouse's electrical consumption. These components collectively represent the multifaceted nature of energy use in greenhouses, underscoring the critical need for operational efficiency and the adoption of sustainable energy solutions to minimize environmental impact and improve economic sustainability. This comprehensive approach to managing electrical loads is important in advancing greenhouse agriculture towards greater energy efficiency and sustainability. Figure 3 shows the load profile of selected case study during a year which has been gathered from past electrical bills.

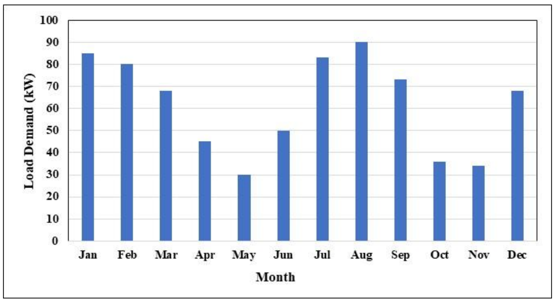

Figure 3. Monthly load profile.

3.4 PV system design

The HOMER® optimizer, a design tool, was employed to design the ideal PV system, considering various factors like the site's solar exposure, consumption patterns, system components, and connectivity options. This process yielded an optimized PV setup, chosen for its technical efficiency and economic viability from among various local solutions. This system is comprised of stationary mono-crystalline solar panels without a tracking mechanism, along with a grid-connected inverter and a meter to monitor production. The panels are positioned at a 34-degree angle, boast 18% efficiency, and are expected to last 25 years. The initial cost for a 1 kW PV panel is estimated at $1000, with annual operating and maintenance expenses of $8. The inverter, crucial for converting solar energy into usable power, costs $310 per kW, operates at 93% efficiency, and has a lifespan of 15 years. For commercial users in Iran, the electricity cost from this system is calculated at $0.11 per kWh. A detailed representation of this PV setup is illustrated in Figure 4.

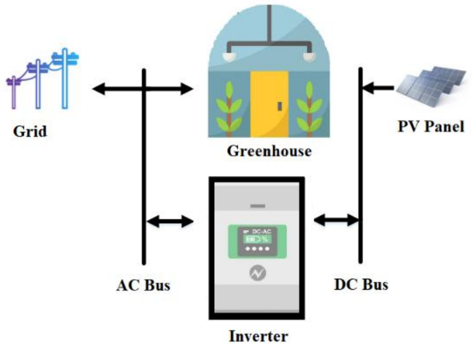

Figure. 4 Grid-connected PV system for greenhouse.

Utilizing the net metering approach eliminates the need for an energy storage system. To reduce the visual disturbance caused by PV panels on the church's historic facade, these panels have been strategically placed behind parapets or on slopes of the roof that face inward. This positioning ensures that the panels remain out of sight from observers, thereby preserving the aesthetic appeal of the site without compromising its visual integrity.

3.5 Economic analysis

This research undertakes a cost evaluation focusing on two pivotal economic indicators critical to financial evaluations: the Total Net Present Cost (NPC) and the Levelized Cost of Energy (COE). These metrics pertain to the system's yearly total costs. The Total Net Present Cost (NPC) encapsulates the current worth of the system's cumulative expenses over its operational lifespan, subtracted by the current worth of all income generated throughout the system's life. The formula for NPC is articulated as follows:

$$C_{NPC} = \frac{C_{TANN}}{CRF_{(i,N)}} \quad (1)$$

Where C_{TANN} is the total annual cost which can be calculated by following equation:

$$C_{TANN} = CRF_{(i,R_{proj})} \times C_{NPC} \quad (2)$$

In addition, CRF $_{(i,\ N)}$ is the capital recovery factor, which is given by:

$$CRF_{(i,N)} = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (3)$$

Considering i as the yearly actual interest rate, N represents the project's duration in years, and R_{proj} as the project's expected lifespan. COE stands for the mean cost of producing one kilowatt-hour (kWh) of electricity with the system in question. To determine the levelized cost of electricity (COE), the equation below is given.

$$COE = \frac{C_{TANN}}{E_{Is} + E_{grid}} \quad (4)$$

The microgrid system's demand for electrical energy is represented by E_{Is}, and the excess electricity that is fed back into the grid by the microgrid is indicated by E_{grid}. For the system outlined, a multi-objective optimization technique is employed, focusing on minimizing both the total Net Present Cost (NPC) and achieving a levelized Cost of Electricity (COE) as the targeted outcomes. The operating cost is delineated as the annualized sum of all expenses, excluding the upfront capital costs. The formula is presented as follows:

$$C_{Operating} = C_{ann,tot} - C_{ann,cap} \quad (5)$$

$C_{ann,tot}$ represents the comprehensive annualized cost (measured in dollars per year), whereas $C_{ann,cap}$ corresponds to the total annualized capital cost (also in dollars per year). The latter is derived from multiplying the total initial capital cost by the capital recovery factor.

4. RESULTS AND DISCUSSION

In conducting an economic analysis, Homer considers a range of economic factors. This includes the Net Present Cost (NPC), which is calculated as the present value of the total costs associated with the installation and operation of a component throughout the project's lifetime, subtracting the present value of all revenues generated during this period. Furthermore, it evaluates the Levelized Cost of Energy (LCOE), defined as the average cost per kilowatt-hour (kWh) of useful electricity generated by the system. The results of the optimized simulations are presented in Table 1.

Table 1. The simulation results of grid connected PV system.

Component	Value
PV	35 kW
Grid	19 kW
Converter	35 kW
NPC	$86940
COE	$0.0673
Operating Cost	$890.65
Initial Capital	$72000
Capital Cost	$59000
Production	61,769 (kWh/yr)

Table .2 presents the comprehensive cost breakdown of the proposed system, highlighting that the photovoltaic (PV) panel constitutes most expenses. Furthermore, the replacement parts and operation and maintenance costs have been tabulated. The term 'salvage value' refers to the residual value of a power system component upon conclusion of the project's lifespan which for the designed PV system is zero.

Table. 2. The overall costs of designed PV system for greenhouse

Component	Capital	Replacement	O&M	Total
PV Panel	$35000	0	$3163.7	$38163.7
Converter	$10850	$5676	0	$16526
Grid	0	0	$1164.6	$1164.6
System	$45850	$5676	$4328.3	$55854.3

Table 3 displays the technical results, indicating a near equilibrium in energy exchange—both selling to and purchasing from—between the PV system and the utility grid. Remarkably, there are no instances of unmet electrical demand or surplus electricity, with the shortfall in capacity being virtually nonexistent.

Table .3 Technical details for designed PV system.

Production	Unit (kWh/year)	Percent (%)	Consumption	Unit (kWh/year)	Percent (%)
PV Panel	66400	66.84	Load	63448	66.16
Grid Purchase	32930	33.16	Grid Sale	32451	33.84
Total	99330	100	Total	95899	100

Additionally, Figure 5 illustrates the monthly electrical output generated by the PV panels and the grid.

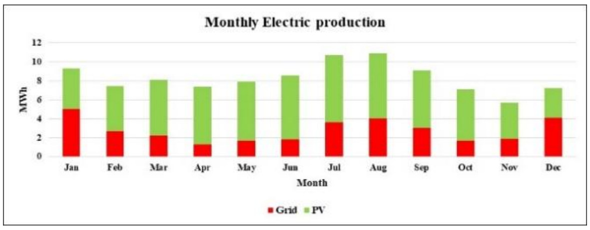

Figure .5 The monthly electrical energy production.

The net metering approach reveals that January experiences the peak electricity demand for load support, during which 3611 kWh of electricity is procured from the grid. Conversely, the month of May has the maximum electricity supply back to the grid, amounting to 2930 kWh. Figure 6 visualizes the monthly fluctuations in electricity transactions, detailing the quantities either sold to or purchased from the grid.

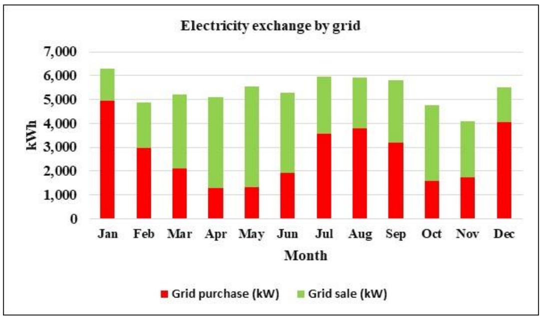

Figure. 6. Energy exchange between grid and PV system.

5. CONCLUSION

The integration of photovoltaic (PV) systems into greenhouse operations presents a viable solution to the environmental and economic challenges facing the agricultural sector. This research demonstrated that a well-designed grid-connected PV system could enable greenhouses to achieve net-zero energy consumption, significantly reducing greenhouse gas emissions and dependence on fossil fuels. The case study of a commercial greenhouse in Mashhad, Iran, served as a practical example of how solar energy can be effectively harnessed to meet agricultural energy needs while promoting sustainability. By optimizing the PV system design through simulations with HOMER software, which identified a configuration that balances technical performance with economic feasibility. The electrical assessment reveals an annual power surplus of 32451 kWh being exported to the utility grid, contrasted with 32930 kWh imported annually to fulfill the building's load in periods of insufficient solar irradiation. This results in a nearly balanced annual energy exchange between the building and the utility grid. The study contributes valuable insights into the design and implementation of renewable energy systems in agriculture, offering a path towards more sustainable and resilient food production systems. Future research should focus on integrating energy storage solutions and exploring the scalability of such systems across different climates and geographical locations to further enhance the sustainability of agricultural practices worldwide.

6. REFERENCES

[1] Faisal, M., Desa, A., Abdul, R., Ishak, A., Rimfiel, J., & Rezuwan, K. (2007). Design and development of a photovoltaic power system for tropical greenhouse cooling. *American Journal of Applied Sciences*, *4*(6), 386-389.

[2] Jin, Y., Jiang, W., Han, Y., Nan, S., Liu, G., Guo, W., ... & Li, D. (2024). Comprehensive optimization of shading and electrical performance of roof-mounted photovoltaic system of Venlo-type greenhouse in the severe cold region. *Energy*, 131125.

[3] Rahman, M. M., Khan, I., Field, D. L., Techato, K., & Alameh, K. (2022). Powering agriculture: Present status, future potential, and challenges of renewable energy applications. *Renewable Energy*, *188*, 731-749.

[4] Geri, A., Gatta, F. M., Maccioni, M., Dell'Olmo, J., Carere, F., Bucarelli, M. A., ... & Paulucci, M. (2022, July). A Low-Cost Smart Monitoring Device for Demand-Side Response Campaigns. In *Proceedings of Seventh International Congress on Information and Communication Technology: ICICT 2022, London, Volume 2* (pp. 593-603). Singapore: Springer Nature Singapore.

[5] Geri, A., Gatta, F. M., Maccioni, M., Dell'Olmo, J., Carere, F., Bucarelli, M. A., ... & Paulucci, M. (2022, March). Distributed generation monitoring: a cost-effective Raspberry Pi-based device. In *2022 2nd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET)* (pp. 1-6). IEEE.

[6] Aghapouramin, K. (2020). Technical, economical, and environmental feasibility of hybrid renewable electrification systems for off-grid remote rural electrification areas for East Azerbaijan Province, Iran. *Technology and Economics of Smart Grids and Sustainable Energy*, *5*(1), 20.

[7] Ahmed, A., Ge, T., Peng, J., Yan, W. C., Tee, B. T., & You, S. (2022). Assessment of the renewable energy generation towards net-zero energy buildings: A review. *Energy and Buildings*, *256*, 111755.

[8] Ekren, O., Canbaz, C. H., & Güvel, Ç. B. (2021). Sizing of a solar-wind hybrid electric vehicle charging station by using HOMER software. *Journal of Cleaner Production*, *279*, 123615.

[9] Hadifar, N., & Ayanlou, A. (2021). A Comparative Feasibility Study of Stand-Alone and Grid-Connected PV System for Residential Load: A Case Study in Iran. In *E3S Web of Conferences* (Vol. 239, p. 00008). EDP Sciences.

[10] Maraveas, C., Karavas, C. S., Loukatos, D., Bartzanas, T., Arvanitis, K. G., & Symeonaki, E. (2023). Agricultural greenhouses: Resource management technologies and perspectives for zero greenhouse gas emissions. *Agriculture*, *13*(7), 1464.

[11] Sajid, M. U., Khan, S. A., Koc, M., Al-Ghamdi, S. G., & Bicer, Y. (2023). Life cycle assessment of spectra-managed greenhouses for sustainable agriculture. *Cleaner Environmental Systems*, *9*, 100127.

[12] Bouadila, S., Baddadi, S., Ali, R. B., Ayed, R., & Skouri, S. (2023). Deploying low-carbon energy technologies in soilless vertical agricultural greenhouses in Tunisia. *Thermal Science and Engineering Progress*, *42*, 101896.

[13] Schallenberg-Rodriguez, J., Rodrigo-Bello, J. J., & Del Río-Gamero, B. (2023). Agrivoltaic: How much electricity could photovoltaic greenhouses supply?. *Energy Reports*, *9*, 5420-5431.

[14] Jiang, W., Jin, Y., Liu, G., Ju, Z., Arıcı, M., Li, D., & Guo, W. (2023). Net-zero energy optimization of solar greenhouses in severe cold climate using passive insulation and photovoltaic. *Journal of Cleaner Production*, *402*, 136770.

[15] Mohammadzadeh, M., Hadifar, N., & Mohammadzadeh, B. (2021). A sustainable PV-powered energy retrofit modelling to achieve net ZEB in churches: a simulation study for San Marcello Al Corso. *International Journal of Exergy*, *36*(2-4), 191-207.

[16] Ansari, A. B. (2024). Multi-objective size optimization and economic analysis of a hydrogen-based standalone hybrid energy system for a health care center. *International Journal of Hydrogen Energy*, *62*, 1154-1170.

[17] Marcelino, C. G., Leite, G. M. C., Wanner, E. F., Jiménez-Fernández, S., & Salcedo-Sanz, S. (2023). Evaluating the use of a Net-Metering mechanism in microgrids to reduce power generation costs with a swarm-intelligent algorithm. *Energy*, *266*, 126317.

[18] Biglo, A. H. A., Farhangi, S., & Iman-Eini, H. (2021, February). A Novel Zero Voltage Transition soft-switching PWM Boost Converter with low voltage stress. In *2021 12th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC)* (pp. 1-5). IEEE.

[19] A. H. Ali biglo, S. Farzamkia, S. Farhangi and H. Iman-Eini, "Utilization of Soft-Switched Boost Converter for MPPT Application in Photovoltaic Single-Phase Grid-Connected Inverter," *2020 11th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC)*, Tehran, Iran, 2020, pp. 1-6, doi: 10.1109/PEDSTC49159.2020.9088432.

[20] Mohammadzadeh, Shahir Farzad, et al. "A Novel Topology of Quasi-Resonant DC-DC Boost Converter for Electric Vehicle Charging Stations." *2024 15th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC)*, Tehran, Iran, 2024

[21] Liu, Z., Zhang, Y., Yuan, X., Liu, Y., Xu, J., Zhang, S., & He, B. J. (2021). A comprehensive study of feasibility and applicability of building integrated photovoltaic (BIPV) systems in regions with high solar irradiance. *Journal of Cleaner Production*, *307*, 127240.

[22] Johnson, Les, et al. "Status of solar sail technology within NASA." *Advances in Space Research* 48.11 (2