J. Electrical Systems 21-1 (2025): 1100 - 1108

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Towards a Greener Future: Life Cycle Assessment of Solar Panels

Journal of Electrical Systems

Abstract:-This study primarily intends to develop a life cycle analysis (LCA) to provide an understanding of the life cycle environmental impacts of solar panels, in order to characterize the sustainability benefits and challenges associated with solar energy technology. By examining the full life cycle of solar panels—from raw material extraction through manufacturing, installation, use, and end of life—greater understanding may be developed regarding the sustainability aspects of solar panels. In order to achieve the LCA, life cycle analysis framework based on ISO 14040 standards was used. Data from various points in the solar panel life cycle including extraction of raw materials (silicon, metals), energy consumed in the manufacturing, emissions during installation, and potential impacts while the technology is in use and when decommissioned was collected. Environmentally extended input-output, greenhouse gas (GHG) emissions, net energy payback times, and resource depletion were also assessed. Overall, the research illustrated that while future projected carbon emissions, during typical operational characterizations, have a major reduction in GHG, system-wide sustainability challenges occur as a complication of energy-intensive manufacturing processes, and the associated environmental effects of sourcing raw materials. The findings herein highlight the necessity of improving sustainability practices through energy optimization of the manufacturing process, the exploration of recycling, and improvement of producer responsibility, is paramount to realizing solar's potential as a sustainable energy technology. In addition, it has been discovered that energy payback time is much lower than what has been documented in the literature previously, which suggests increasing efficiencies in the energy and life cycle analysis characteristics of solar technologies being employed. This study enhances the knowledge base by providing a LCA of solar panel technology and provides a significant contribution to resolving the identified gaps in previous studies focused on solar energy technology's environmental sacrifices. The knowledge produced is critical for informing policy, manufacturers, and consumers on some of the sustainable trade-offs related to solar technology, and finding a pathway to sustainable clean energy.

Keywords —Photovoltaic (PV), life cycle assessment, end-of-life management and greener future.

1. INTRODUCTION

Climate change, the world is faced with the worsening effects of climate change every year, with the increased frequency of climate disasters, habitat loss, disruption to the food chain (the insect collapse), erratic weather patterns, social unrest, political conflict and environmental difficulties seem to be on the rise (Saleem et al., 2024). The adoption of renewable energy resources has become necessary in order to achieve sustainable development. Solar energy is one of these resources that is leading the charge due to abundance and advances in technology, with a decreasing cost of materials for manufacture and installation of solar panels. Solar panels (or photovoltaic (PV) systems) collect sunlight and convert it into electricity; they serve as a sustainable alternative to energy produced by burning fossil fuels (Reddy et al., 2024). There are serious environmental implications related to the manufacturing, use and disposal of solar panels that warrants consideration in order to determine if solar energy really is an environmental benefit (Algarni et al., 2023).

Life cycle assessment (LCA) is a comprehensive method that evaluates the environmental costs of a product throughout its entire life cycle: including raw material extraction, production, use, and disposal (at end-of-life) (Pacana et al., 2023). Conducting an LCA for solar panels will yield important evaluation of the environmental impacts of their use and a more complete understanding of sustainability (Hasan et al., 2023). An LCA evaluates both benefits of solar energy and environmental costs attributed to production and use of the solar panel. LCA considers a multitude of important aspects including energy use, greenhouse gas emissions, water use and material waste. LCA provides stakeholders with a process to more totally assess their options regarding solar technology (ul Haq et al., 2023).

The entire production chain associated with solar panels encompasses many steps from the extraction of raw materials to the processing and manufacturing stage, shipping to site, installation, and the end of life/recycling (Aravindan et al., 2023). All of these, with respect to solar panels, have environmental impacts. Silicon extraction is one area of concern for most solar panels and takes energy to extract (Eikeng et al., 2024). Silicon extraction can also have extreme ramifications on the ecosystem depending on how well the silicon mining and extraction

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and processing take place. As another example, many processes employed in manufacturing utilize toxic chemicals that may potentially impact humans and the ecosystem. Unpacking all of the possible impacts is essential for identifying steps to minimize negative impacts and improve sustainability of solar systems (Jackson, 2024).

The operational phase (actual use phase) of solar panels and the environmental costs related to operational phase must also be addressed. Solar panels produce energy from a clean source during the operational phase, however, the energy input to produce solar panels has the potential to mitigate some of the upside of the energy resource (Nnabuife et al., 2024). ”Energy payback time” describes the time it takes for a solar panel to produce the same amount of energy that was used to produce the panels (Chala and Al Alshaikh, 2023). Energy payback time calculations are important indicators for LCA studies. Due to technological advancements and therefore sustainability of solar energy systems, energy payback periods have improved. Energy payback time depends on geographical location, geospatial area, technologies used, and the mix of energy used to manufacture the systems.

It is necessary to use kWh/kWh rather than just time to determine the energy payback time of each panel in the evaluations and this varies as there are different production conditions, all of which should be considered in the reviews with respect to payback time and also to consider different methodologies to assess energy payback in this case (Allouhi et al., 2023). The time of terminal lifecycle maintenance of solar panels is a crucial consideration in LCA too. As solar energy systems continue to develop, there are, and will be, issues regarding the disposal and recycling of decommissioned or end-of-life solar panels. Recent estimates have shown that millions of tons of solar panels will be coming to end-of-life terms over the next few decades (Artas¸ et al., 2023). The inappropriate disposal of these panels is concerning for hazardous waste panels, injury and lost valuable resources. Thus, the globe is faced with managing the end-of-life of solar panels. There should also be an adequate disposal and recycling process for the more sustainable interactions of solar technologies (Goh et al., 2024).

The aim of this research is to offer a complete LCA of solar panels, including developments, use, and disposal, potential gains environmentally as well as potential concerns. The objective of this research study is to provide an equal and fair analysis of solar energy as a sustainable alternative compared to energy supplies, through using LCA. The research study will seek to better inform the conversation regarding renewable energy and helps to sustain the sustainability of the environment which is less harmful for the future.

2. LIFE CYCLE STAGES OF SOLAR PANELS

2.1 MATERIAL EXTRACTION

The extraction of materials to make solar panels, such as silicon, silver, and rare earth elements, raises significant environmental issues. This phase includes petroleum extraction used for plastics, and natural gas extraction for heat, thus covering all the materials processes involved in the manufacturing of the PV panesl and other electronics to the delivery point of being operational (Bosnjakovic et al., 2023). The predominant device component in PV systems is silicon—a widely available semiconductor material. Besides, the silicon used in PV panels must be exceptionally pure, called solar grade. Most solar panels have a glass face to protect the solar cells and allow sunlight radiation. Aluminum and copper: they are used for the frame and electrical circuits associated with the panel. Silver is used for the electrical connections for solar cells due to its superior electrical conductivity (Valizadeh et al., 2024). Polymers: The back layer of the solar panel is made from polymers that protect the solar cells and give insulating support (Martınez et al., 2024). In fact, studies show that the extraction and processing materials required have serious environmental impacts as these methods may be associated with habitat loss, and water pollution (Duan et al., 2024). Moreover, as these processes are energy intensive, they also contribute fossil fuel associated with greenhouse gas (GHG) emissions which negates some of the benefit of solar energy (Saad, 2024).

2.2 MANUFACTURING PROCESS

Solar panel production consists of a number of important steps, including silicon extraction and assembly of the panel (Chen et al., 2023). With the first step in solar panel production being to get high purity silicon. Silicon is derived from quartz which is a naturally occurring mineral in the sand. Quartz is then heated to approximately 2000 °C in electric arc furnace, the result is oxygen weathered silicon, which is metallurgical grade silicon. Once metallurgical grade silicon is reached, it is still not pure enough for production for a silicon solar panel (it still must be processed). The purification process as solar grade is the Siemens process which consists of converting silicon to trichlorosilane gas then the trichlorosilane gas is reduced to pure silicon (Bosnjakovic, 2024). At the end of the purification, the silicon is made into cylindrical ingots or rectangular blocks. Once the silicon has been purified, it is poured into solid, cylindrical ingots. The ingots are cut into thin wafers with a diamond wire saw. The thickness of these wafers is typically from 160 to 200 microns in thickness, which is optimal to convert solar energy with the smallest amount of material used. The wafers are inspected for contamination, cracks or defects-and these silicon wafers are the actual building block of every solar cell (Rafin, et al., 2023).

To qualify as an effective semiconductor, silicon must be altered through a process called doping (Fan et al., 2023). Doping introduces impurities to the silicon (boron and phosphorus are common) that alter its electrical properties. The upper layer of silicon is treated with phosphorus (n-type silicon), creating excess electrons so that the circuit element becomes negative. The substrate is treated with boron (p-type silicon), creating an electron surplus, so that the substrate becomes positive (Pal and Nandi, 2024). The interface of the two layers (the p-n junction) is where solar cells generate power from sunlight. The reflectivity of silicon wafers means that a lot of sunlight that hits the surface does not get absorbed in the solar cell. To minimize that, a film is placed on the surface of the wafer that is most commonly called an anti-reflective coating and is typically made from silicon nitride (Rout et al., 2025). This film further refracts some sunlight and reduces the reflected sunlight so that the most sunlight finds its way into the solar cell, improving efficiency. After the wafers have been doped and coated, metal contacts are added to the surface of the cell. These contacts is typically made from silver or aluminum and collect the electrons generated from the sunlight (Wright et al., 2023). The front of the solar cell has a grid pattern of thin lines, and the back has just a solid layer of metal to produce the electrical circuit. Solar cells produce very little power on their own, and therefore they are aggregated together to make it into a bigger assembly to create a full solar panel. This translates to a group of solar cells that are electrically connected (wired) together to form a solar module (Tepner and Lorenz, 2023).

The modules are encapsulated in ethylene vinyl acetate, a polymer that protects the cells from moisture, dirt and damage. The cells are also thermally bonded to the ethylene vinyl acetate layer under heat and pressure (Adothu et al., 2024). The front of the module is tempered glass, which is fairly sturdy, has good weather resistance (e.g. hail and torrential rain), and does not corrode. The back is polymer to create a separate space behind the cells. After stacking, the modules are typically framed in a durable and robust frame that is often made from aluminum. The frame has two roles. It structurally supports the panel and provides a means to permanently attach the panel to roofs or solar farms (Del Pero et al., 2024). The frame, in that capacity, provides a protective barrier from the cells to physical forces and weather (wind or snow). Significant testing is done on each solar panel prior to it being sent out for use to ensure that performance and durability targets are met. The types of tests are:

- Electrical tests that involved testing conditions in which the panel would be expected to demonstrate expected voltage and current;
- Durability tests that involved running the panel through different weather conditions, such as extreme heat and cold, prolonged wind and rain; and
- Ultrasonication tests that somewhat mimicked the panel being in prolonged sunlight.

These tests are meant to determine the reliability and preparedness for the installation and utilization (Raman et al., 2024).

2.3 TRANSPORTATION

Increases in material costs and a global supply shortage have resulted in a 20 % increase in prices of solar panels from year over year (Gerarden, 2023). These issues created delays in getting solar panels delivered globally. Global efforts to promote solar PV technology have largely focused on stimulating demand and minimizing costs (Ibegbulam et al., 2023). There are a number of ways that global supply chains and transportation can impact the solar panel industry:

- Price inflation: Supply chain congestion, high commodity costs and transportation delays can lower the demand of solar panels. For instance, in 2021 analysts believe increased shipping costs and equipment expenses could lead to the delay or cancellation of half the world's utility scale solar projects;
- Delivery disruptions: Supply chain interruptions can delay deliveries of solar panels.
- Inventory management: Delayed shipments, customs clearance problems, and available transportation networks can make inventory management difficult;
- Geopolitical tensions: Geopolitical tensions around the world can impact supply of raw materials and responsible sourcing versus sustainability;
- Natural disasters: Natural disasters can disrupt supply chains;
- Technological failures: Technological failures can disrupt supply chain, and

- Market fluctuations: Market variation can disrupt supply chains.

To guarantee the prompt and economical delivery of solar panels, governments can:

- Evaluate the vulnerabilities and risks within their domestic solar PV supply chain;
- Formulate plans to mitigate supply chain vulnerabilities and hazards; and
- Advocate for indigenous solar PV production (Durga and Gaurav, 2024).

2.3 USAGE PHASE

Solar power generation efficiency has increased dramatically in recent years, and the return on investment for solar power has become very positive (Ma and Xu, 2023). The actual power generated and savings from the solar system depend upon many factors, that need to be analyzed when considering statements about the efficiency of solar systems, savings generated, and benefits over time. Solar power systems are affected by many key facets. One of the most common misinterpretations of a solar power system is that high temperatures actually improve the performance of solar panels, which is not correct. Higher temperatures decrease voltage and there is an overall loss in power from the negative temperature coefficient of solar cells (Qudrat-Ullah, 2024).

Although the solar panels operate at a constant temperature of 25 °C, in reality, the outside temperature may significantly differ from this temperature. So, if the temperature is higher than 25 °C, the output for crystalline cells will be 0.4-0.5 % (Alaas, 2024). In the summer when the temperature is high, and because of the temperature, the solar panels could potentially produce up to 25 % less electricity than during temperature conditions that are not heated, including additional consideration along with them (Duroha and Macht, 2023). With the technology the solar panels are open to the wind and lightning; consequently, these cause damage to the solar cells. Furthermore, the PV conversion efficiency of solar panels is strongly affected by external climate and external factors such as light, wind, temperature, etc.; therefore, some variables will have a negative effect of the performance and safety of the solar panels. When designing a solar power system, it is essential to collect all weather report factors, and other information that encompasses environmental data (Liu et al., 2023).

The power generation capacity of a solar system drops when the solar panel experiences shading either by something in the environment or by the shading from the other panels themselves. When determining the spacing of solar panel arrays, it is important to account both the shadowing of the solar panels by the building and also the self-shading of the solar panels from each other (Lionar et al., 2024). This is because current flow in a solar power system relies on solar cells that are wired in series inside a solar panel. Hence, if one panel is shaded, then all other panels connected in series (as in a string) will be influenced by the shadow of the one panel. The best way to avoid the complexity of a solar panel shaded area is to avoid the shaded areas if that is possible. The amount of sunlight received varies depending upon location (Narasimman et al., 2023). A solar array for an application that is economically feasible can be designed by ascertaining the solar radiation that is received at the site using all relevant information including latitude, longitude, time and conditions in the local environment. The output from the solar panel varies from season to season, so this must be factored into calculations for annual production (Domınguez et al., 2024).

Solar panel tilt requires change to dynamically adapt to changes in seasons, latitude, and daylight-saving time (Hartono et al., 2024). Therefore, solar panels must orient towards the sun in an arrangement to maximize net electricity generation. Solar panels mounted on a roof generally orient towards true south (in the northern hemisphere) or true north (in the southern hemisphere) and changing by tilt angle requires changing tilt angle to maximize power production or savings. Remember solar panels produce max power when allirned perpendicular to the sun (Shang and Shen, 2023). The cleaning of solar modules, based on the effectiveness of PV power conversion is subject to dirt accumulation on the surface of the PV module (Said et al., 2024). There are several environmental factors that contribute to the accumulation of dirt on solar panels throughout the year and their accumulation varies from year to year through differing intervals of time, rains, snow falls, dust storms, negligence, etc (Dehshiri and Firoozabadi, 2023). If these conditions exist, maintenance and or cleaning is necessary on a repetition interval because dirt will reduce the efficiency of the equipment. The accumulation of dirt on PV modules will differ based on the location of the solar plant but also if the dirt is relatively a dust particle which floats. Dust on solar PV systems decreases sunlight and therefore electrical output. It is said that dust comes from many various sources including but not limited to construction sites, agricultural land, industrial activities (Vijayan et al., 2023). The typical frequency of cleaning is once every two weeks on solar panels but again this differs depending on the various components involved. Understanding these conditions, it should be understood that no matter how good of a design or scalable the solar panels are, environmental conditions will negatively impact some of what has been calculated in this section, if left unattended for long periods of time (Perotti and Colicchia, 2023).

3. END-OF-LIFE AND RECYCLING

PV technology continues to be one of the most environmentally sustainable forms of energy and power generation when taken from a life-cycle perspective (including end-of-life considerations). End-of-life considerations are a requirement of ”clean” energy technology (Ndeto, 2024). All technologies eventually reach their end-of-life stage and need to be replaced. PV modules typically have a life span of 30 years. Since the growth in deployment of PV continues to increase exponentially, the total number of PV modules reaching the end of usable life also increases exponentially, after a time lag corresponding to the length of the operational life of each module, thus generating an equivalent growing volume of waste (Monticelli et al., 2025).

A schematic description of the life cycle of a PV module is shown in Figure 1 from the material extraction to end-of-life; additionally, the figure outlines an integration of recycling pathways for PV module waste. The pathways are described as a ”butterfly diagram” exhibiting the cyclical opportunities within the PV industry and life cycle, from the extraction of a raw material to end-of-life (Genovese and Zoure, 2023). The outer circles indicate opportunities for recycling secondary raw materials, while the inner circles indicate reuse and repair opportunities. The cascades are labelled C1 - C4 from the least circular (C1) to the most circular (C4) (Olipp et al., 2024). The laminated and encapsulation design approach of PV systems creates functional constraints to opportunities for repair, maintenance, reuse and remanufacturing of PV cells, and for the associated secondary materials without extensive processing. The integrated design indicates that opportunities for circular economy typically occur at the recycling/re-manufacturing step in the waste hierarchy for current PV panels (Diez-Suarez et al., 2024).

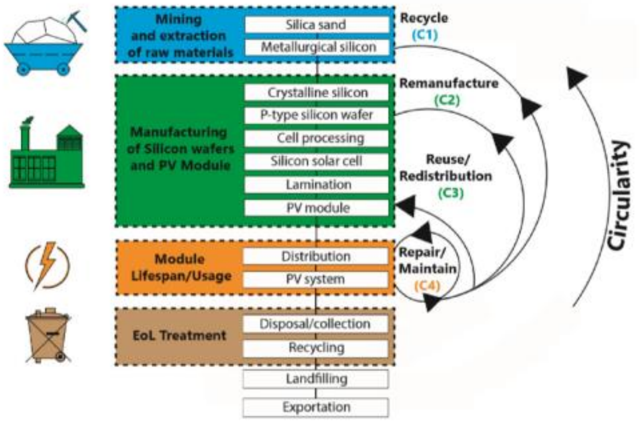

Figure 1: Life cycle of a PV module from the extraction of raw materials to end-of-life management (Farrell et al., 2020).

Recycling processes should provide the greatest value possible, in which the best possible recyclate is produced and able or possibly made into a useful product, or become productively reintroduced back into the economy, in accordance with recycling by definition as determined by the Australian Bureau of Standards (Nur-A-Tomal et al., 2023). Closed-loop recycling attempts to recover products and secondary materials from goods to put them back into the supply chain of the parent goods. In this case, materials and products (e.g. silicon wafers) are recovered and made into new PV cells. Open-loop recycling occurs when materials may not be appropriate for their original use as their quality has deteriorated, but they still can be harvested value and utility in other industries (Delbari and Hof, 2024).

The depreciation of value, while preserving utility as a final product after processing, can be viewed as a recycling “cascade” meaning a material can have multiple design lives and therefore recoveries in lower value products (Wang et al., 2024b). Currently there are three families of techniques, often used alone or in combination, to recycle PV cells. These techniques are:

- Physical processes;
- Chemical processes; and
- Thermal processes.

The applications and sequence of these techniques affect the quality and value of the recovered materials (Seo et al., 2023). The issue of solar panel end-of-life management is significant and multi-dimensional, as there are many stakeholders including manufacturers, installers, owners/operators, regulators, and communities. Responsible end-of-life management can:

- Minimize negative environmental impacts;
- Improve precious material recovery;
- Stimulate smart design of components;
- Promote resource efficiency;
- Enable product re-use;
- Value recovery from waste; and
- Support achievement of sustainable development goals (SDG) (Iakovou et al., 2024).

The end-of-life management approaches for solar panels include the following:

- Chemical means: use acid or alkali solutions to remove metallic contamination;
- Organic solvents: use solvents to dissolve ethylene-vinyl acetate for the purpose of separating and isolating the individual components;
- Land-filling: send panels to a landfill;
- Burning: burn panels;
- Re-using: re-use panels;
- Recycling: recycle panels (Acharya et al., 2024).

4. TOWARDS A GREENER FUTURE

Illustration of the positive impact of solar energy on the environment is shown in Figure 2. Typically, the lifecycle of most solar energy technologies has lower greenhouse gas and air pollution emissions than their fossil energy source counterparts because there is no operational impact of these when in operation (AlMallahi et al., 2022). The operational benign indirect environmental effect of solar energy comes from the displacing or lessening of greater environmental alternatives for energy sources. As a sustainable energy source, solar energy plays a major role in lowering greenhouse gas emissions and addressing climate change, which protects human beings, wildlife, and ecosystems (Dai, 2024).

Figure 2: Beneficial impact of solar energy on the environment (AlMallahi et al., 2022).

5. DISCUSSION

Climate change is growing urgently, along with the need to reduce greenhouse gas emissions. This increases the uptake of renewable energy and use solar energy as one of the major solutions. This research has undertaken a life cycle assessment (LCA) of solar panels that examined the sustainability impacts of solar panels through extraction of raw materials, production, installation, operation, and end-of-life. The findings showed that solar panels have an important future in achieving a sustainable future, and where improvements can be made in their life cycle to improve on their sustainability performance. This study saw significant carbon savings in the life cycle of solar panels in comparison to fossil fuel sources of energy, however, there are important considerations during the operating stage when solar panels deliver clean energy and offset the carbon emissions which occurred during the manufacturing stage. The study found that solar panels could reduce carbon emissions more than fossil fuel-based sources of energy during operation, indicating the great potential of using solar energy strongly as a good tool to address climate change

Nevertheless, it is important to remember that the LCA highlights not only the environmental impacts associated with the end of use and disposal of solar panels but also that the extraction and refinement of raw materials, particularly silicon and rare metals, exemplifies considerable environmental challenges, such as resource depletion and environmental degradation, and especially habitat destruction. While solar panel production is energy demand and therefore contributes to greenhouse gas emissions, it is far less impactful at that stage than the production of energy from fossil fuel. These findings indeed reveal that solar panels are a more sustainable energy production option. However sustainable material and production processes should be emphasized by the industry.

A significant component of the LCA is the solar panel end-of-life treatment. As the global solar market grows, more panels will be removed from service and the amounts needed to be sustainably recycled or disposed in the right way will increase. Currently many panels are not recycled, and landfilling could have potential environmental impacts. Developing circular economic ideas in this instance might include investing in recycling technology, including legislative changes that support materials processing and divert panels from landfills, is vital to reducing solar panels' environmental impact over their entire life cycle.

This study discovered that there are also alternative solutions that might help with recycling solar panels and improving the sustainability of solar panel production. The solar industry can invest in research and development to improve solar panel production consistency and reduce finite material reliance. Solutions can include utilizing alternative materials and innovative manufacturing methods which will reduce the environmental damage of raw material their extraction and basin of production.

Second, policymakers have substantial influence in creating a favorable regulatory environment to encourage sustainability in the solar sector. Incentives in the form of recycling programs, enhanced regulations on waste management, and funding opportunities for the research of sustainable materials will help push the use and disposal of solar panels into a more circular economy.

Ultimately, awareness and educational information regarding the life cycle impacts of solar panels is necessary. Regardless of stakeholder group (i.e., consumers, manufacturers or even policymakers) all need to be made aware of the environmental and materiality benefits and challenges that solar has. Enhanced awareness can ultimately lead to better informed decisions and better practices in the solar sector.

6. CONCLUSION

Although solar panels are a good way to utilize renewable energy, they must be assessed in terms of their life cycle impacts. If the negative impacts of production and end-of-life care can be dealt with, the benefits of solar energy would be larger than ever. The findings of this study inspire all participants at all levels to strive to a sustainable future while acknowledging the known potential that solar energy can provide. There is confidence that continuing technological innovation, regulation, and public awareness will allow solar panels to contribute not only to carbon emissions reductions, but also to achieving a true sustainable energy system.

ACKNOWLEDGMENT

I would like to express my gratitude to the University of South Africa for the financial support.

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