Electrical Systems and Energy Technologies

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Edited by

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CHAPTER 1

EVALUATING THE ENVIRONMENTAL IMPACT AND SUSTAINABLE SOLUTION OF RECYCLING WASTE SOLAR PANEL

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Abstract

The global commitment to using renewable energy sources means that by 2050, solar power installations are expected to rise from 764 GW to over 7 TW. This would result in 60,000 to 78,000 tons of trash annually, presenting a significant disposal challenge. If the waste from solar panels is not adequately managed, it could lead to environmental problems. Due to these features, recycling and disassembling the panel present various difficulties. Solar panel waste is frequently disposed of in landfills and remains an unresolved issue. The recovery of components from waste and the control of solar waste will prevent various harmful materials from leaching into the environment. Recycling photovoltaic modules is a multi-step process that involves the recovery of metals and disassembly. There are several methods for recovering the intrinsic parts of PV modules, such as chemical delamination, which results in intact solar cells that can be reused either directly or indirectly after refurbishment. Conversely, mechanical and combustion delaminating produce damaged solar cells, which are then processed electrochemically or metallurgically to recover the metals. To mitigate the environmental harm, it is essential to conduct a thorough investigation and employ scientific management techniques for the recycling and disposal of waste from solar panels. This paper discusses how to handle and recycle solar trash, which will be abundant. It also explains the recycling of solar waste and the technological advancements made possible by recycling photovoltaic waste.

Keywords: Renewable Sources, Recycling Process, Solar Panel, Solar Waste Management

I. Introduction

Over the last decade, the capacity of photovoltaic (PV) generation worldwide has grown to unprecedented levels. In 2016, the total PV generation capacity reached 302 GW [1]. It is anticipated that end-of-life (EOL) solar panels will contribute significantly to the accumulation of materials that are hazardous to the environment. The significance of recycling EOL solar panels is highlighted by this [2]. Environmental damage could result from continuing to dispose of retired PV systems in landfills. Future waste solutions can be achieved by enacting rules for the disposal of solar panels and developing new technologies, given that not all solar projects can utilize the recycling methods currently available for their end-of-life plans. In order to make sure of the sustainable and ethical discarding of solar panels that have reached the end of their useful life, alternative options must be explored and developed as landfills are not a long-term feasible solution to the waste problem caused by solar panels. Approximately 29% of the energy mix comes from renewable sources, which include biomass, solar, wind, and hydroelectric power. 1.75 TW of PV will be produced in the US by 2050, utilizing 97 million metric tons of virgin material and 8 million metric tons of life cycle waste. The typical lifespan of solar photovoltaic panels is 25 to 30 years; this is constant irrespective of the manufacturer or business. In essence, all solar panels turn sunlight into renewable energy that can be used, even though their power outputs, efficiency, and warranties vary.

Residential solar panel installations typically last seven years, and the owners are responsible for their maintenance costs, so there is ample time to enjoy the full benefits of solar panel installation, even though the panels themselves will not last forever. Figure 1 shows the material used in solar panels. Every solar panel has a rate of deterioration that leads to its eventual demise. The rate at which a panel loses output and efficiency over time is referred to as its degradation. Most solar panels deteriorate at an average rate of 0.5% to 1% annually due to technological advancements. The primary factor contributing to solar panels' extended lifespan is their absence of moving parts, which reduces the need for maintenance to replace damaged components. If there is a rapid decrease in power production, though, get in touch with a professional for maintenance and servicing.

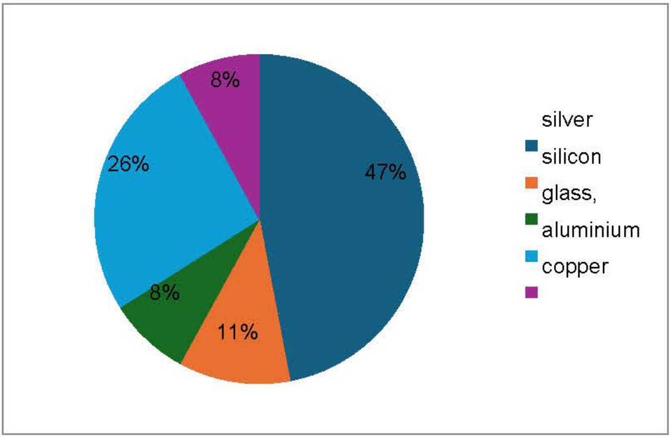

Figure 1: Material Used in Panel

II. Life cycle of solar panels

This evaluation analyzes the capacity requirements and the associated capacity of two circular economy strategies: one involves lifetime extension and closed-loop recycling, and the other aims to reduce the need for life cycle waste with the aid of the PV in Circular Economy Tool (PV ICE). A 3% reduction in the number of modules with 50-year lifespans can be achieved by reducing their deployment. The need for virgin materials and waste will increase if closed-loop recycling accounts for 90% or more of the mass of replacement modules, given a 15-year life duration. At least 90% of all PV technologies are now made from closed-loop recycled materials [3]. The amount of waste produced by PV panels is expected to increase to between 1.7 and 8 million tons by 2030 and between 60 and 78 million tons by 2050 [4]. This number is predicted to increase from 1.7 to 8.0 million tons of wasted panels by 2030 to 60 to 78 million tons of PV waste by 2050. Consequently, this forecast suggests that the PV waste stream will grow exponentially over the next several years, prompting discussions on the best way to handle it in various nations [5]. PVC has a high chlorine content, which is easily removed through various recycling processes as hydrogen chloride (HCl). This causes catalyst poisoning and reactor damage [6].

A. Toxic material in solar panels

Glass and aluminum make up about 80–85% of the weight of crystalline silicon (c-Si) solar modules because they are used as coating substrates on the top and back, where they are less hazardous, as shown in Figure 2. The majority of harmful contaminants are produced during the manufacturing or destruction processes. These consist of Si trash, dust, housing-material polymers, and metal compounds in different solar panel locations. The potential health risks associated with these pollutants hinder the process of recycling, recovering, and repurposing spent silicon solar modules. Processing solid waste necessitates the accumulation of chemical treatments that release a lot of water.

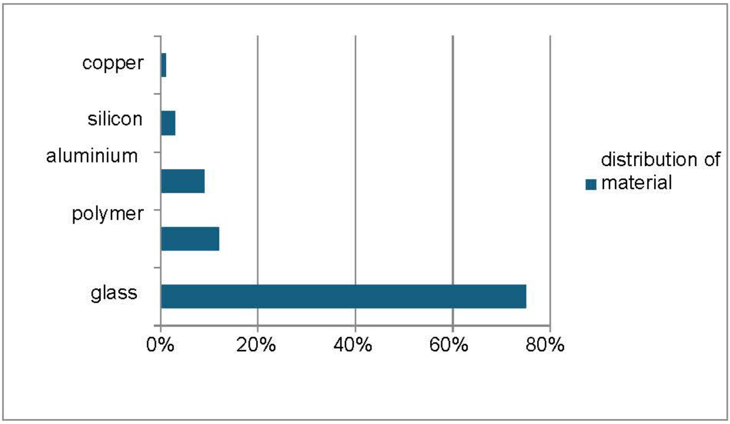

Figure 2: Distribution of material

All of these facts underscore the need to reassess the current manufacturing process and highlight the development of an affordable, highly effective, and environmentally friendly technique that can be utilized for both recycling and manufacturing. Meanwhile, there has been a notable increase in the quantity of scrapped panels; by the end of 2030, PV waste is expected to produce 1.7–8 million tons, and by 2050, it may reach 60–78 million tons cumulatively. More than 80% of these discarded photovoltaic panels were made of crystalline Si PV modules [7]. Some research places a strong emphasis on examining the environmental effects of waste photovoltaic modules across their complete life cycle, frequently evaluating variables such as carbon emissions, land ecotoxicity potential, and human toxicity potential [8]. The industry that generates electricity needs to significantly reduce its carbon footprint in order to become carbon neutral [9]. The majority of these Se-based thin-film devices have a typical sandwich structure, in which other functional layers, such as transparent conducting layers (TCLs), electron and hole transport layers (HTLs), and charge transport layers (CTLs), are layered on top of the active Se layers [10]. Methylammonium lead iodide (MAPbI3) is an example of a hybrid halide perovskite material designed to be a highly productive light harvester in solid-state solar cells [11]. Over the past few decades, the PV industry's cumulative annual growth rate (CAGR) has consistently exceeded 20%.

B. Landfill and recycling issues

As for the glass industry as a whole, publicly accessible market predictions have its estimated growth at over 3.5% [12], a pace significantly higher than this one. Aluminum and copper ore imports are in high demand due to the PV industry, accounting for a significant portion of consumption. These remarkable cost savings are mainly due to the rapid advancements in solar technology. By comparison, Europe’s solar capacity expanded at a much slower rate during this time, increasing by only 25% over the previous ten years. This pattern of solar expansion was also observed in Latin America [13]. Two half-cells containing a potassium chloride (KCl) salt bridge were used to electrooxidize the leachate, which had a mole ratio of 1.5:1 H2O2: Pb, with no stirring. Applying a voltage of -0.8 V in relation to the silver/silver chloride (Ag/AgCl) reference electrode caused the formation of gray-colored dendrites on a graphite working electrode [14]. However, according to a recent survey, about 70% of nursing students have never been taught how to dispose of medications safely [15]. While accounting for pressure loss throughout the flow, the study examines the substantial effects of changing values on thermal and electrical efficiency, net electrical power generation, and other factors [16].

C. National policies on solar panel disposal

Since solar energy has the most tremendous potential among all renewable energy sources, the Indian government has focused on promoting solar energy. The need for electricity is growing daily; therefore, developing and producing more renewable energy will be crucial in addressing power outages. The issue of managing solar panels as their useful life comes to an end is becoming increasingly apparent due to the growing number of decommissioned solar panels worldwide. It is well known that burning only fossil fuels causes pollution and other environmental issues. However, the process of generating power still requires a significant amount of fossil fuels.

A significant portion of energy needs to come from renewable sources to produce electricity and safeguard future generations from the adverse effects of pollution. The article examines several secure methods for disposing of the potentially hazardous components of discarded solar panels. China bought 5.87 million tons of unwrought copper and copper products in 2022, 492,300 tons of aluminum and aluminum products, and 125 million tons of bauxite [17]. According to the energy ministry, everyone who uses solar energy, including householders, must make sure that both expired and operational solar energy is disposed of safely. Except for the EU, no large nation with a target or installation share of PV modules has specific laws governing the use of EoL solar panels. This equates to over 78 million tons of rubbish that are improperly disposed of in landfills [18]. Studies on life cycle assessment have shown that the PV industry can gain from creating industrial symbiosis synergies [19]. By the end of 2022, the global capacity for solar power had reached an astounding 1.2 terawatts (TW) [20]. However, regulations are starting to restrict these options in several states. For instance, we must consider the situation in Florida, where homeowners in communities with homeowner association restrictions often opt for third-party ownership. There are incentives to help defray the high upfront costs.

III. Current practice in solar panel disposal

Focusing on solar and wind power, there has been a significant increase in interest in renewable energy over the past decade. Solar-grade silicon, crystalline silicon, compound semiconductors (including selenides, sulfides, and oxides of copper, cadmium, indium, gallium, and zinc), and dye-sensitized solar cells comprise the semiconductor materials that make up photovoltaic (PV) solar panels. The safe management of discarded solar cells is emerging as a significant long-term issue, alongside numerous health risks and environmental dangers resulting from pollution, including the formation of hazardous mists, the release of toxic metals, and gaseous emissions during solar cell fabrication. Specific recycling procedures are not cost-effective, despite the goal of many recycling operations being to recover rare metals from used solar cells.

IV. Impact of improper disposal

The issue of safe solar panel disposal is pertinent and current in the renewable energy and sustainability sectors, as newer solar panels are just entering the market. In contrast, the majority of first-generation solar panels have reached the end of their useful lives. After 25–30 years of solar panel working life, there will likely be 78 million solar panels worldwide when the machines are finally retired. It is estimated that such garbage weighs about 79 kilotons in physical form. The United States is expected to produce 250,000 metric tons of trash from solar panels by 2030. As the use of solar energy technologies is expected to increase over time, safe and effective procedures and methods for disposing of solar panels must be well-documented and implemented. It is now acknowledged that extraordinarily specialized and specific techniques are necessary to minimize the environmental impact of solar panels throughout their life cycle and to safely and effectively remove and dispose of any potentially hazardous materials used in each of the panel's components. The sections that follow will provide a more detailed examination of these materials.

A. Environmental risk on improper disposal

Solar panels can be challenging to dispose of due to their complex composition and potential environmental impacts. Some of the main obstacles include material complexity, hazardous substances, technological obsolescence, economic viability, and the transportation and logistics required for segregating and disposing of the panel. Materials such as glass, metals, silicon, polymers, and other chemicals are among the components that make up solar panels. It might be difficult and expensive to disassemble and separate these materials for recycling or appropriate disposal. Cadmium, lead, and other toxic materials are among the hazardous substances found in some solar panel components. Inadequate disposal practices can endanger public health and contaminate the environment. The amount of retired solar panels that need to be disposed of is growing as solar energy becomes more widely used. Efficient infrastructure and procedures are necessary to handle this volume. Older solar panels, which may not be as efficient or economical as newer models, are prematurely retired due to the rapid developments in solar technology, a key component of technological Obsolescence.

It is challenging to dispose of outdated panels while retaining valuable materials. Recycling solar panels can present specific financial difficulties. In particular, if recycling technologies are not very efficient, the cost of recycling can exceed the value of the materials recovered. Transportation and Logistics are challenging when assembling and moving discarded solar panels to recycling facilities, particularly in rural areas where solar installations are common. Regulatory Compliance:

Adhering to rules concerning recycling and the management of hazardous waste is frequently necessary for the proper disposal of solar panels. The disposal process becomes much more complex when compliance is ensured. Lack of Infrastructure: Certain areas may lack the necessary facilities for recycling and disposing of solar panels. It is common to overlook planning for solar panel disposal at the end of their useful life when installing them for the first time. Manufacturers, installers, recyclers, and legislators are among the stakeholders who must collaborate to implement successful end-of-life policies. A multifaceted strategy, including corporate collaboration, public awareness initiatives, regulatory frameworks, and technical innovation, is needed to address these issues. For solar energy to be sustainable over the long term, recycling technologies must be improved, sustainable disposal methods must be developed, and responsible end-of-life management must be encouraged.

V. Challenges in waste management

When solar panels are decommissioned, they become glass panel waste, hazardous waste, and non-hazardous waste, despite the fact that solar panels are generally acknowledged as a value-added addition to the sustainability concept of environmental conservation in the generation of green power. According to government and power company assistance programs, as well as improvements in the solar sector, solar panels have a lifespan of 25–30 years. The maximum lifespan, however, is actually only 15–20 years due to several internal and external issues, including corrosion caused by hydrolysis or chloride, potential delamination, crack formation, and power loss.

A. Importance of safe disposal

It is anticipated that the European Union (EU) would produce roughly 250,000 tons of waste from solar panels by 2026 and over 5.7 million tons by 2040. The total amount of rubbish produced is expected to exceed 10 million tons by 2050, equivalent to roughly 10,000 Eiffel Towers. When a solar panel assembly is not being serviced, it is left unprotected and vulnerable to the elements. Minerals such as cadmium, gallium, germanium, and tellurium are used in its construction to create modules; however, most of the panel assemblies are eventually discarded and end up in landfills and other areas, where they become pollutants. In addition to contributing to the world's technological waste, improper disposal of solar panels can lead to the release of hazardous materials, posing a risk to human health and the environment by contaminating water and soil. For each of the five cell types, the amount of glass and recoverable semiconductor material in a 1 m2 solar module is measured both physically and in terms of possible financial gain from recycling. For every type of solar module, the cost of disposing of the entire module, including the glass and semiconductor in a landfill, was also calculated.

Without suitable policies, it was shown that most PV modules had no economic incentive to be recycled. For instance, there is a risk that hazardous components found in solar panels, including lead and cadmium, could leak into the environment if they are subjected to severe weather or mishandled during recycling or disposal. If the panels inside the dump sites are not entirely sealed, this can result in soil and subsurface water contamination. In the worst-case scenario, it may have a negative impact on biodiversity and human health. As demand for renewable energy grows, it is predictable that more types of solar panels will be developed, necessitating the creation of newer, more advanced panel recycling techniques and facilities to keep pace with this expanding sector.

As a result, the efficient and correct handling of solar panel waste is essential for more reasons than just preserving the atmosphere and public health. The production of hazardous end-of-life photovoltaic (PV) module waste has surged as a result of the solar industry's explosive expansion. With an array of crystalline silicon PV cells and components composed of glass, polymer, and aluminum, a regular silicon-based photovoltaic panel should survive for thirty years before needing to be replaced. However, the industry is leaving behind a wider array of waste materials as research into more efficient solar technologies continues. One such technology is thin-film photovoltaic modules, which are even lighter and have the potential to harvest solar electricity from low or diffuse sunlight. It must also be acknowledged that some of these wastes are potentially toxic and need to be handled carefully.

To effectively accomplish this and preserve stakeholder confidence in this growing renewable economy, long-term thinking is needed. Recent waste electronic and electrical equipment (WEEE) legislation in Europe further emphasizes the significance of efficient, responsible waste management. Waste solar panels are now classified as WEEE since new regulations, which went into effect on August 15, 2018, specifically required manufacturers to collect the panels separately. The manufacturer of these products has been tasked with making sure that this trash is handled properly and does not damage the environment during disposal. The ultimate goal of this regulation is to encourage product designers to reduce waste at the end of a product's life and to increase producer awareness of the true environmental cost of their work. Because the items are relatively new, manufacturers are just now realizing how important it is to maximize replacement. This is evidenced by the fact that, despite the lack of current guidelines, thin-film waste management has started to garner attention.

VI. Recycling process

Researchers are looking on ways to commercialize recycling so that the majority of a solar panel's components can be profitably recovered; the solar panel recycling industry is still in its infancy. Figure 3 presents the process of recycling a solar panel. Solar panels and other solar power system components can be recycled because the glass, metals, and electronics sectors have already established recycling programs. These procedures normally entail the removal of the junction box and frame, followed by crushing, shredding, and grinding. Glass, aluminum, and copper may be salvaged in these procedures, while the remaining materials—including the silicon solar cells—may be burned.

A distinct recycling procedure is applied to thin film cadmium-telluride solar panels, which make up a smaller portion of the solar market. In addition to copper and glass, at least one American firm operates specialized recycling facilities for thin-film solar panels that retrieve the semiconductor material (cadmium and tellurium). After the 25 years that are promised, photovoltaic panels still generate energy, but their yield is 15% lower. Therefore, there is no guarantee that the plant will be disposed of once the guaranteed term has passed. Replacement should only be discussed when it truly makes financial sense, that is, when maintenance costs outweigh productivity gains. Even though the modules can be recycled, the process of separating the elements can be laborious and complicated, requiring complicated equipment. The primary actions needed to properly recycle a silicon module are to removing the 100% reusable aluminum frame.

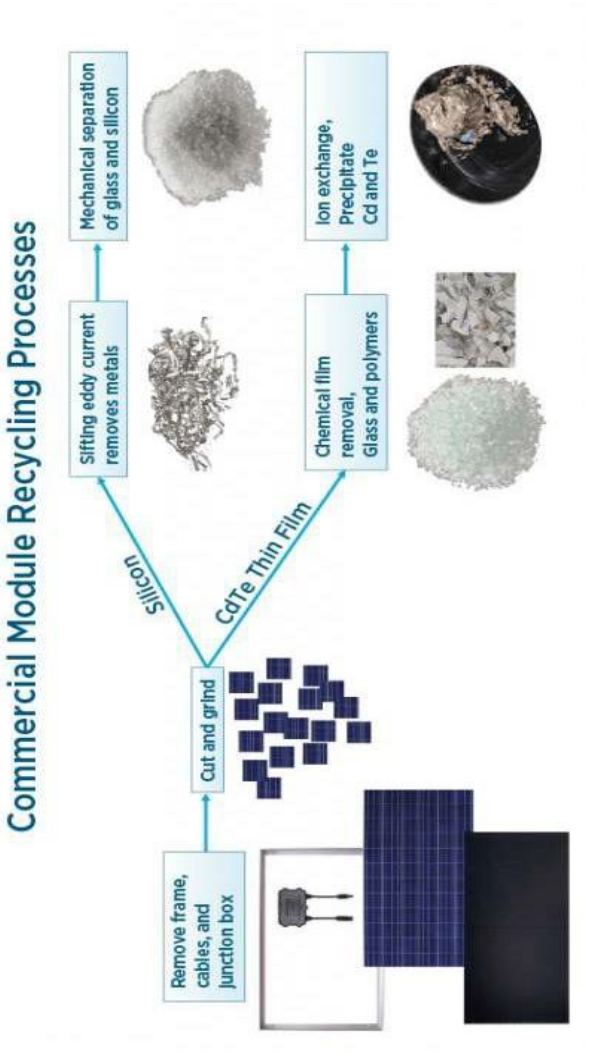

Figure 3: Recycling process

Figure 4 shows the challenges in the recycling process of solar panels. Glass is separated by a conveyor belt that is 95% reusable. Processing at 500 degrees Celsius via thermal mechanisms makes it possible for tiny plastic particles to evaporate and makes cell separation simple. Smelting silicon wafers into reusable slabs (85% reusable) and etching them away.

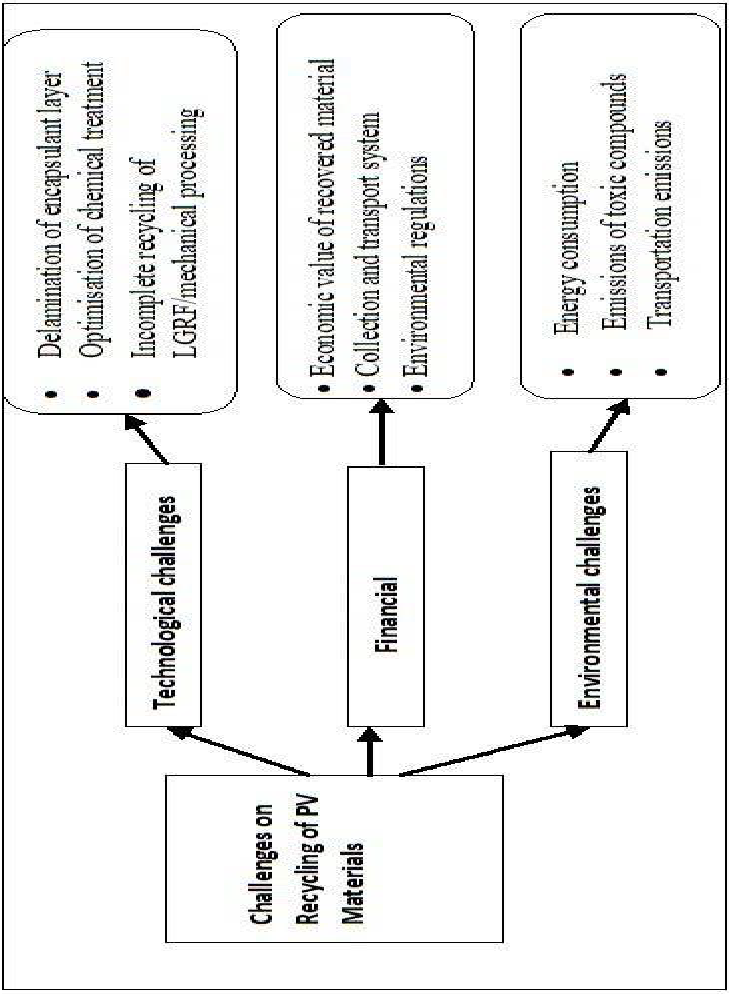

Figure 4: Challenges in Recycling

Retired, damaged, and faulty solar PV equipment will find their way into the trash stream in the absence of efficient and secure recycling systems. It will wind up in an incinerator (where burning can release hazardous elements into the air) or a landfill (where hazardous materials might leak into groundwater). Toxins can be kept out of landfills and municipal incinerators by recycling solar PV panels at established, ethical e-waste recycling facilities or at facilities that recycle lead and cadmium batteries.

Method for Chemical Recycling typically, monocrystalline solar cells are chosen for chemical recycling. Chemical procedures may be used to remove the shattered components of the PV cells. Unfortunately, the efficiency of the chemical approach was not high enough. This was caused by the high cost of the solvents and the relatively long action period of the etchant. Chemical processing for one solar cell takes more than twenty minutes. Large-scale commercial use is not acceptable for this strategy. The most challenging step was determining the optimal concentration, temperature, and composition for the etching solution. Even though the efficiency of these panels is declining, they still constitute PV waste since they contain metals like lead and tin, which are harmful to human health and the environment. Solar panel recycling is essential, as is the extraction of raw materials such as silicon, aluminum, copper, polymer, etc. Reusing these solar panels offers a significant recycling business opportunity and is anticipated to see increased demand in the next year.

Method of Thermal Recycling: The solar panel was heated to a temperature exceeding 420 degrees Celsius within a vessel. The pace of temperature increase is approximately 20 degrees Celsius each minute. In the furnace, the photovoltaic module is heated for twenty-five minutes.

This technology is more straightforward and efficient than the chemical procedure, making it a viable option for recycling commercial photovoltaic modules. One disadvantage of thermal recycling is the production of exhaust gases during the EVA copolymer's thermal.

Silicon

Silicon makes up over 95% of the solar modules currently on the market, making it the most widely used semiconductor in solar cells. It is the most widely used semiconductor in computer chips and the second most abundant substance on Earth. Silicon atoms joined together to create a crystal lattice make up crystalline silicon cells. Currently available solar cells with silicon construction offer a long lifespan, remarkable efficiency, and low cost.

Thin-film photovoltaic

An array of thin layers of photovoltaic material is deposited onto a supporting substrate, such as metal, plastic, or glass, to create a thin-film solar cell. Today’s thin-film photovoltaic (PV) semiconductors come in two primary varieties: CdTe (cadmium telluride) and CIGS (copper indium gallium diselenide).

Pervoskite photovoltaic

Thin-film cells of the perovskite variant get their name from the distinctive crystal structure of these cells. The substrate, an underlying support layer, is the foundation onto which layers of materials for perovskite cells are printed coated.

Organic photovoltaic

By providing specialized knowledge and expertise in PV panel repairs, it is straightforward to address the defects and faults that arise in the early stages of a PV panel's lifecycle. This will increase the market for repaired PV panels, allowing them to be sold for less money than new or used panels while also prolonging their lifespan. Panels that have undergone essential repairs and those that have survived beyond their stated lifespan can both find a home in the secondary market.

VII. Future direction and conclusion

The removal of dispersion materials will make recycling procedures more straightforward and more consistent in the future. These pragmatic recycling methods align with informed industry decisions and favorably impact the product life cycle. establishing a solder-free connection among the solar cells, the use of graphite films, and other compatible back-contact technologies will make recycling processes more efficient; establishing a compatible interconnection process or technique for connecting solar cells, which will also aid end-of-life applications in a simplified solar panel structure; further material substitution for conventional materials in the manufacturing of solar cells, such as the use of polymers, cadmium telluride, amorphous silicon, and copper indium dieseline.

To minimize the impact of recycling and maximize recovery, future panel designs will heavily utilize life cycle assessment findings. In addition to the solar PV industry's explosive growth, a suitable strategy for the recovery and recycling of EOL wastes is suggested. It is advised that following their EOL, recycling becomes a requirement for all manufacturing firms. In conclusion, the government must enact laws requiring manufacturers to consider the environmental impact of their waste. Encouraging the entire solar manufacturing sector to recycle, reuse, and recover their merchandise is essential.

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CHAPTER 2

POWER QUALITY ENHANCEMENT OF PV-INTEGRATED GRID SYSTEM WITH ADAPTIVE NEURO-LMS CONTROLLER-BASED DSTATCOM

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Abstract

This paper presents an adaptive neuro-controller-based control of DSTATCOM to enhance the power quality of solar photovoltaic (PV) integrated into the three-phase grid. In this system, the perturb-and-observe (P&O) method maximum power point tracking (MPPT) controller and adaptive neuro controller-based LMS (ANCLMS) control algorithm are used. (P&O) based MPPT controller extracts the solar PV array's peak power output. ANCLMS control algorithm, working on a multi-layer neural network, generates a reference grid current to control the VSC of the DSTATCOM. Combining various weighting factors such as learning rate, step size, and integral weight, the proposed adaptive controller controls the DSTATCOM precisely. It showcases superior capabilities in weight adjusting, minimizing errors, and updating the control parameters in response to dynamics in solar irradiance and connected loads, thus enhancing power quality. Grid currents are sinusoidally balanced and adhere to IEEE-519 harmonic standards and IEEE-1547 specifications for grid-interfaced PV systems under all test cases. Comparative analyses with recent publications demonstrate the proposed system's outperformance, showcasing its effectiveness in transient and steady-state responses.

Keywords: ANCLMS, MPPT, power quality, PV-DASTATCOM

Introduction

The extensive reliance on environmentally unfriendly and polluting fossil fuels has increased the emission of air pollutants, resulting in global warming and climate change. Consequently, a growing shift has been towards clean energy sources, such as wind and solar photovoltaic (PV) energy[1]. Solar energy is growing more rapidly than others due to its minimal environmental impact, cost, and technological advancements. It can deliver real power to the grid and loads to optimize and maintain energy balance, enhance grid resilience, and reduce operational costs [2]. However, the intermittency of solar irradiance and the nonlinear characteristics of connected loads like adjustable speed drives and single-phase nonlinear loads contribute significantly to PQ issues. As a result, various control techniques and mitigation measures to improve PQ in solar PV-tied grid systems have been explored.

The DSTATCOM, among others, is noted for its superior load balancing, harmonics mitigation, reduced costs, and complexity [3]. Moreover, PV modules have moderate efficiency due to their manufacturing, which needs maximum power point tracking (MPPT) algorithms to extract an extent of power from solar PV array that shows nonlinear characteristics. Techniques such as model predictive control [4], model reference adaptive controller-based approaches [5], and the P&O method-based MPPT [6] have been used to maximize power extraction. The P&O method is favored for its straightforward implementation, minimal complexity, good efficiency, and ease of execution using voltage reference and duty ratio [6]. The P&O-based MPPT with a duty ratio is used in this paper.

The VSC of DSTATCOM integrates the utility grid to the solar PV array, processes the PV power to feed it to the local loads and the grid, and improves PQ when controlled precisely. Numerous control techniques for this are reported in [7-12]. Conventional control techniques like synchronous reference theory (SRFT) and instantaneous reactive power theory (IRPT) [7] improve PQ. However, they need transformation from one reference frame to another and face difficulties such as computational complexity, lack of adaptability, and slow dynamic response. NN-based techniques like ANN [8] and backpropagation-based NN (BPNN) [9] were used for the same. However, BPNN [9] involves complex and time-consuming training processes.

Adaptive techniques such as least mean fourth [LMF] [3], Hebbian LMS (HLMS) [10], and the adaptive neuro- controller based-LMS (ANCLMS), also called the anti-Hebbian learning-based LMS algorithm [11]. Standard adaptive control techniques, such as LMF, can offer fast responses, lower computation, and improved PQ compared to conventional ones. However, they suffer from higher mean square error and oscillations. Unsupervised learning methods such as HLMS combine the supervised conventional LMS algorithm with the unsupervised Hebbian learning principle to get an unsupervised learning algorithm and improve PQ. It strengthens neuron connections when active together [10]. Being an ANN controller, parallel computing highlights its significance by enabling efficient adaptability and management of complex functions. However, ANN-based algorithms face challenges such as selecting the right size, managing noisy weights, handling insufficient hidden neurons, etc., which are exacerbated when training with minimal error signals [11]. To tackle these concerns, an ANCLMS algorithm has been developed [11]. It enhances learning by reducing synaptic connections during simultaneous neuron activity, aiding pattern separation and dynamic adaptation. Incorporating integral weight, learning rate, and step size ensures suitable weights and minimizes static error, improving PQ. However, [8-11] do not address PQ issues associated with solar PV integration into grid. Modified adaptive LMS algorithms such as smooth LMS (SLMS) [12] and LMF [3] have been utilized to improve PQ in double stage PV-integrated grid systems. These methods are effective in enhancing PQ.

The ANCLMS algorithm performs well in enhancing PQ under various test cases by controlling the DSTATCOM [11]. However, it does not address challenges related to PV- integration into the grid. This study introduces the ANCLMS control algorithm for DSTATCOM, enhancing PQ in double - stage PV-integrated three-phase grids. The system effectively improves PQ by maintaining IEEE standards and demonstrates strong dynamic performance in varying environmental conditions.

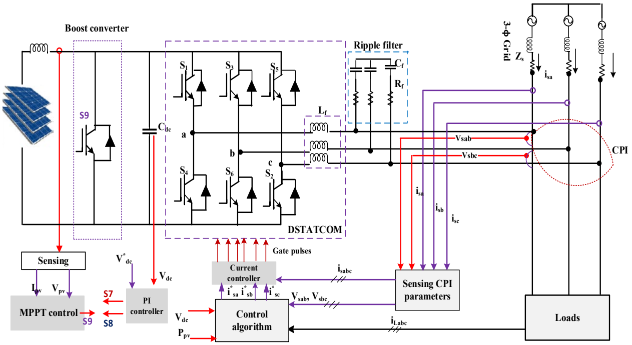

Fig. 1. System Configuration

Table I Design of solar PV parameters

Module (KC200GT)		**Solar PV array designed value**	
Parameter	**Selected value**	**Parameter**	**Design Value**
Open circuit voltage	32.9V	PV-power (PMPP)	30kW
Short circuit current	8.21A	PV-voltage (VMPP)	657.5V
Voltage at MPP(V_m)	26.3V	PV-current (IMPP) $I_{MPP} = \frac{P_{MPP}}{V_{dc}}$	45.8A
Current at MPP(I_m)	7.61A	No. of modules: $N_s = \frac{V_{dc}}{V_m} = 24.9$	25 (in series)
		$N_p = \frac{I_{MPP}}{I_m} = 6$	6 (in parallel)

System Topology

The configuration of the double-stage solar PV system integrated with the utility grid (Fig. 1) comprises a PV array, boost (DC-DC) converter, interfacing inductors (Lf), a ripple filter, and nonlinear and linear loads, all intertwined at a point of interconnection (POI). The solar PV array tied at POI links to a three-phase distribution grid with specifications of 400V and 50Hz, and the array generates a peak power of 30kW. The comprehensive specifications for the chosen solar PV model [13], are provided in Table I. The boost converter designed in [14] is used in this study.

A well-designed interfacing inductor enhances system efficiency and extends equipment lifespan. Ripple filters smoothen voltage waveforms and eliminate switching harmonics. V_{dc} should be high for optimal dynamics but minimal to reduce switching losses, with capacitance designed to regulate V_{dc} during disturbances quickly. The time constant should not exceed the fundamental switching time. i.e., $R_f \times C_f \leq \frac{1}{f_s}$. Each of these components is designed and given in Table II.

Table II Design of DC link voltage and capacitor, interfacing inductor, and ripple filter

Parameter	**Calculation**	**Value at normal condition**	**Calculated value**	**Selected value**
DC-link voltage	$V_{dc} = \frac{2\sqrt{2} \times V_{p-p}}{\sqrt{3} \times m}$	V_{p-p}=400V, m=1	653.2V	658V
DC-link capacitor	$C_{dc} = \frac{P_{MPP}/V_{dc}}{6 \times \omega \times V_{dcr}}$	P_{MPP}=30kW, w=314rad/s and V_{dcr}=1.5% of V_{dc}	2451.87 µF	4000 µF
Interfacing inductor	$L_f = \frac{\sqrt{3} \times m \times V_{dc}}{12 \alpha f_{sw} I_r}$	α=1.2, f_{sw}=10kHz and I_r=5% peak current	2.57mH	3mH
Ripple filter	$R_f \times C_f \leq \frac{1}{f_s}$	Rf=5Ω	C_f=20 µF	C_f=10 µF

Control structure

The adaptive ANCLMS control algorithm to control the DSTATCOM, which integrated PV array into a 3-phase distribution grid at POI, and P&O method-based MPPT, is shown in Fig. 2. The P&O-based MPPT controller has been used to maximize power output from (P_{pv}) [14]. It takes current (I_{pv}) and voltage (V_{pv}) as inputs and outputs PV power (P_{pv}). The control algorithms that have been used in this proposed system are explained as follows:

ANCLMS Control Algorithm

The ANCLMS control algorithm generates VSC switching pulses and performs PQ enhancement tasks. It incorporates elements like past weight, learning rate, and normalization weight, which are adjusted to reduce computational complexity, improve dynamic performance, and enhance the estimation rate. Its learning procedures, illustrated in Fig. 2.

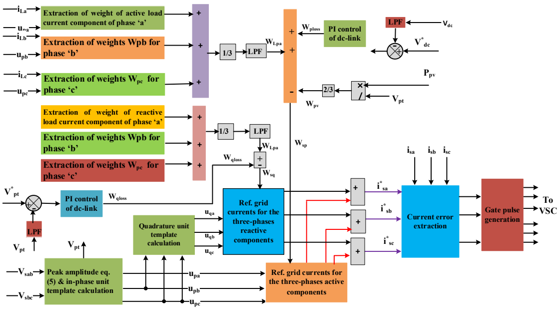

Fig. 2. Schematic diagram of ANCLMS control algorithm

The magnitude (V_{pt}) and the unit templates are evaluated by calculating the phase voltages of the three phases from the measured 3-phase phase-to-phase voltages at POI (V_{sab}, V_{sbc}), as given in equations (1)-(3).

$$V_{pt} = \sqrt{\frac{2}{3}({V_{sa}}^2 + {V_{sb}}^2 + {V_{sc}}^2)} \qquad (1)$$

The unit templates of active and reactive components are calculated in (2) and (3), respectively:

$$u_{pn}(t) = {V_{sn}(t)}\Big/{V_{pt}},\ u_{pb}(t) = {V_{sb}(t)}\Big/{V_{pt}} \text{ and}$$
$$u_{pa}(t) = {V_{sc}(t)}\Big/{V_{pt}} \qquad (2)$$

$$u_{qa} = \frac{-u_{spb}+u_{spc}}{\sqrt{3}},\ u_{qb} = \frac{\sqrt{3}u_{spa}+u_{spb}-u_{spc}}{2\sqrt{3}} \text{ and}$$
$$u_{qc} = \frac{-\sqrt{3}u_{spa}+u_{spb}-u_{spc}}{2\sqrt{3}} \qquad (3)$$

The DC-link voltage error (V_{dce}) is computed as the disparity between reference DC-link voltage (V^*_{dc}) and the detected Vdc as given in equation (4), and it is sent to the DC side PI controller.