Review

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Posted Date: 24 May 2024

doi: 10.20944/preprints202405.1591.v1

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Review

Advancements in Solar Cell Fabrication Techniques: A Comprehensive Review

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Abstract: Solar energy has emerged as a promising alternative to traditional fossil fuels due to its abundant availability and sustainability. Solar cells, the fundamental units of solar energy conversion, have undergone significant advancements in fabrication techniques to enhance their efficiency, durability, and cost-effectiveness. This review aims to provide a comprehensive overview of various methods employed in the preparation of solar cells, including thin-film, crystalline silicon, organic, and perovskite-based technologies. By analyzing recent research developments, challenges, and future prospects, this article sheds light on the evolving landscape of solar cell fabrication, contributing to the ongoing efforts in achieving widespread adoption of solar energy.

Keywords: solar cell; energy conversion; thin-film; crystalline silicon; organic

1. Introduction

The pressing need for sustainable energy sources in the face of environmental concerns and energy security challenges has propelled the rapid development of solar energy technologies[1]. At the forefront of this energy revolution are solar cells, the building blocks of photovoltaic systems that directly convert sunlight into electricity[2]. Over the past few decades, remarkable progress has been made in enhancing the efficiency, reliability, and affordability of solar cells through innovative fabrication techniques[3].

Solar energy offers a clean and abundant resource that holds the potential to significantly reduce greenhouse gas emissions and mitigate the impacts of climate change[4]. Unlike finite fossil fuels, solar power is inexhaustible and widely distributed, making it a compelling solution for meeting the world's growing energy demand sustainably[5]. However, the widespread adoption of solar energy hinges on the continued advancement of solar cell technologies to improve performance, reduce costs, and expand applicability across diverse environments and applications[6].

This review aims to provide a comprehensive overview of the various methods employed in the preparation of solar cells, encompassing a range of materials and fabrication techniques. From thin-film technologies offering flexibility and scalability to crystalline silicon cells renowned for their high efficiency and durability, and from organic solar cells enabling low-cost fabrication to perovskite-based cells demonstrating rapid efficiency gains, each approach contributes uniquely to the diverse landscape of solar energy conversion.

By examining recent research advancements, challenges, and future prospects in solar cell fabrication, this review seeks to elucidate the evolving state of the art in solar energy technology. Through a synthesis of scientific literature and industry developments, this article aims to inform esearchers, engineers, policymakers, and stakeholders about the current state of solar cell fabrication and the pathways toward realizing a sustainable and resilient energy future powered by the sun.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 24 May 2024 doi:10.20944/preprints202405.1591.v1

2. Fabrication Techniques

2.1. Thin-Film Solar Cells

Thin-film solar cells represent a promising class of photovoltaic devices characterized by their lightweight, flexibility, and potential for low-cost production[7]. Unlike traditional crystalline silicon solar cells, which require thick semiconductor wafers, thin-film technologies utilize thin layers of semiconductor materials deposited onto substrates, thereby reducing material usage and manufacturing costs[8]. Several fabrication techniques are employed to produce thin-film solar cells, each offering unique advantages and challenges.

2.1.1. Chemical Vapor Deposition (CVD)

Chemical vapor deposition is a widely used technique for depositing thin films of semiconductor materials onto substrates. In the context of thin-film solar cells, CVD is often employed to fabricate cadmium telluride (CdTe) and hydrogenated amorphous silicon (a-Si:H) solar cells[9]. In this process, precursor gases containing the desired elements are introduced into a reaction chamber, where they undergo chemical reactions to form thin films on heated substrates. CVD offers precise control over film thickness and composition, enabling the optimization of device performance[10].

2.1.2. Sputtering

Sputtering is another common method for depositing thin films in thin-film solar cell fabrication. In sputtering, a target material (e.g., cadmium sulfide, indium tin oxide) is bombarded with high-energy ions in a vacuum chamber, causing atoms to be ejected and deposited onto a substrate[11]. Sputtering allows for the deposition of uniform and dense films over large areas, making it suitable for industrial-scale production of thin-film solar cells[12]. Various sputtering techniques, including radio frequency (RF) sputtering and magnetron sputtering, offer flexibility in film composition and deposition rate[13].

2.1.3. Electrodeposition

Electrodeposition, also known as electroplating, is a cost-effective and scalable technique for depositing thin films of semiconductor materials onto conductive substrates[14]. In the fabrication of thin-film solar cells, electrodeposition is often used to deposit materials such as copper indium gallium selenide (CIGS) and copper zinc tin sulfide (CZTS)[15]. The process involves immersing a conductive substrate and a counter electrode in an electrolyte solution containing ions of the desired material. Upon the application of an electric current, the ions are reduced and deposited as thin films on the substrate surface. Electrodeposition offers advantages such as high deposition rates, low energy consumption, and compatibility with flexible substrates[16].

2.1.4. Roll-to-Roll Printing

Roll-to-roll (R2R) printing, also known as reel-to-reel printing, is a high-throughput manufacturing process used to produce flexible thin-film solar cells on continuous rolls of substrate material[17]. In R2R printing, semiconductor inks or precursors are deposited onto flexible substrates (e.g., polymer films) using techniques such as inkjet printing, screen printing, or gravure printing[18]. The deposited layers are then annealed or cured to form thin-film solar cell structures. R2R printing offers advantages such as rapid production, low material wastage, and compatibility with large-area and flexible substrates, making it well-suited for applications such as building-integrated photovoltaics and wearable electronics[19].

2.1.5. Spray Pyrolysis

Spray pyrolysis is a versatile and cost-effective technique for depositing thin films of semiconductor materials onto substrates[20]. In this process, a precursor solution containing the desired metal salts or organic compounds is atomized into fine droplets and sprayed onto a heated substrate[21]. As the solvent evaporates, the precursor molecules undergo chemical reactions and crystallize to form thin films. Spray pyrolysis offers advantages such as simplicity, scalability, and compatibility with various substrates and deposition conditions. It is commonly used to fabricate thin-film solar cells based on materials such as cadmium sulfide (CdS) and zinc oxide (ZnO).

 doi:10.20944/preprints202405.1591.v1

2.2. *Crystalline Silicon Solar Cells*

Crystalline silicon (c-Si) solar cells are the most mature and widely deployed photovoltaic technology, accounting for a significant portion of the global solar energy market[22]. These cells are renowned for their high efficiency, long-term stability, and compatibility with existing manufacturing infrastructure[23]. The fabrication process of crystalline silicon solar cells involves several key steps, from ingot growth to module assembly, each aimed at optimizing the performance and reliability of the final device.

2.2.1. Ingot Growth

The fabrication of crystalline silicon solar cells begins with the growth of silicon ingots, which serve as the raw material for wafer production[24]. Silicon ingots are typically produced using the Czochralski (Cz) or float-zone (FZ) method[25]. In the Czochralski process, high-purity silicon feedstock is melted in a crucible and slowly pulled upwards using a seed crystal, resulting in a single-crystal ingot with controlled crystal orientation and doping[26]. In the float-zone method, a silicon rod is melted using radiofrequency induction heating while being translated through a zone of molten silicon, yielding a high-purity single-crystal ingot.

2.2.2. Wafering

After ingot growth, the silicon ingots are sliced into thin wafers using wire saws or diamond saws[27]. These wafers typically have thicknesses ranging from 100 to 300 micrometers and diameters of 125 to 200 millimeters[28]. Diamond wire sawing has become the preferred method for wafering due to its higher throughput, lower kerf loss, and reduced consumable costs compared to traditional slurry-based sawing techniques[29].

2.2.3. Surface Texturing

Surface texturing is employed to enhance light trapping and reduce surface reflectance, thereby increasing the absorption of incident sunlight in the silicon wafer. Common methods for surface texturing include wet chemical etching and plasma texturing[30]. Wet chemical etching involves immersing the silicon wafer in an acidic or alkaline solution to selectively remove surface layers and create a rough texture[31]. Plasma texturing utilizes reactive ion etching to create nano-scale surface structures that scatter incident light, improving light trapping efficiency.

2.2.4. Doping

Doping is a critical step in crystalline silicon solar cell fabrication, as it introduces impurities to modify the electrical properties of the silicon material[32]. Phosphorus and boron are commonly used as dopants to create n-type and p-type regions, respectively, in the silicon wafers[33]. Dopants are introduced into the silicon lattice through processes such as diffusion, ion implantation, or deposition of doped layers. Control of dopant concentration and distribution is crucial for achieving the desired electrical characteristics and performance of the solar cell[34].

2.2.5. Passivation

Surface passivation is essential for minimizing recombination losses at the semiconductor-electrolyte interface and improving the minority carrier lifetime in crystalline silicon solar cells[35]. Passivation layers, typically composed of dielectric materials such as silicon nitride (SiNx) or aluminum oxide (Al2O3), are deposited onto the silicon wafer surface using techniques like plasma-enhanced chemical vapor deposition (PECVD) or atomic layer deposition (ALD)[36]. These passivation layers help reduce surface recombination velocities and enhance the overall efficiency of the solar cell.

2.2.6. Metallization and Encapsulation

The final steps in crystalline silicon solar cell fabrication involve metallization and encapsulation to connect the individual solar cells into modules and protect them from environmental factors[37]. Metal contacts, typically made of silver or aluminum, are screen-printed onto the front and back surfaces of the solar cell to collect current generated by the photogenerated carriers[38]. The solar cells are then encapsulated within a transparent and durable encapsulant material, such as ethylene-vinyl acetate (EVA) or polyvinyl butyral (PVB), to provide mechanical support and protection against moisture, dust, and mechanical stress.

2.3. Organic Solar Cells

Organic solar cells (OSCs), also known as organic photovoltaics (OPVs), offer a promising approach to solar energy conversion, characterized by their low cost, lightweight, and flexibility[39]. Unlike traditional silicon-based solar cells, OSCs utilize organic semiconductor materials composed of carbon-based molecules to absorb and convert sunlight into electricity[40]. The fabrication of OSCs involves several key steps, including material deposition, device architecture design, and encapsulation, each aimed at optimizing device performance and stability.

2.3.1. Solution Processing

Solution processing is the most common method for depositing organic semiconductor materials onto substrates in OSC fabrication[41]. Techniques such as spin-coating, inkjet printing, doctor-blading, and slot-die coating are used to deposit thin films of organic active layers and charge transport materials onto flexible or rigid substrates[42]. Solution processing offers advantages such as low-cost, high throughput, and compatibility with large-area and flexible substrates, making it suitable for scalable production of OSCs.

2.3.2. Thermal Evaporation

Thermal evaporation is another method used for depositing organic semiconductor materials in OSC fabrication, particularly for small molecule-based OSCs[43]. In this process, organic materials in the form of pellets or powders are heated in a vacuum chamber, causing them to vaporize and condense onto a cooled substrate to form thin films. Thermal evaporation offers precise control over film thickness and composition, enabling the fabrication of high-performance OSCs with well-defined interfaces and morphology[44].

2.3.3. Vacuum Deposition Techniques

Various vacuum deposition techniques, such as organic vapor-phase deposition (OVPD), molecular beam epitaxy (MBE), and pulsed laser deposition (PLD), are employed in OSC fabrication to deposit organic materials under controlled conditions. These techniques offer advantages such as high purity, uniformity, and reproducibility of thin film deposition, leading to improved device performance and reliability[45]. Vacuum deposition methods are particularly well-suited for depositing multilayered structures and heterojunction interfaces in OSCs[46].

2.3.4. Roll-to-Roll Printing

Roll-to-roll (R2R) printing, also known as reel-to-reel printing, is a high-throughput manufacturing technique used to produce flexible OSCs on continuous rolls of substrate material[47]. In R2R printing, organic semiconductor inks or solutions are deposited onto flexible substrates (e.g., polymer films) using techniques such as gravure printing, flexographic printing, or screen printing[18]. The deposited layers are then annealed or dried to form thin-film OSC structures. R2R printing offers advantages such as rapid production, low material wastage, and compatibility with large-area and flexible substrates, making it well-suited for commercial-scale production of OSCs[48].

2.3.5. Device Architecture Design

The design of the device architecture plays a crucial role in determining the performance and stability of OSCs[49]. Common OSC architectures include single-layer, bilayer, bulk heterojunction (BHJ), and tandem structures. BHJ OSCs, in which electron donor and acceptor materials are intimately mixed at the nanoscale to form a continuous interpenetrating network, have gained widespread attention due to their high efficiency and versatility[50]. Tandem OSCs, which combine multiple active layers with complementary absorption spectra to maximize light harvesting, offer further potential for efficiency enhancement[51].

 doi:10.20944/preprints202405.1591.v1

2.3.6. Encapsulation and Packaging

Encapsulation and packaging are essential for protecting OSCs from environmental factors such as moisture, oxygen, and light-induced degradation. Encapsulation materials such as glass, polymers, or metal foils are used to seal OSC devices and prevent ingress of harmful contaminants[52]. Flexible encapsulation techniques such as barrier coatings, laminates, and thin-film encapsulants are employed to accommodate the flexibility and lightweight nature of OSCs, enabling the development of durable and portable photovoltaic systems[52].

2.4. Perovskite Solar Cells

Perovskite solar cells (PSCs) have garnered significant attention in recent years due to their rapid efficiency gains, low-cost materials, and versatility in fabrication[53]. PSCs are based on organometal halide perovskite materials with a unique crystal structure that enables efficient light absorption and charge carrier transport. The fabrication process of PSCs involves several key steps, including perovskite film deposition, interface engineering, and device encapsulation, each aimed at optimizing device performance and stability[3].

2.4.1. Solution Processing

Solution processing is the predominant method for depositing perovskite thin films in PSC fabrication[54]. Techniques such as one-step and two-step solution processing are commonly employed to deposit perovskite layers onto substrates. In one-step solution processing, a precursor solution containing perovskite precursors (e.g., lead halide salts and organic cations) is spin-coated or drop-cast onto a substrate and annealed to form the perovskite film[55]. In two-step solution processing, a layer of precursor solution containing the lead halide salt is first deposited, followed by deposition of the organic cation solution to form the perovskite layer[55]. Solution processing offers advantages such as simplicity, scalability, and compatibility with various substrate materials, making it suitable for large-scale production of PSCs.

2.4.2. Vapor Deposition Techniques

Vapor deposition techniques, such as vapor-assisted solution deposition (VASP), chemical vapor deposition (CVD), and physical vapor deposition (PVD), are also used in PSC fabrication to deposit perovskite thin films under controlled conditions[56]. VASP involves exposing the substrate to vapor-phase precursors in the presence of a solvent vapor, allowing for controlled nucleation and growth of perovskite crystals[57]. CVD and PVD techniques enable precise control over film thickness and composition by evaporating or sputtering perovskite precursors onto substrates in a vacuum chamber[58]. Vapor deposition techniques offer advantages such as uniform film morphology, high crystallinity, and compatibility with complex device architectures, making them suitable for research-scale fabrication of PSCs.

2.4.3. Interface Engineering

Interface engineering is critical for optimizing the performance and stability of PSCs by controlling the charge transport and recombination processes at the interfaces between different layers. Interface layers, such as hole and electron transport materials (HTMs and ETMs), interfacial modifiers, and charge-selective contacts, are incorporated into PSC devices to improve charge extraction, reduce interfacial recombination, and enhance device stability[59]. Common interface materials used in PSCs include organic small molecules (e.g., spiro-OMeTAD, PTAA), inorganic oxides (e.g., $TiO2$, ZnO), and self-assembled monolayers (SAMs). Interface engineering strategies such as surface passivation, doping, and interfacial dipole alignment contribute to the development of high-performance PSCs with improved efficiency and stability[60].

2.4.4. Perovskite Crystal Growth Techniques

Various techniques are employed to control the crystal growth and morphology of perovskite thin films in PSC fabrication, including solution engineering, solvent engineering, and additive engineering[61]. Solution engineering involves optimizing the composition and concentration of perovskite precursor solutions to promote nucleation and growth of high-quality perovskite

 doi:10.20944/preprints202405.1591.v1

crystals[62]. Solvent engineering techniques such as anti-solvent dripping and solvent annealing are used to control the solvent evaporation rate and film formation kinetics, leading to improved film morphology and device performance[61]. Additive engineering involves incorporating additives such as surfactants, Lewis acids, or salts into the perovskite precursor solutions to tailor the crystallization kinetics, defect passivation, and grain boundary properties of perovskite thin films[63].

2.4.5. Encapsulation and Device Packaging

Encapsulation and device packaging are essential for protecting PSCs from environmental factors such as moisture, oxygen, light-induced degradation, and mechanical stress[64]. Encapsulation materials such as glass, polymers, or metal foils are used to seal PSC devices and prevent ingress of harmful contaminants[65]. Flexible encapsulation techniques such as barrier coatings, laminates, and thin-film encapsulants are employed to accommodate the flexibility and lightweight nature of PSCs, enabling the development of durable and portable photovoltaic systems.

3. Recent Advances and Challenges

3.1. Recent Advances

3.1.1. Perovskite Solar Cells (PSCs)

Perovskite solar cells have witnessed remarkable progress in recent years, with power conversion efficiencies (PCEs) exceeding 25%. Advances in perovskite materials, device architectures, and fabrication techniques have contributed to the rapid efficiency gains[3]. Strategies such as interface engineering, defect passivation, and tandem cell integration have enabled the development of high-performance PSCs with improved stability and scalability[66].

3.1.2. Tandem Solar Cells

Tandem solar cells, which combine multiple absorber materials with complementary absorption spectra to maximize light harvesting, have emerged as a promising approach for achieving high efficiencies[51]. Recent advancements in tandem cell design, such as perovskite-silicon tandems and perovskite-CIGS tandems, have demonstrated PCEs exceeding 30%. Tandem cells offer the potential to surpass the efficiency limits of single-junction solar cells and further reduce the cost per watt of solar energy[67].

3.1.3. Advanced Materials and Nanotechnology

The development of novel materials and nanotechnologies has led to significant improvements in solar cell efficiency, durability, and cost-effectiveness[68]. Quantum dots, nanostructured electrodes, and plasmonic nanoparticles are being explored to enhance light absorption, charge separation, and carrier transport in solar cells[69]. Additionally, advances in materials synthesis, such as solution processing and vapor deposition techniques, have enabled the fabrication of thin-film and perovskite solar cells with controlled morphology and composition[70].

3.1.4. Manufacturing Scalability

Scalability is a critical factor for the commercialization of solar cell technologies[71]. Recent advancements in manufacturing techniques, such as roll-to-roll printing, slot-die coating, and automated assembly processes, have enabled high-throughput production of solar cells at reduced costs. Scalable manufacturing approaches facilitate the mass production of solar cells and accelerate their deployment in large-scale photovoltaic installations[72].

3.2. Challenges:

3.2.1. Stability and Reliability

Despite significant progress, the stability and reliability of solar cells remain key challenges for widespread adoption[73]. Perovskite solar cells, in particular, are prone to degradation when exposed to moisture, oxygen, light, and thermal stress. Addressing stability issues requires the development of robust encapsulation materials, interface engineering strategies, and defect mitigation techniques to prolong the device lifetime and ensure long-term performance.

3.2.2. Material Toxicity and Environmental Impact

Some materials used in solar cell fabrication, such as lead-based perovskites and rare earth elements, raise concerns regarding toxicity and environmental sustainability[74]. Research efforts are focused on developing alternative materials with lower toxicity and abundance, as well as implementing recycling and waste management strategies to minimize the environmental impact of solar cell production and end-of-life disposal[75].

3.2.3. Cost Reduction

Despite significant reductions in the cost of solar photovoltaic systems, further cost reduction is needed to compete with conventional energy sources. The high cost of materials, fabrication processes, and balance-of-system components remains a barrier to the widespread adoption of solar energy. Innovations in materials synthesis, manufacturing technologies, and supply chain optimization are required to drive down the cost of solar cell production and improve the economics of solar energy deployment[76].

3.2.4. Performance Limitations

While recent advancements have pushed the efficiency limits of solar cells, there are still fundamental performance limitations that need to be addressed. Efficiency losses due to optical losses, non-radiative recombination, and parasitic resistances hinder the overall performance of solar cells. Research efforts are focused on developing innovative device architectures, materials, and fabrication techniques to minimize efficiency losses and maximize the power conversion efficiency of solar cells[77].

4. Future Prospects

4.1. Efficiency Breakthroughs

Future advancements in solar cell fabrication techniques are expected to focus on achieving higher efficiencies beyond the current limits[78]. Innovative approaches such as multi-junction cells, hot-carrier extraction, and spectral splitting could enable solar cells to exceed theoretical efficiency limits and approach the maximum potential of sunlight conversion. Integration of emerging materials such as perovskites, quantum dots, and 2D materials into novel device architectures holds promise for further efficiency gains[79].

4.2. Tandem and Multi-Junction Technologies

Tandem and multi-junction solar cells, which combine multiple semiconductor materials with complementary absorption spectra, are poised to become mainstream technologies in the coming years[80]. Continued research and development efforts in tandem cell design, materials optimization, and manufacturing scalability could lead to commercially viable tandem cells with efficiencies surpassing Tandem cells offer the potential to capture a broader range of solar spectrum and maximize energy conversion efficiency, paving the way for cost-competitive photovoltaic systems.35%[66].

4.3. Thin-Film and Flexible Solar Cells

Thin-film and flexible solar cells hold great potential for diverse applications such as building-integrated photovoltaics, wearable electronics, and portable power generation. Future advancements in thin-film deposition techniques interface engineering, and encapsulation technologies could lead to lightweight, low-cost, and durable solar cells with high efficiency and mechanical flexibility. Roll-to-roll printing, inkjet printing, and spray deposition methods could enable large-scale production of thin-film solar modules at reduced costs, revolutionizing the solar energy industry[81].

4.4. Sustainable and Eco-Friendly Materials

The shift towards sustainable and eco-friendly materials in solar cell fabrication is expected to accelerate in the future[82]. Research efforts are focused on developing alternative materials with low toxicity, abundance, and environmental impact. Perovskite materials free from lead and other heavy metals, as well as organic and bio-inspired materials derived from renewable sources are being explored as viable alternatives for next-generation solar cells[83]. Implementing green manufacturing practices, recycling technologies and lifecycle assessments will further enhance the sustainability of solar energy production.

4.5. Advanced Manufacturing Technologies

Advancements in manufacturing technologies and processes are crucial for scaling up solar cell production and reducing manufacturing costs[23]. Additive manufacturing, robotics, automation, and machine learning techniques could streamline the fabrication process, improve yield rates, and optimize material usage[84]. Smart manufacturing concepts such as digital twins, predictive maintenance, and real-time monitoring could enhance productivity, quality control, and energy efficiency in solar cell manufacturing facilities[85].

4.6. Integrated Photovoltaic Systems

The integration of photovoltaic systems with other technologies such as energy storage, electric vehicles, and smart grids holds promise for maximizing the value and impact of solar energy[86]. Future advancements in system-level integration, grid integration, and energy management technologies could enable seamless integration of solar power into existing infrastructure and promote the transition towards a distributed and resilient energy system. Hybrid solar photovoltaic-thermal systems, solar-hydrogen systems, and solar-powered desalination systems could address multiple energy and water challenges simultaneously[87].

5. Conclusions

The advancements in solar cell fabrication techniques represent a pivotal step towards achieving a sustainable and renewable energy future. From the early development of crystalline silicon cells to the recent breakthroughs in perovskite and tandem cell technologies, the evolution of solar cell fabrication has been marked by continuous innovation, driven by the pursuit of higher efficiency, lower costs, and broader applicability.

The recent strides in solar cell fabrication have been particularly remarkable, with novel materials, device architectures, and manufacturing processes pushing the boundaries of efficiency and scalability. Perovskite solar cells have emerged as a frontrunner in the photovoltaic landscape, demonstrating unprecedented efficiency gains and offering the potential for cost-effective, high-performance solar energy solutions.

Furthermore, the integration of advanced materials such as quantum dots, 2D materials, and nanostructures into solar cell designs has opened up new avenues for enhancing light absorption, charge separation, and carrier transport. Thin-film and flexible solar cells have expanded the range of applications for solar energy, enabling integration into building materials, consumer electronics, and off-grid power systems.

However, challenges such as stability, material toxicity, and manufacturing scalability remain significant hurdles to overcome. Addressing these challenges will require collaborative efforts from researchers, engineers, policymakers, and industry stakeholders to develop robust encapsulation methods, eco-friendly materials, and efficient manufacturing processes.

In conclusion, the future of solar cell fabrication holds immense promise for achieving higher efficiencies, lower costs, and broader applications of solar energy. By harnessing the collective expertise and ingenuity of the global community, we can accelerate the transition towards a sustainable and resilient energy system powered by the sun, thereby mitigating climate change, enhancing energy security, and improving the quality of life for generations to come.

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