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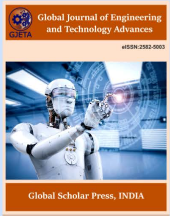

(Research Article)

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Large scale utility solar installation in the USA: Environmental impact and job creation

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Abstract

Large-scale utility solar installations in the United States have gained momentum as a key component of the nation's renewable energy transition. This review examines the environmental impact and job creation associated with these projects, focusing on their contribution to decarbonizing the energy sector and stimulating economic growth. Utility-scale solar installations offer significant environmental benefits, particularly in reducing greenhouse gas emissions and displacing fossil fuel-based energy sources. They also contribute to improving air quality and mitigating climate change. However, challenges such as land use, habitat disruption, and water usage in arid regions present potential environmental concerns. To address these, mitigation strategies such as dual-use projects and siting solar farms on degraded lands are becoming more common. In addition to environmental advantages, utility-scale solar installations play a pivotal role in job creation and economic development. These projects generate a wide range of employment opportunities, particularly in construction, operations, and maintenance. The solar energy sector has grown rapidly, creating tens of thousands of jobs across various regions, including economically disadvantaged and rural areas. The economic ripple effect of solar job creation extends to local communities and related industries, further boosting economic activity. Workforce training and development initiatives are crucial for preparing workers to meet the demands of this growing sector, ensuring that job creation benefits are widespread and inclusive. Despite the positive impacts, challenges related to regulatory barriers, grid integration, and financing remain. This review underscores the importance of supportive policy frameworks and continued innovation to overcome these obstacles and maximize the potential of large-scale solar installations. Looking ahead, advancements in technology, energy storage, and grid infrastructure will be essential for sustaining the environmental and economic gains from utility-scale solar energy in the U.S.

Keywords: Solar Installation; USA; Environmental Impact; Job Creation

1. Introduction

The landscape of energy production in the United States is undergoing a significant transformation, with solar energy emerging as a key player in the nation's pursuit of a cleaner, more sustainable future (Azarpour *et al.*, 2022; Bassey, 2022). Over the past decade, the growth of renewable energy, particularly solar power, has dramatically reshaped the U.S. energy mix. According to the U.S. Energy Information Administration (EIA), solar energy contributed approximately 4% of the total electricity generation in 2021, a substantial increase from less than 1% in 2010 (Tabassum *et al.*, 2021). This surge is primarily attributed to technological advancements, declining costs, and favorable policies that have paved

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the way for widespread adoption. Among the various forms of solar energy deployment, large-scale utility solar installations have gained significant traction, transforming vast areas of land into productive solar farms that harness the sun's energy to meet growing electricity demands (Silva and Sareen, 2021; Bassey, 2023).

The rise of large-scale solar projects is crucial in addressing the energy demands of an increasingly electrified society while simultaneously reducing carbon emissions (Mathew and Ejiofor, 2023). As climate change poses an existential threat, transitioning away from fossil fuels toward renewable energy sources has become imperative. Utility-scale solar installations not only provide a clean source of energy but also help mitigate greenhouse gas emissions associated with conventional energy production. In line with national energy goals and climate targets set forth in various legislative frameworks, large-scale solar projects contribute to the United States' commitment to achieving net-zero emissions by 2050. By integrating more renewable sources into the energy grid, these installations play a vital role in reducing the carbon footprint of the energy sector while ensuring a reliable power supply for homes and businesses (Hoang and Nguyen, 2021; Mathew and Adu-Gyamfi, 2023).

The objective of this review is to explore the environmental impact of large-scale solar installations and analyze their contribution to job creation in the United States. As the deployment of utility-scale solar continues to expand, understanding its ecological implications is essential for informed decision-making. This includes examining factors such as land use, water consumption, and effects on local ecosystems. Furthermore, large-scale solar projects have significant economic implications, particularly concerning job creation. The solar industry has become a substantial source of employment, providing jobs in manufacturing, installation, maintenance, and support services. Analyzing these dimensions will provide insights into how large-scale solar projects can be leveraged to promote both environmental sustainability and economic growth. As the United States moves towards a more sustainable energy future, large-scale utility solar installations represent a critical component of this transition. By addressing energy demands, reducing carbon emissions, and contributing to job creation, these projects hold the potential to transform the energy landscape while supporting economic development. This review aims to contribute to the growing body of knowledge surrounding utility-scale solar energy, providing a comprehensive understanding of its impacts and opportunities for further advancement in the field.

2. Current Status of Utility-Scale Solar in the USA

Utility-scale solar energy is experiencing a remarkable expansion in the United States, significantly contributing to the nation's renewable energy landscape (Sharpton *et al*., 2020). The growth of large-scale solar projects has been driven by a combination of technological advancements, favorable policies, and a growing recognition of the need for clean energy alternatives. This outlines the current status of utility-scale solar in the USA, including growth trends, factors driving adoption, and notable case studies.

In recent years, the installed capacity of utility-scale solar projects in the United States has surged dramatically (Singh and Pandey, 2021). According to the Solar Energy Industries Association (SEIA), the total installed solar capacity reached over 130 gigawatts (GW) by the end of 2022, with utility-scale solar representing a significant portion of this growth. In 2021 alone, approximately 26.9 GW of new utility-scale solar capacity was added, marking a 21% increase from the previous year. Key states leading the charge in solar installations include California, Texas, and Florida. California remains the undisputed leader in solar energy, accounting for nearly 50% of the nation's total installed solar capacity (Schelly *et al*, 2021). The state's ambitious renewable energy targets and abundant sunlight make it an ideal location for large-scale solar projects. Texas follows closely, experiencing rapid growth in utility-scale solar due to its vast land availability and favorable regulatory environment. Florida, known as the "Sunshine State," has also made significant strides, becoming one of the top states for new solar installations in recent years.

Several factors have contributed to the accelerated adoption of utility-scale solar in the USA (Bolinger *et al*., 2021; Heeter and Reames, 2022). One of the primary drivers has been the declining costs of solar panels and related technologies. The cost of solar photovoltaic (PV) systems has fallen by more than 80% over the past decade, making solar energy increasingly competitive with traditional fossil fuels. This trend is attributed to advancements in manufacturing processes, economies of scale, and increased competition in the solar market. Additionally, supportive federal and state policies have played a crucial role in promoting renewable energy adoption. The federal Investment Tax Credit (ITC), which allows developers to deduct a percentage of the installation costs from their federal taxes, has been a significant incentive for solar projects. Many states have also implemented Renewable Portfolio Standards (RPS) that require utilities to source a certain percentage of their energy from renewable sources, further incentivizing the development of utility-scale solar projects (Zhou and Solomon, 2020; Bassey and Ibegbulam, 2023). Moreover, states like California have established ambitious clean energy goals, aiming for 100% carbon-free electricity by 2045, which has spurred investment in solar infrastructure.

Several notable large-scale solar installations exemplify the current status of utility-scale solar in the USA (Brown *et al*., 2022; Mathew, 2022). One prominent example is the Topaz Solar Farm in California, which has a capacity of 550 MW and spans approximately 9.5 square miles. As one of the largest solar farms in the world, Topaz generates enough electricity to power around 160,000 homes annually, contributing significantly to the state's renewable energy goals. Another noteworthy project is the Desert Sunlight Solar Farm, also located in California. With a capacity of 550 MW, this installation utilizes advanced solar technology to produce clean energy for over 160,000 homes. Desert Sunlight has not only contributed to the state's energy mix but has also created numerous job opportunities in the local community, underscoring the economic benefits of utility-scale solar projects (Sareen and Shokrgozar, 2022; Bassey, 2022). These case studies highlight the significant contributions of utility-scale solar installations to the United States' renewable energy landscape, showcasing the potential for large-scale solar projects to drive both environmental sustainability and economic growth.

The current status of utility-scale solar in the USA reflects a robust and growing sector within the renewable energy landscape. With impressive growth trends, declining costs, and supportive policies, utility-scale solar is well-positioned to play a pivotal role in the transition to a cleaner energy future (Khosla *et al*., 2020). The success stories of installations like the Topaz Solar Farm and Desert Sunlight Solar Farm exemplify the potential for large-scale solar projects to contribute to energy demands while promoting sustainability and economic development. As the nation continues to advance its renewable energy goals, the role of utility-scale solar will undoubtedly become even more significant in the years to come (Jayachandran *et al*., 2022).

3. Environmental Impact of Large-Scale Solar Installations

As the demand for clean energy sources increases, large-scale solar installations have emerged as a critical component of the renewable energy landscape. While the environmental benefits of solar power are well-documented, the deployment of utility-scale solar systems also presents challenges that must be addressed to ensure sustainable development (Jackson *et al*., 2021; Mathew and Fu, 2024). This examines the environmental impact of large-scale solar installations, highlighting their positive contributions and the associated challenges, including land use, water management, and strategies for mitigating adverse effects.

Large-scale solar installations play a significant role in reducing greenhouse gas emissions and air pollution. By displacing fossil fuel-based energy sources such as coal and natural gas, solar power contributes to cleaner air and lower levels of harmful emissions (Holechek *et al*., 2022). According to the U.S. Environmental Protection Agency (EPA), solar energy production can prevent the release of millions of tons of carbon dioxide (CO_2) annually, contributing to climate change mitigation efforts. Furthermore, solar installations do not produce air pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which are associated with respiratory issues and other health problems (Izah *et al*., 2024). In addition to their direct environmental benefits, large-scale solar projects support national and international climate goals by providing a sustainable alternative to traditional energy sources (Maka and Alabid, 2022). The transition to solar energy is essential for meeting commitments under global agreements, such as the Paris Agreement, aimed at limiting global temperature rise and mitigating the impacts of climate change. By investing in utility-scale solar, countries can accelerate their shift toward a low-carbon economy and promote sustainable development.

Despite their positive contributions, large-scale solar installations require significant land, which raises concerns about land use and habitat disruption. Utility-scale solar farms typically occupy extensive areas to maximize energy generation, leading to potential conflicts with agricultural land, natural habitats, and protected areas (Dunnett *et al*., 2022). The construction and operation of these facilities can result in habitat fragmentation and loss, posing risks to local ecosystems, wildlife, and biodiversity. The impacts on ecosystems can vary depending on the location and design of the solar installation. For example, solar farms situated in desert regions may disrupt fragile desert ecosystems, affecting native flora and fauna. To mitigate these impacts, developers must carefully assess potential sites and engage in environmental impact assessments to minimize disruption to critical habitats (Bassey *et al*., 2024).

Water usage is another critical aspect of the environmental impact of large-scale solar installations. Although solar energy generation itself does not require significant water resources, water may be necessary for cleaning solar panels, particularly in arid regions where dust accumulation can reduce efficiency (Mathew and Orie, 2015; Shenouda *et al*., 2022). This requirement raises concerns about water availability and management, especially in areas already facing water scarcity. Comparatively, large-scale solar installations are less water-intensive than traditional energy sources, such as coal and nuclear power, which require substantial amounts of water for cooling and processing. For instance, a study by the National Renewable Energy Laboratory (NREL) indicates that solar photovoltaic (PV) systems use approximately 0.3 to 0.5 gallons of water per megawatt-hour (MWh) of electricity produced, significantly lower than coal (approximately 1,000 gallons/MWh) and nuclear power (approximately 800 gallons/MWh). Nevertheless, the management of water resources in solar project design and operation remains essential to ensure sustainable practices (Tawalbeh *et al*., 2021).

To address the environmental challenges associated with large-scale solar installations, several mitigation strategies can be employed (Bassey, 2023). One effective approach is to prioritize the development of solar projects on degraded or disturbed lands, such as brownfields or former industrial sites, which can minimize impacts on pristine ecosystems. Additionally, dual-use projects, such as agrivoltaics, can enable land to be utilized for both solar energy production and agriculture, promoting sustainable land management practices (Richardson *et al*., 2022). Furthermore, implementing policies and regulations that guide environmentally responsible solar development is crucial. This includes establishing zoning regulations that consider environmental factors, encouraging stakeholder engagement, and conducting thorough environmental assessments before project approval. Collaboration between government agencies, environmental organizations, and the solar industry can foster the development of best practices that balance renewable energy needs with environmental conservation (Kylili *et al*., 2021).

Large-scale solar installations offer significant environmental benefits, including reductions in greenhouse gas emissions and contributions to climate change mitigation efforts. However, the challenges associated with land use, habitat disruption, and water management must be carefully addressed to ensure sustainable development (McElwee *et al*., 2020). By employing effective mitigation strategies and fostering a collaborative approach among stakeholders, the solar industry can continue to grow while minimizing its environmental impact, ultimately supporting a cleaner and more sustainable energy future.

4. Job Creation and Economic Impact of Utility-Scale Solar Installations

Utility-scale solar installations are rapidly transforming the energy landscape, not only by contributing to renewable energy goals but also by creating significant employment opportunities and driving economic growth (Gielen *et al*., 2021; Mathew, 2024). This explores the job creation and economic impacts associated with large-scale solar projects, examining employment opportunities, geographic distribution of jobs, the economic multiplier effect, and workforce development initiatives.

Large-scale solar installations generate a diverse array of employment opportunities across various job categories (Bassey, 2023). Key roles include construction workers, engineers, project managers, and technicians responsible for operations and maintenance. During the construction phase, labor-intensive jobs such as equipment operators and general laborers are in high demand, while ongoing operations and maintenance require skilled technicians who ensure optimal performance of solar installations. The job creation potential of utility-scale solar projects is notable when compared to other energy sectors (Semelane *et al*., 2021). According to the Solar Foundation’s National Solar Jobs Census, the solar industry employed over 250,000 workers in 2021, showcasing a substantial increase from previous years. In contrast, fossil fuel sectors like coal and natural gas have seen job declines due to automation and market fluctuations. Additionally, solar jobs tend to be more stable and less susceptible to economic downturns, given the increasing focus on renewable energy as a long-term solution for energy production (Mathew, 2024).

The geographic distribution of solar job creation is heavily concentrated in key states known for their commitment to renewable energy, such as California, Texas, and Florida. These states have witnessed significant solar job growth due to favorable policies, abundant sunlight, and substantial investment in solar infrastructure (Pascaris *et al*., 2021). Furthermore, utility-scale solar projects have the potential to revitalize economically disadvantaged areas, providing much-needed employment opportunities in regions that may lack diverse job markets. For example, rural communities often benefit from large-scale solar installations, as these projects can create jobs during construction and provide ongoing employment for local residents in operations and maintenance roles. This influx of jobs can help stimulate local economies, reducing unemployment rates and fostering community development (Rodrik, 2022). In many cases, utility-scale solar projects have been instrumental in transitioning local economies away from declining industries, such as coal mining, toward sustainable energy practices.

The economic impact of solar job creation extends beyond direct employment opportunities. The solar industry has a significant economic multiplier effect, whereby each job created in solar energy can lead to additional jobs in related sectors (Bassey *et al*., 2024). For instance, as solar projects require materials, components, and services, the demand for local suppliers and manufacturers increases. This creates indirect job opportunities in manufacturing, logistics, and the supply chain, further amplifying the positive economic impact of utility-scale solar installations. A study by the National Renewable Energy Laboratory (NREL) estimated that the solar industry could generate more than 1.5 jobs for every megawatt of installed solar capacity, leading to substantial economic growth at the local and regional levels. This multiplier effect can stimulate local economies by increasing household incomes, boosting consumer spending, and enhancing overall economic vitality (Kraiwanit, 2021).

To fully capitalize on the job creation potential of the solar industry, initiatives to train and prepare the workforce for solar-related jobs are essential. Various programs aimed at addressing skill gaps and promoting inclusivity in the solar workforce have emerged across the country (Gai *et al*., 2021). These initiatives often involve partnerships between educational institutions, industry stakeholders, and nonprofit organizations. For instance, community colleges and vocational schools are increasingly offering specialized training programs that equip students with the necessary skills for careers in solar energy. Additionally, initiatives aimed at promoting diversity and inclusion within the solar workforce are critical for ensuring that underrepresented groups have access to job opportunities in this growing sector. By focusing on workforce development, the solar industry can not only meet the demand for skilled labor but also contribute to economic equity and social mobility in communities that have historically faced barriers to employment (Zabin, 2020; Dicce and Ewers, 2021).

The economic impact of utility-scale solar installations is profound, encompassing job creation, geographic revitalization, and the economic multiplier effect (Bassey *et al*., 2023). As the solar industry continues to grow, it will play an increasingly important role in driving employment opportunities and fostering economic development, particularly in disadvantaged communities. By investing in workforce training and development, the solar sector can ensure a skilled, diverse workforce that supports the transition to a sustainable energy future (Briggs *et al*., 2022). This comprehensive approach will not only enhance the economic viability of solar energy but also contribute to the broader goals of environmental sustainability and social equity.

5. Policy and Regulatory Support for Solar Development

The growth of utility-scale solar energy in the United States has been significantly influenced by a variety of policies and regulatory frameworks at both the federal and state levels (Mathew, 2023). This explores the various forms of support that facilitate solar development, including federal policies, state-level initiatives, and public-private partnerships, all of which play critical roles in accelerating the transition to renewable energy.

At the federal level, several policies and incentives have been established to promote solar energy adoption. One of the most significant is the Investment Tax Credit (ITC), which allows solar energy systems to deduct a substantial percentage of the installation costs from federal taxes (Scoville, 2020). Originally set at 30%, the ITC has been instrumental in driving the rapid growth of the solar industry by reducing the financial burden on developers and encouraging investment. The ITC has been extended multiple times, reflecting the federal government's commitment to fostering renewable energy development. In addition to tax incentives, federal agencies, such as the Department of Energy (DOE) and the Bureau of Land Management (BLM), play a crucial role in supporting solar projects. The DOE provides funding for research and development, aiming to advance solar technologies and improve their efficiency and affordability. The BLM is responsible for managing public lands and has streamlined the permitting process for solar projects on these lands, making it easier for developers to obtain the necessary approvals (Zellmer and Glicksman, 2022). These federal efforts collectively enhance the viability of solar installations and contribute to the expansion of the renewable energy sector.

State governments have also implemented various initiatives to promote solar energy development. Leading states such as California, New York, and Massachusetts have established ambitious renewable energy targets, often mandating a certain percentage of their energy supply to come from renewable sources (Mai *et al*., 2021; Bassey *et al*., 2024). These targets create a favorable environment for solar energy by signaling a long-term commitment to clean energy solutions. In addition to renewable energy targets, states offer a range of incentives to encourage solar development, including net metering policies, feed-in tariffs, and renewable portfolio standards (RPS). Net metering allows consumers with solar panels to sell excess energy back to the grid, effectively reducing their utility bills and increasing the financial viability of residential and commercial solar systems. Furthermore, regional partnerships and collaborations, such as the Regional Greenhouse Gas Initiative (RGGI) in the Northeast, have emerged to address climate change collectively, providing a framework for coordinated solar development efforts across state lines (Baldwin and Tang, 2021; Mathew and Fu, 2023).

Public-private partnerships (PPPs) are essential for financing and implementing large-scale solar projects. The private sector plays a critical role in investment, bringing capital and expertise necessary for developing solar installations (Awuku *et al*., 2021). These partnerships allow for sharing risks and resources, leading to more efficient project delivery. For instance, collaboration between government entities and private companies can facilitate the identification of suitable sites for solar farms, streamline the permitting process, and address potential environmental concerns.

Moreover, PPPs can enhance the scale and scope of solar initiatives. For example, large corporations, such as tech giants, are increasingly entering into power purchase agreements (PPAs) to procure renewable energy directly from solar farms. This trend not only ensures a stable market for solar energy but also drives investment in new solar projects. Governments can further incentivize such collaborations through grants, loans, and other financial mechanisms, effectively leveraging private sector resources to advance public policy goals related to renewable energy (Fu and Ng, 2021; Bassey *et al*., 2024).

The policy and regulatory support for solar development in the United States is multifaceted, encompassing federal initiatives, state-level targets and incentives, and public-private partnerships (Mathew and Fu, 2023; Bade and Tomomewo, 2024). These frameworks have collectively contributed to the significant growth of the solar industry, driving job creation, economic development, and environmental sustainability. As the nation continues to shift toward renewable energy sources, sustained policy support and innovative collaborations between government and industry will be vital to overcoming existing challenges and ensuring a robust solar future. By fostering an enabling environment for solar energy, policymakers can help secure a sustainable and resilient energy landscape that benefits both the economy and the environment (Liu *et al*., 2023; Bassey, 2024).

6. Challenges in Solar Installation Expansion

The expansion of solar energy installations, particularly utility-scale projects, faces several challenges that can hinder progress and limit the potential benefits of this renewable resource (Cousse, 2021). This explores the primary obstacles to solar installation expansion, focusing on regulatory and permitting barriers, technological and infrastructure challenges, and financial and investment difficulties.

One of the most significant challenges to the expansion of solar installations is the complex regulatory and permitting landscape. The approval processes for large-scale solar projects often involve multiple stakeholders and can be protracted and cumbersome. Delays in obtaining necessary permits can slow down project timelines and increase costs, deterring potential investors (Cook *et al*., 2021). The lengthy and unpredictable nature of these processes can create uncertainty, making it difficult for developers to plan and execute projects effectively. Additionally, zoning and land use restrictions can pose significant barriers to solar installation. Many regions have specific regulations that govern the types of developments allowed in certain areas, which can limit the availability of suitable sites for solar farms. In some cases, land designated for agricultural use may be restricted from conversion to solar energy production, even if the land is not actively being utilized. As demand for land for solar projects increases, the competition for suitable sites may also lead to conflicts with local communities and stakeholders who may have differing priorities regarding land use (Brunet *et al*., 2020; Frantál *et al*., 2023).

Integrating solar energy into existing grid infrastructure presents another set of challenges. Many electrical grids were not designed to accommodate the large-scale influx of intermittent renewable energy sources like solar power (Kebede *et al*., 2022). As a result, there can be difficulties in managing the balance between supply and demand, leading to potential instability in the grid. Upgrading grid infrastructure to enhance its capacity and flexibility is necessary but can be a costly and time-consuming process. The issue of intermittency, inherent to solar energy generation, poses additional challenges. Solar energy production is contingent on sunlight availability, which varies throughout the day and across seasons. This variability can complicate energy planning and dispatching, as grid operators must ensure a stable supply of electricity. To address these challenges, energy storage solutions, such as batteries, are increasingly seen as a necessary complement to solar installations. However, the technology for large-scale energy storage is still developing and can be prohibitively expensive, further complicating efforts to expand solar energy adoption (Shaqsi *et al*., 2020).

Financial and investment challenges also play a critical role in hindering solar installation expansion (Sher and Qiu, 2022). The high upfront costs associated with large-scale solar installations can be a significant barrier for developers. Although costs for solar technology have declined in recent years, the initial investment required for site development, equipment procurement, and installation remains substantial. This financial burden can deter potential investors and limit the number of projects that move forward. Furthermore, managing risks and securing long-term financing can be difficult in the solar sector. Investors may be hesitant to commit capital to solar projects due to uncertainties related to policy changes, market dynamics, and technological advancements (Polzin *et al*., 2021). The perception of risk can lead to higher financing costs, making it even more challenging for developers to secure the necessary funding to bring their projects to fruition. Innovative financing mechanisms, such as green bonds or public-private partnerships, could help alleviate some of these financial barriers, but their widespread adoption is still in its infancy (Taneja *et al*., 2022; Zhang *et al*., 2022).

The expansion of solar installations faces a range of challenges, including regulatory and permitting barriers, technological and infrastructure issues, and financial and investment difficulties. Addressing these challenges requires coordinated efforts from policymakers, industry stakeholders, and local communities to create a more supportive environment for solar development (Elia *et al*., 2020; Wu *et al*., 2022). Streamlining regulatory processes, investing in grid infrastructure, and developing innovative financing solutions are essential steps to overcoming these obstacles and unlocking the full potential of solar energy. By working collaboratively, stakeholders can help facilitate the transition to a more sustainable energy future, ultimately benefiting the economy, the environment, and society as a whole (Mihailova *et al*., 2022).

7. Future Trends and Opportunities in Solar Energy

As the world continues to confront the pressing challenges of climate change and the need for sustainable energy solutions, the solar industry stands at the forefront of this transition (Kabeyi and Olanrewaju, 2022). Innovations in technology, emerging markets, and the essential role of solar energy in decarbonizing the energy sector highlight the future trends and opportunities in large-scale solar installations (Hayashi, 2020).

One of the most promising aspects of the solar energy landscape is the rapid advancement in solar technology. Innovations in solar panel efficiency are pivotal in enhancing energy output and making solar installations more economically viable (Ahmad *et al*., 2020). Recent developments in materials science, such as the use of bifacial solar panels, which can capture sunlight from both sides, have shown substantial increases in energy generation. Furthermore, the integration of advanced storage solutions, like lithium-ion and emerging solid-state batteries, is vital for addressing the intermittency of solar power. These storage technologies allow for excess energy generated during peak sunlight hours to be stored and used during periods of low generation, thus improving the reliability of solar energy (Guerra *et al*., 2020). Additionally, the incorporation of artificial intelligence (AI) and smart grid technologies is transforming the management of large-scale solar operations. AI can optimize energy production through predictive analytics, enabling operators to forecast energy generation based on weather patterns and historical data. Smart grids facilitate real-time data exchange between energy producers and consumers, allowing for improved demand response and energy distribution (Estebsari *et al*., 2021). This technological synergy not only enhances operational efficiency but also maximizes the economic benefits of solar installations.

The global shift toward renewable energy is paving the way for emerging markets to adopt large-scale solar projects. Regions that have historically relied on fossil fuels are now exploring the potential for solar energy development (Breyer *et al*., 2022). Countries in Africa, Latin America, and parts of Asia are witnessing significant investments in solar infrastructure, driven by decreasing costs and favorable sunlight conditions. The expansion of solar projects into new regions not only contributes to energy diversification but also enhances energy security in areas that previously experienced energy shortages. Moreover, cross-state energy trading and interconnection offer exciting prospects for solar energy growth (Ansolabehere *et al*., 2021). As the U.S. moves toward a more integrated energy market, states can share renewable resources more effectively. This collaboration can optimize energy distribution, reduce reliance on fossil fuels, and enable states with abundant solar resources to supply clean energy to regions with higher demand. Developing robust transmission networks will be critical in facilitating these interconnections, ensuring that solar energy can be harnessed and utilized efficiently across state lines (Mlilo *et al*., 2021).

Solar energy is integral to the broader energy transition aimed at decarbonizing the U.S. energy sector. As the nation seeks to achieve ambitious climate targets, solar power presents a sustainable solution for reducing greenhouse gas emissions (Rahman *et al*., 2021). With the potential to provide a significant portion of the nation’s electricity needs, solar energy can help mitigate the adverse impacts of climate change while promoting public health by improving air quality. The long-term outlook for job creation in the solar sector is also promising. As the industry expands, new job opportunities will arise in various areas, including manufacturing, installation, maintenance, and research and development. Investing in workforce training programs will be essential to equip individuals with the skills needed to thrive in this evolving landscape. Additionally, the environmental benefits of large-scale solar installations, such as reduced carbon emissions and conservation of water resources, further underscore the importance of solar energy in achieving a sustainable future (Kılkış *et al*., 2022; Ottonelli *et al*., 2023).

The future of large-scale solar installations is bright, characterized by technological advancements, emerging market opportunities, and a vital role in the energy transition (Pulli *et al*., 2020). By embracing innovations in solar technology, capitalizing on growth potential in new regions, and leveraging solar energy's contributions to decarbonization, the solar industry can continue to drive positive change. Policymakers, industry stakeholders, and communities must work collaboratively to harness these trends, ensuring that solar energy remains a cornerstone of a sustainable, resilient, and equitable energy future (Bisaga, 2021; Kandpal *et al*., 2024).

8. Conclusion

In summary, large-scale solar installations offer significant environmental and economic benefits that are crucial for a sustainable energy future. The positive environmental impacts of these projects are manifold, including substantial reductions in greenhouse gas emissions and air pollution, contributing significantly to climate change mitigation efforts. By displacing fossil fuel-based energy sources, large-scale solar systems play a vital role in promoting cleaner air and healthier ecosystems. Furthermore, the solar industry presents immense job creation potential, spanning various sectors such as construction, operations, and maintenance. This growth can revitalize local economies, particularly in regions that have historically relied on more traditional energy sectors.

To sustain this momentum and facilitate continued growth in solar energy, addressing the challenges that lie ahead is imperative. Robust policy support at both federal and state levels is essential to streamline regulatory processes and incentivize investment in solar infrastructure. Additionally, fostering technological innovation will help overcome barriers related to efficiency, energy storage, and grid integration, ensuring that solar energy can meet increasing demands while maintaining reliability.

Ultimately, the call for sustainable solar expansion necessitates a careful balancing act between environmental stewardship and economic growth. As we move forward, it is essential to prioritize sustainable practices that minimize ecological disruption while maximizing the economic benefits derived from solar energy. By engaging in responsible solar development, we can create a more resilient and equitable energy future that supports both the environment and society. This holistic approach will be crucial in harnessing the full potential of solar energy as a driving force in the transition to a cleaner, more sustainable world.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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