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Solar Photovoltaic Technology and its Impact on Environmental, Social and Governance (ESG) Performance: A Review

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Abstract.
To mitigate greenhouse gas (GHG) emissions in the environment, renewable energy sources hold significant potential to offer clean and green energy, and reduce carbon emissions. Utilizing solar power systems can ensure the generation of clean and sustainable energy, leading to reduced GHG emissions during the electricity production process. The adoption of solar energy systems has witnessed a remarkable surge in recent years due to the evident surge in demand for environmentally friendly power sources. There are multiple avenues for prospective research and development in the realm of solar power systems. Gaining familiarity with the requisite technology and its suitability for the diverse demands and consumption patterns is of paramount importance. In this context, the focus of this study centers around solar photovoltaic (PV) technologies. Solar PV technology is positioned to significantly contribute to global energy requirements, offering multi-terawatt capacity for clean and green energy. Notably, due to its well-established infrastructure and economic feasibility, solar PV technology emerges as an optimal choice for both small and large-scale projects. This study places a special emphasis on sustainability as a lens through which recent advancements in solar PV technology are examined. In a world where concerns about climate change mitigation and sustainability are mounting, solar PV technology stands out as a foremost source of clean and environmentally friendly energy, serving as a pragmatic solution for fostering sustainable development.

Keywords: solar PV technology, ESG risks, sustainability approaches, solar power systems, sustainable energy

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1. Introduction

Solar photovoltaics (PV) has evolved into a viable technology that is geared for deployment at the multi-terawatts scale and thereby helps in reducing emissions in the short run (Victoria et al., 2021a). In view of the rising greenhouse gas (hereafter GHG) emissions and growing energy demands, the International Energy Agency (IEA) estimated renewable energy technologies for reducing emissions by the year 2050. According to the projection of IEA (2016), global emissions might be reduced by approximately 70% by using renewable energy sources such as wind, biomass, and solar system for clean and green electricity. Moreover, the IEA report asserts that solar PV may provide approximately 11% of global green electricity along with 2.3 gigatons of carbon dioxide (CO_2) emissions every year (Choudhary and Srivastava, 2019a). Researchers have projected the future of energy sources with a 100% solar PV system by the year 2050, which is not only technically possible but also economically feasible by one-third price (Fattouh et al., 2019). Solar PV has become a mainstream technology that significantly contributes to the energy storage system for electromobility (Bullich-Massagué et al., 2020). There is no way to save the earth without switching to renewable energy, and a system that relies only on renewable resources is the best option for dealing with future crises (Barasa et al., 2018).

Producing clean energy supports environmental sustainability and makes a society more self-sustainable (Jan et al., 2021b). Whereas water scarcity, human capital, resource efficiency, economic saturation, fairness, and regulations are a few other significant sustainability aspects that require consideration with the development of solar PV efficiency. The growing energy demand and extensive use of traditional energy sources anticipate a devastating scenario and suggest the notion of "Transforming our World" while emphasizing sustainability in all aspects of life (Jan et al., 2022b; Shad et al., 2020; Jan et al., 2023). Due to widespread public support and technological advancements, solar PV sources have emerged as a prominent player in the global energy market and have the potential to generate enough clean energy to meet global needs and ensure sustainability. In clean energy sources, the sun is the most abundant energy source, which has proven a tremendous potential to satisfy future energy demands (Khan and Arsalan, 2016a). Although significant technological progress has been made, many estimates of future energy scenarios have overlooked the crucial role that solar PV might play in the requirement of net-zero emissions by the year 2050. For instance, the development of clean energy sources like solar PV technology has long-term environmental, social, and economic benefits. As such, having a power source that does not rely on imports, increases a country's power security; this also has effects of enhanced durability, fewer environmental risks, and lower costs.

In view of the foregoing debate, this study aims to thoroughly review the solar PV technologies that may be utilized for sustainable energy production, which consequently have a great impact on sustainability performance – environmental, social, and governance (ESG). Accordingly, the literature on solar PV technologies has been thoroughly reviewed and the most significant research on such technologies has been recognized. The solar PV technology in common practice, its performance, efficiency, and impacts have been reviewed and addressed. Subsequently, section 2 focuses on research methods and material, section 3 provides the results and discusses solar PV technology and its environmental and social impacts, and the last section concludes the paper.

2. Materials and Methods

An extensive literature search was undertaken to locate relevant papers in order to provide a comprehensive evaluation of solar power systems for long-term, environmentally friendly electricity generation. The acquired research has been broken down into the many solar energy-producing systems and their respective applications. The solar photovoltaic (PV) technologies and their respective concentration systems have been reviewed. The impacts of Solar PV technologies have been evaluated on the basis of sustainability factors. The social acceptance and environmental impacts along with the cost-effectiveness have been discussed.

2.1. Literature Search and Identified Studies

A comprehensive literature search was undertaken at Google Scholar and Science Direct in order to retrieve research studies that conducted an analysis of renewable energy sources such as solar PV technologies published in recent years. Whilst solar PV technology is not a novel notion and several studies have previously been undertaken by academics throughout the world, there is always room for improvement. Based on the literature search, a vast variety of most appropriate studies were identified. Moreover, this study identified studies that focused on sustainable growth and sustainability discussions while focusing on energy and cleaner production sources, for example, (Ali et al., 2021; Jan et al., 2019, Tahir et al., 2020; Shahzad et al., 2022; Tahir et al., 2023; Ali and Khurram, 2017; Shah et al., 2022a; Shah et al., 2022b; Shah et al., 2022c;

Tahir et al., 2022; Jan et al., 2022a; Hussain et al., 2023; Hussain et al., 2022a; Hussain et al., 2022b; Hussain et al., 2021; Abbasi et al., 2021; Abbasi et al., 2020; Mazhar et al., 2022). The appraised solar PV technology, the methods used, and the discussion of sustainability criteria have been used to classify the identified body of knowledge. Studies related to solar PV technology and its applications were considered. For example, Ghaffour et al. (2015) conducted a study on different solar PV technologies for sustainable desalination systems. Similarly, Liu et al. (2015) studied solar thermoelectric cooling technologies and their applications in active building envelopes. Ghaffour et al. (2014) conducted research on solar PV thermal for sustainable seawater desalination technologies. Batman et al. (2012) performed a feasibility study of grid-connected PV technologies with their economic assessment. Panwar et al. (2011) evaluated various solar technologies for environmental protection. Choudhary and Srivastava (2019a) assessed solar photovoltaic trends for sustainable development opportunities. Victoria et al. (2021b) studied solar photovoltaic technologies for a sustainable future. More recently, Izam et al. (2022) evaluated solar PV technology from the sustainable development perspective. Similarly, Dhonde et al. (2022) focused on solar PV technology for sustainable agriculture farming. In sum, all those studies focused on the adoption of solar PV technologies for addressing sustainability parameters around the world.

2.2. Selection criteria for Sustainability Parameters

In 1989, the “United Nations Environment Program” (UNEP) coined the term “Cleaner Production” and states that “*the continuous application of an integrated preventive environmental strategy applied to processes, products, and services to increase overall efficiency and reduce risks to humans and the environment*” (Choudhary and Srivastava, 2019b) Also, the UN’s sustainable development goals (SDGs) stress the decision-making of management for the adoption of cleaner technologies (Jan et al., 2021b, Khan et al., 2022; Jan et al., 2022b; Khan at al., 2023; Khan et al., 2021). The concept of cleaner manufacturing has given rise to idealistic convictions that have materialized in the creation of clean energy and, eventually, become standard practice across all industries. Although the rate of actualization was significantly slower, the concept’s evolution toward realization was labeled ”sustainable development.” An all-encompassing view of efficient energy utilization, green ideas, environmental philosophies, supply chain, sustainable transport, industrial ecology, network partnerships, policies, and principles could result from the development of renewable energy as a means to combat climate change and advance sustainable development.

To ensure long-term success and guide smart decision-making, a sustainability analysis must incorporate impact evaluations (Jan et al., 2021a; Shad et al., 2019; Shah et al., 2021; Shad et al., 2022). A number of factors are taken into account, including long-term objectives, practical decision-making frameworks, formal and transparent mechanisms, pluralistic evaluation certainties, and ongoing education and training. The purpose of a sustainability evaluation is to provide long-term benefits and guide efficient decision-making through the results of impact assessments (Shah et al., 2022d; Jan et al., 2020; Hamad et al., 2020; Ali et al., 2022; Khan and Johl, 2020; Khan and Johl, 2019; Hamad et al., 2022; Hamad et al., 2023). Among the factors taken into account in these evaluations are long-term objectives, practical decision-making frameworks, formal and transparent mechanisms, pluralistic evaluation certainties, and ongoing education and improvement. In light of this, a thorough evaluation of prospective techniques for risk assessment, cost-benefit analysis, ecological balance, system integration, life cycle analysis, and social justice must include the sustainability assessment as a crucial component.

2.3. Review Parameters of Solar PV

Although solar photovoltaic (PV) technologies have grown quickly to meet rising energy demand, technical obstacles such as inefficient cells, high upfront costs, a lack of financing mechanisms, and ineffective balance-of-systems performance prevented the research community from thinking beyond these limitations (Few et al., 2019). Research expansion on lifetime decisions and process parameters is made possible by smart and sustainable manufacturing using data analytics. Scalable growth, anticipated technology performance, and environmental protection are all benefits of combining renewable energy sources with energy storage solutions. Decision-makers, implementers, policymakers, planners/consultants, and most importantly scholars throughout the world would benefit from micro-engineering for the notion of energy for sustainable development.

The purpose of this study is to accurately examine the solar PV system and its numerous technical characteristics for effective conversion of solar energy and to clearly demonstrate the breadth and depth of the room for improvement that has been revealed. While emphasizing the sustainability notion, a thorough literature review of conventional approaches for adopting solar PV technologies has been summarized. The thoughtful review takes into account relevant factors like green energy initiatives, power system planning, energy storage, hybrid frame modules, energy optimizing techniques, and several others.

3. Results and Discussion

3.1. Solar Photovoltaic (PV) Technology

The solar photovoltaic (PV) technology directly transforms incoming solar energy into electrical energy, based on the concept of the photoelectric effect. Solar PV technology is applicable to both regions with low and high direct irradiation because it makes use of the dispersed components of incoming solar radiation. Solar panels, made from a variety of photovoltaic materials, are used in PV energy generation. Monocrystalline silicon, polycrystalline silicon, Cadmium telluride (CdTe), Gallium arsenide (GaAs), and Indium gallium phosphide (InGaP) comprising triple-junction solar cells are among the most commonly utilized materials (Khan and Arsalan, 2016b). Solar cells are typically modest devices that can convert sunlight into power. Solar cells are integrated to form a module of several cells; these modules are then accumulated into a (photovoltaic) PV array with a length of up to several meters in order to generate power on a larger scale. According to the solar energy development program, there are hundreds of solar arrays connected to build a massive system for utility-scale solar power generation.

Solar photovoltaic systems may either be grid-connected to the current power infrastructure or completely self-sufficient (independent units). Both fixed PV systems (often oriented to the south in north-facing latitudes and vice versa) and PV tracking systems (which follow the direction of the sun in the sky on a single or multiple-axis track) are categorized into two distinct types. Solar PV systems with sun tracking capabilities are far superior to fixed systems due to their capacity to track and face the sun at all times thereby capturing the larger quantity of incoming solar radiation. However, PV tracking systems need more space than stationary PV systems, and some of the power generated is consumed by the tracking mechanism. Initially, PV technology was used to provide energy for artificial satellites and other spacecraft, but now, the vast majority of PV modules are used to generate solar power either for the grid or independently. Moreover, solar PV technology is also being implemented in a wide variety of other fields, including transportation, telecommunication, solar highways, rural electrifications, and the integration of PV systems in buildings, etc.

Solar PV technologies are mainly divided into three main generations. For example, the first-generation PV technology consists of single Crystalline Silicon (c-Si) and

Polycrystalline Silicon (p-Si). The second-generation PV technology is comprised of Amorphous Silicon (a-Si), Copper Indium Gallium Di-selenide (CIS/CIGS), and Cadmium Telluride Cells (CdTe). While the third-generation PV technology focused on Concentrated Photovoltaic (CPV), Dye-sensitized (DSSC), and Organic or Polymer (OPV). Variations in the semi-conductor materials utilized have led to vast differences in the overall efficiency and performance of these PV generation waves.

3.2. Sustainability Impacts of Solar PV Technology

Today, one of the most pressing issues is how to prevent environmental degradation while simultaneously fostering sustainable development (Jan et al., 2021b). Increased carbon dioxide (CO_2) released from the combustion of fossil fuels is currently the largest source of greenhouse gas (GHG) emissions, which is the primary contributor to global warming. It is worth stressing that the selected solar PV technology must be beneficial to the environment, and economy, and must be widely accepted by society. Consequently, this has led to the investigation of the sustainability impacts of solar PV technology – including a novel blend of socially acceptable, economically viable, and environmentally friendly – as discussed subsequently.

3.2.1. Environmental Impacts

The viability of solar energy systems, such as solar PV technology, in the long run, is determined by their impacts on the environment. In terms of environmental impact, solar power plants have the most trouble during the assembly and decommissioning phases. After a power plant has been commissioned and put into service, it does essentially little environmental damage. There is more environmental benefit from PV technology-based solar power systems during the assembly phase compared to others (Desideri et al., 2013). While comparing the environmental consequences associated with producing 1 MWh of energy, PV solar power plants have an overall greater environmental impact. The cleaning of semi-conductor surfaces during the production of PV cells requires a variety of hazardous compounds, and as a result, employees run into the danger of breathing from the silicon dust. In this respect, (Khan and Arsalan, 2016a) disclosed that second-generation PV cells include more harmful chemicals than regular PV cells. It is important to note that solar power plant operations have a minor influence on the use of the land. Solar energy production has not been associated with any documented global warming emissions. Nonetheless, transportation, materials, maintenance, decommissioning phase, etc., all contribute to emissions throughout the solar life cycle. The "National Renewable Energy Laboratory" reported that the harmonized median GHG emissions of c-Si and thin-film (TF) PV-based systems are below 50 g CO_2 eq/kWh (Khan and Arsalan, 2016a). Hence, when comparing the solar power plants in terms of their combined life cycle GHG emissions, solar PV technology reveals a more favorable environmental profile.

3.2.2. Social Acceptability

Social acceptance is one of the key prerequisites for any technology to be successfully adopted. The social acceptability of solar PV systems has acquired great relevance. Numerous studies have focused on the social acceptability of solar power technology at the end-user level, for instance, (Heras-Saizarbitoria et al., 2011, Yuan et al., 2011, Solangi et al., 2013; Mukhtar et al., 2023a; Mukhtar et al., 2023b; Mukhtar et al., 2023c). The rapid increase in both small and large-scale solar power projects demonstrates the widespread use of solar power technology as a clean and reliable energy source across the world. The energy that does not deplete natural resources. In renewable energy sources, concentrated sun power (CSP) systems have witnessed significant growth in the United States and Spain, while solar power plants based on photovoltaic (PV) systems have grown rapidly in China and India. In recent years, there has been a widespread acceptance of solar energy, as seen by its use in both large-scale power plants and smaller-scale applications including rural electrification in distant locations, solar air conditioning, street lighting, solar heating, etc. While CSP is appropriate for large-scale commercial purposes, solar PV technology is more suitable for both small and large-scale applications.

3.2.3. Governance Risk

Successful implementation and widespread social acceptance of solar power technologies have been hampered by their high upfront and ongoing governance. Companies dealing in solar energy technologies mostly alluded to regulatory risks as their primary concern. These firms frequently worry about new laws, rules, and regulatory assessments, which makes it harder for them to do business and for all businesses to function. Given that regulatory uncertainty has an impact on project decision-making, investment strategy is an essential factor that needs to consider, and is important to think about how it affects investments. The initial investment cost is of paramount relevance for the implementation of clean and green power technologies. The investment costs for solar PV technology are comparatively lower than others such as CSP. Also, the maintenance costs for the PV technology are less than others because of the complex mechanism. An additional critical risk is the lack of political and governmental support for solar power. Many business leaders nowadays emphasize the importance of policy support for economically viable solar power technologies. The government's encouragement of solar power technology has significant importance in making renewable solar power commercially feasible.

4. Conclusion

Since the advent of solar power technologies, the use of solar photovoltaic (PV) technology to generate environmentally friendly electricity has been on the rise. Recent years have seen a dramatic increase in the popularity of solar power technologies, which have proven themselves to be a viable alternative to traditional energy generation. Solar PV technologies harness the sun's rays to produce renewable energy in a wide range of forms and applications. This study rigorously reviews the currently available literature on solar PV technologies. This study reviewed the solar power systems and their impact on the sustainability criteria such as environmental, social, and governance. This study disclosed that the initial investment cost is of paramount relevance for the implementation of clean and green power technologies. The investment costs for solar PV technology are comparatively lower than others such as CSP. Also, the maintenance costs for the PV technology are less than others because of the complex mechanism. It is important to note that different solar power technologies have different advantages and disadvantages, so deciding which one is best depending on factors like the intended use and the weather. In such a situation, where climate change mitigation and sustainability are becoming increasingly pressing global concerns, solar PV technology emerges as a leading source of clean and green energy and a key factor for sustainable development.

5. Implications for Practice and Research

This study provides novel policy insights for the world leaders, regulatory authorities, legislative institutions, and corporation to strike out in new directions to embrace more sustainable and inclusive energy sources and technologies such as Solar Photovoltaic

(PV) system. The world leaders and influential institutions must have the courage to strike out in new directions and embrace a cleaner energy source which is not only low-carbon and environmentally sustainable but also turns poverty, inequality, and lack of financial access into new market opportunities for smart, progressive, profit-oriented companies. These complex challenges need the full and combined attention of government, civil society, and businesses.

Pertaining to the forgoing discussion, this study recommends future research to explore the impact of Solar PV technology on the Sustainable Development Goals (SDGs). Based on a detailed review of the existing literature on Solar PV system and ESG, this study suggests the establishment of a conceptual framework linking the nexus of solar PV technology implementation and ESG performance. Subsequently, the study suggests future research to empirically test the effect of Solar PV adoption on the ESG and consequently link the ESG measurement indicators with the UN SDGs. For example, the environment factor of the ESG is contributing to SDG-7 affordable and clean energy, SDG-9 industry, innovation and infrastructure, SDG-11 sustainable cities and communities, SDG-12 responsible consumption and production, SDG-13 climate action, and SDG-15 life on land. Social contributes to SDG-1 no poverty, SDG-2 zero hunger, SDG-6 clean water and sanitation, SDG-8 decent work and economic growth, SDG-9 industry, innovation and infrastructure, SDG-10 reduced inequalities, SDG-12 responsible consumption, and production. Where the governance elements contribute to SDG-8 decent work and economic growth, SDG-9 industry, innovation and infrastructure, SDG-11 sustainable cities and communities, SDG-12 responsible consumption and production, SDG-13 climate action, SDG-16 life on land, SDG-17 peace, justice, and strong institutions. Hence, the Solar PV technology is expected to enhance the environmental, social, and governance performance and thereby the United Nations' Agenda for achieving the sustainable development goals.

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