M. A. KHALID, D. S. MALIK, R. A. BALIKAI,
BASEEM TAMINI, K. K. YADAV & P. R. YADAV *Editors*

ENVIRONMENTAL PROBLEMS, PROTECTION AND POLICIES

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This book on "Environmental Problems, Protection and Policies" goes on to highlight the unfavourable conditions created by the human approach to nature. In other words, this book highlights what environmental pollution is! It can be understood how important the issue of environmental pollution is in the situation where even the air we breathe is threatened with pollution. The book contains 30 chapters encompassing different aspects of environmental problems, protection, and policy issues. This book summarizes the Green technologies for sustainable development, Soil pollution, Microplastic pollution in the aerial, soil and marine ecosystem, Plastic pollution, Water pollution, Ozone layer depletion, Biodiversity loss, Air pollution, Marine pollution, Deforestation, Acid rain, Environment degradation and disasters, Human impact on the environment, Pollution and its impact on animal and human health, and Light pollution as the driving force behind loss of biodiversity.

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ASSESSING THE INFLUENCE OF AIR QUALITY ON PHOTOVOLTAIC PERFORMANCE

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ABSTRACT : The rapid proliferation of photovoltaic (PV) systems as a clean and sustainable energy source has underscored the importance of understanding the various factors affecting their performance. Among these, air quality has emerged as a critical yet often overlooked parameter that can significantly impact PV efficiency and longevity. This comprehensive review aims to provide a detailed analysis of the influence of air quality on PV performance, encompassing both the direct and indirect effects. The direct effects of air quality on PV performance include the deposition of particulate matter, pollutants and contaminants on the surface of PV modules, which can lead to reduced light absorption and efficiency losses. Furthermore, pollutants such as nitrogen oxides (NOx) and sulfur dioxide (SO_2) can contribute to the degradation of materials within PV cells, potentially leading to a decrease in overall performance over time. Indirectly, air quality can also affect PV performance through alterations in atmospheric conditions, including changes in solar irradiance due to scattering and absorption by aerosols and pollutants. Additionally, variations in temperature and humidity levels driven by air quality parameters can influence the thermal behavior and operating temperature of PV modules, further affecting their efficiency. This review systematically examines studies and experiments conducted over the past decade, encompassing a wide range of geographical locations and environmental conditions. It synthesizes findings related to the impact of specific air pollutants, such as particulate matter, ozone, and heavy metals, on PV performance, as well as the mechanisms underlying these effects.

Key words : Photovoltaic, air quality, air pollutants.

Introduction

Photovoltaic (PV) electricity generation has seen remarkable growth worldwide over the past few decades. This expansion has been driven by factors such as declining costs, increasing environmental awareness, and government incentives. The global expansion of photovoltaic electricity generation signifies a significant shift towards a more sustainable and renewable energy future. Continued innovation, investment, and international cooperation will be vital in furthering the development and deployment of solar PV technologies. Here’s an overview of the state of PV electricity generation globally.

Capacity growth : The globally installed capacity of solar PV has experienced exponential growth, with total capacity reaching over 800 gigawatts (GW) by the end of 2020 (IEA, 2021).

Regional Dominance : China has been a leading player in PV installation, consistently accounting for a significant portion of the world's total capacity. Other major contributors include the United States, India, and European countries (IEA, 2021).

Cost reduction : The cost of solar PV modules and installations has dropped dramatically over the years, making solar energy more competitive with conventional sources. This trend is expected to continue, further accelerating adoption (Fraunhofer, 2020).

Utility-Scale and Distributed Generation : PV installations range from utility-scale projects, which feed electricity into the grid, to smaller-scale distributed generation systems on rooftops or in communities. Both segments have seen substantial growth (SEIA, 2021).

Technological advancements : Ongoing research and development in PV technology have led to improved efficiency and durability of solar panels. This has contributed to the increased feasibility of large-scale PV projects (Green *et al*, 2020).

Energy Transition Goals : Many countries have set ambitious renewable energy targets, with solar PV playing a pivotal role in achieving these goals. These targets are often linked to reducing carbon emissions and combating climate change (IRENA, 2018).

Off-Grid and Remote applications : Solar PV is being used in various off-grid and remote areas to provide reliable and sustainable electricity for communities, healthcare facilities, and schools that are not connected to the central grid (The World Bank, 2021).

Job creation : The PV industry has become a significant employer globally, providing jobs in manufacturing, installation, maintenance, and research and development (IRENA, 2020).

Environmental benefits : Solar PV is a clean energy source that produces electricity without greenhouse gas emissions or air pollutants. This reduces environmental impact and contributes to sustainable development (IPCC, 2018a).

Challenges and Future prospects : Despite its growth, challenges remain, including intermittency, energy storage, and grid integration. Ongoing research aims to address these issues, with a focus on energy storage solutions and smart grid technologies (ETIP PV, 2019).

Policy and Regulatory Support : Government policies and incentives have played a crucial role in fostering the growth of PV electricity generation. These include feed-in tariffs, tax credits, and renewable portfolio standards (UNEP-DTU Partnership, 2021).

International collaboration : Collaboration between countries, organizations, and research institutions is advancing PV technology and facilitating knowledge-sharing to accelerate global adoption (IEA PVPS, 2021).

The role of Photovoltaics in a Green Future

Photovoltaics (PV) hold immense importance in the transition towards sustainable energy. The adoption and expansion of photovoltaics play a pivotal role in transitioning towards a more sustainable, low-carbon, and resilient energy future. As technology continues to advance and costs continue to decrease, the importance of PV in our energy landscape is only set to grow. Several key aspects highlighting the significance of photovoltaics are (Fig. 1):

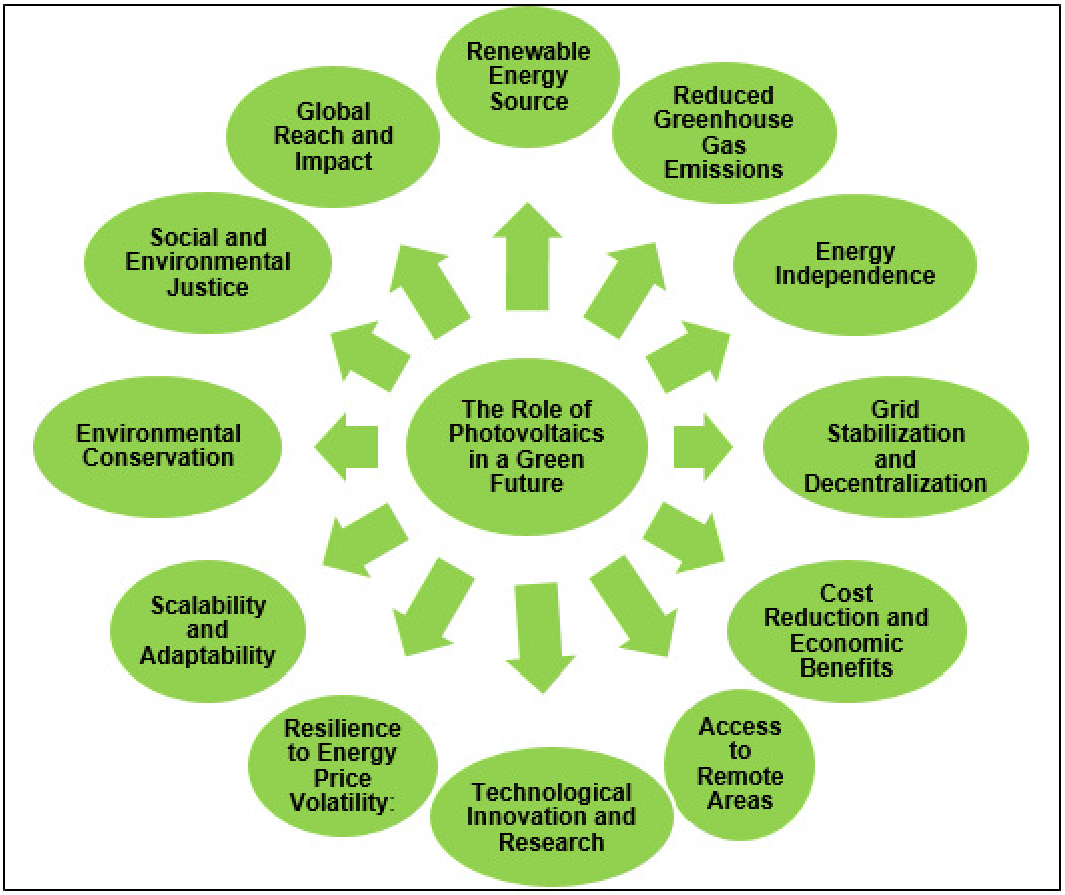

Fig. 1 : Significance of photovoltaic.

Renewable Energy Source: The PV systems harness energy from sunlight, an abundant and infinitely renewable resource. This contrasts with fossil fuels, which are finite and contribute to environmental degradation (IEA, 2019).

Reduced Greenhouse Gas Emissions : Solar energy is a clean, emission-free source of electricity. By utilizing PV systems, we can significantly reduce the release of greenhouse gases, thus mitigating climate change (IPCC, 2018b).

Energy Independence : The PV systems empower individuals, communities, and even entire regions to generate their own electricity. This reduces dependence on centralized power grids and foreign energy sources, enhancing energy security (Hoff and Fidler, 2016).

Grid Stabilization and Decentralization : Distributed solar installations can help stabilize local grids by reducing strain during peak demand periods. This decentralization also enhances grid resilience against disruptions (Raghavan and Smirnova, 2019).

Cost Reduction and Economic benefits : The cost of PV technology has steadily declined over the years. As a result, solar power has become increasingly competitive with conventional energy sources. Moreover, the solar industry supports numerous jobs and economic growth (IREA, 2020).

Access to Remote areas : The PV systems are particularly valuable in remote or off-grid areas where traditional power infrastructure is impractical or too costly to establish. They can provide reliable electricity for essential services like healthcare, education, and communication (Lewis, 2016).

Technological Innovation and Research : The development and deployment of photovoltaic technology drive innovation and research in materials science, electronics, energy storage, and grid integration. This spurs advancements not only in solar energy but also in related fields (Jäger-Waldau, 2016).

Resilience to Energy Price Volatility : PV systems provide a measure of protection against fluctuating energy prices, offering stability and predictability in energy costs (Cochrane *et al*, 2016).

Scalability and adaptability : PV installations can be tailored to various scales, from small residential setups to large-scale utility projects. This adaptability makes them suitable for a wide range of applications (Green *et al*, 2018).

Environmental conservation : Utilizing solar energy reduces the need for resource-intensive fossil fuel extraction and minimizes habitat disruption associated with conventional energy production (Denholm and Margolis, 2008).

Social and Environmental Justice : PV technology can address energy poverty by providing affordable and accessible electricity to underserved communities. It can also reduce the environmental burden on marginalized populations living near conventional power plants (Sovacool and Dworkin, 2015).

Global Reach and impact : Solar energy is a universally available resource, which means that the benefits of PV technology can be extended worldwide, contributing to global sustainable development goals (United Nations, 2015).

Air Quality factors in Photovoltaic System Resilience

Air pollution can significantly impact the performance and efficiency of solar photovoltaic (PV) systems. There are various ways in which air pollutants affect PV systems, emphasizing the need for strategies to mitigate these effects.

Reduction in Energy Output : Airborne particles and pollutants, such as dust, soot, and smog, can accumulate on the surface of solar panels, reducing the amount of sunlight reaching the photovoltaic cells. This leads to a decrease in energy production efficiency (Garg and Agarwal, 2011; Saini and Sudhakar, 2017).

Soiling and shading : Particles like dust and dirt can create a shading effect on the surface of PV panels, further decrease energy production. The accumulation of these particles can also hinder light penetration, reducing the system's overall performance (Rashid *et al*, 2023).

Degradation of materials : Corrosive pollutants in the air can lead to the deterioration of materials used in PV systems, including the protective coatings, frames, and electrical components (Aravindan and Sudhakar, 2018).

Effect on Angle of incidence : Air pollution can scatter sunlight, altering the angle at which sunlight strikes the panels. This can lead to a decrease in energy capture efficiency

(Pillai and Ramakrishna, 2018).

Impact on Inverter performance : Air pollutants can affect the performance of inverters, which convert DC electricity produced by the panels into AC electricity for use in homes or the grid (Amiryar and Xu, 2020).

Increased Maintenance costs : Regular cleaning and maintenance are necessary to mitigate the effects of air pollution on PV systems, leading to higher operational costs (Kazem, 2023).

Regional Variations : The impact of air pollution on PV systems can vary depending on local environmental conditions, such as climate, industrial activity, and urbanization (Sahu and Kota, 2017).

Financial Implications : Reduced energy generation due to air pollution-induced degradation can lead to financial losses, especially in large-scale solar projects (Mroczka and Lech, 2016).

Health and Safety concerns : Air pollution not only affects PV performance but can also have adverse effects on human health. This creates a dual incentive for reducing pollution levels (Landrigan *et al*, 2018).

Need for Technological solutions : To mitigate the impact of air pollution on PV systems, various technological solutions such as advanced coatings, self-cleaning materials, and regular cleaning schedules are being explored (Kazem *et al*, 2020).

Impacts of different Airborne Pollutants on Solar PV Power Generation

Air pollutants can have various impacts on solar photovoltaic (PV) systems. These pollutants can reduce the efficiency and performance of solar panels, leading to decreased energy production. The following are some common air pollutants and their effects on solar PV systems (Table 1):

Table 1 : Air pollutants impacts on solar photovoltaic (PV) systems.

Air pollutants	**Impact on PV Systems**
Particulate Matter (PM)	Reduces transparency, decreases energy production
Nitrogen Dioxide (NO_2)	Can settle on panels, reduces transparency
Sulfur Dioxide (SO_2)	Contributes to acid rain, potential material damage
Ozone (O_3)	Can reduce solar irradiance due to smog
Volatile Organic Compounds (VOCs)	Can contribute to secondary pollutants affecting PV performance
Heavy Metals	Accumulation on panels, potential efficiency reduction

1. Particulate Matter (PM) impact : PM can accumulate on the surface of solar panels, reducing their transparency and blocking sunlight. This leads to a decrease in the amount of sunlight that reaches the PV cells, reducing energy production (Jäger-Waldau, 2017; Abualgasim *et al*, 2018).

Particulate Matter (PM), particularly fine particles (PM2.5) can indeed have several negative impacts on solar photovoltaic (PV) systems. Below are some of the effects of particulate matter.

Reduced Solar irradiance : PM2.5 can scatter and absorb sunlight, reducing the amount of solar irradiance reaching the surface of PV panels. This leads to a decrease in energy production (Forster *et al*, 2007).

Soiling and Dust accumulation : PM2.5 particles can accumulate on the surface of solar panels, forming a layer of dirt or dust. This layer reduces the transparency of the panels, further decreasing the amount of sunlight absorbed by the PV cells (Luque and Hegedus, 2003).

Loss of efficiency : The presence of PM on the surface of solar panels can lead to a decrease in the overall efficiency of the PV system. This result in lower energy output compared to clean panels (Baker and Basore, 1982).

Increased Maintenance costs : Regular cleaning of solar panels is necessary to mitigate the impact of PM. Increased cleaning and maintenance requirements can lead to higher operational costs for solar PV installations (Bellos *et al*, 2017).

2. Sulfur Dioxide (SO_2) : SO_2 can lead to the formation of sulfate aerosols, which can deposit on the surface of solar panels and reduce their transparency. This reduces the amount of sunlight absorbed by the PV cells, lowering energy generation (Jäger-Waldau, 2017).

3. Nitrogen Dioxide (NO_2) : NO_2 can contribute to the formation of nitrogen-based pollutants that may settle on solar panels. This can reduce the transparency of the panels and decrease their efficiency (Jäger-Waldau, 2017).

4. Ozone (O_3) : While ground-level ozone is not a direct pollutant on solar panels, it is an important component of photochemical smog. High levels of ozone are associated with hazy conditions that reduce the amount of direct sunlight reaching the panels, lowering energy production (Wagner *et al*, 2017).

Ground-level ozone can cause the following detrimental effects on Solar PV systems.

Reduced Solar irradiance : Ground-level ozone can contribute to the formation of photochemical smog, which can reduce the amount of direct sunlight reaching the surface of PV panels. This leads to a decrease in energy production (Wagner *et al*, 2017).

Lower efficiency : The reduction in solar irradiance due to ozone-induced smog can result in a decrease in the overall efficiency of the PV system (Luque and Hegedus, 2003).

Long-term degradation : Prolonged exposure to high levels of ozone and the associated smog can lead to degradation of the materials used in PV panels over time, potentially reducing their lifespan and efficiency (Bock *et al*, 2017).

5. Heavy Metals and Chemicals : Heavy metals and other chemicals released into the atmosphere can settle on the surface of solar panels. These substances can accumulate and degrade the transparency of the panels, reducing energy output (Jäger-Waldau, 2017). It's worth noting that the extent of these impacts can vary depending on factors such as the concentration of pollutants in the air, local climate conditions, and the frequency of panel cleaning. Regular maintenance and cleaning of solar panels can help mitigate the effects of air pollutants. Heavy metals and chemicals can indeed have several negative impacts on solar photovoltaic (PV) systems. Here are some of the key effects:

Corrosion and degradation : Exposure to heavy metals and certain chemicals can lead to corrosion and degradation of the materials used in PV panels, potentially reducing their lifespan and efficiency (Li and Zhang, 2015).

Reduced Efficiency and performance : Heavy metals and certain chemicals can affect the electrical performance of PV cells and modules, leading to reduced efficiency in converting sunlight into electricity (Mekhilef *et al*, 2012).

Contamination and soiling : Heavy metals and chemicals can accumulate on the surface of solar panels, leading to contamination and soiling. This reduces the transparency of the panels and decreases the amount of sunlight absorbed by the PV cells (Zhang *et al*, 2015).

Potential Health and Environmental risks : Improper disposal or recycling of PV panels containing heavy metals and chemicals can pose potential risks to human health and the environment (Fthenakis and Kim, 2009).

Strategies for Mitigating the impact of Air Pollution on Solar PV systems

Air pollutants can indeed pose challenges to solar photovoltaic (PV) systems. Implementing effective strategies is crucial to maintain their efficiency.

As shown in Fig. 2 some solutions to mitigate air pollution on Solar PV System are required, such as:

Regular Cleaning and Maintenance : Regularly clean the surface of solar panels to remove dust and pollutants that can reduce their efficiency (Jiang *et al*, 2011).

Advanced Coating Technologies : Apply anti-reflective coatings or hydrophobic coatings to the surface of solar panels to repel dust and pollutants (Basu *et al*, 2016).

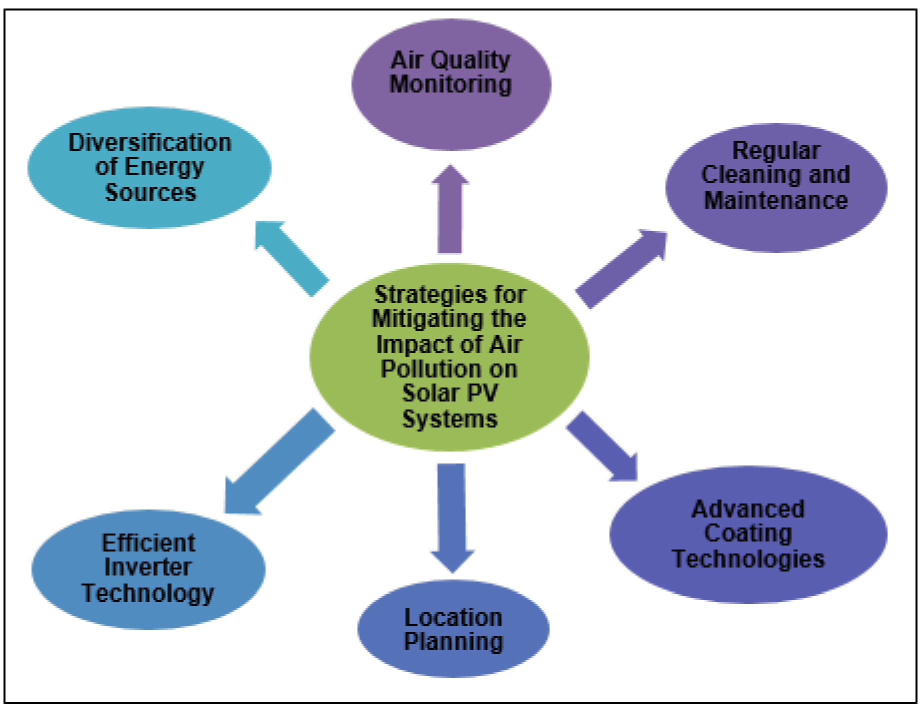

Fig. 2 : Strategies for Mitigating the Impact of Air Pollution on Solar PV Systems.

Location Planning : Consider local air quality conditions when siting PV systems. Avoiding areas with high pollution levels can help mitigate the impact on solar panel performance (Gehlot *et al*, 2016).

Efficient Inverter Technology : Use high-quality inverters that can optimize energy production, even under suboptimal conditions caused by air pollution (Dey and Dey, 2014).

Air Quality Monitoring : Implement air quality monitoring systems to track pollutant levels. This information can help anticipate periods of reduced solar panel efficiency and plan maintenance accordingly (Malik, 2012).

Diversification of Energy Sources : Complement solar PV systems with other renewable energy sources or energy storage solutions to ensure a reliable power supply, especially during periods of reduced solar irradiance (Said, 2015).

Conclusion

In conclusion, a comprehensive understanding of the relationship between air quality and PV performance is essential for optimizing the design, operation, and maintenance of photovoltaic systems in diverse environmental contexts. This review provides a valuable resource for researchers, engineers, and policymakers seeking to enhance the efficiency and resilience of PV technology in the face of evolving air quality challenges. Additionally, it highlights the need for continued research in this area to develop targeted mitigation strategies and advance the sustainable integration of solar energy into the global energy landscape.

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