

When Clean Energy Meets Real-World Conditions: The Impact of Atmospheric Pollution on Solar Energy Performance

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Abstract

The transition to renewable energy has accelerated worldwide due to growing concerns about climate change and increasing global energy demand. Among renewable energy sources, solar energy has emerged as one of the most promising technologies because of its scalability and declining costs. However, environmental factors such as atmospheric pollution can significantly influence solar panel performance. This paper examines how haze, aerosols, particulate matter, and dust affect solar radiation and reduce the efficiency of photovoltaic systems. It also discusses how changes in the spectral composition of sunlight may impact different solar technologies, including silicon, perovskite, and gallium arsenide (GaAs) solar cells. In addition, the study highlights regional examples, particularly Türkiye, where strong solar potential may not always translate into maximum energy generation due to environmental conditions. The findings suggest that improving solar energy systems requires not only technological advancement but also a better understanding of real-world atmospheric conditions.

Keywords: *Solar energy, Photovoltaic systems, Atmospheric pollution, Aerosols and haze, Particulate matter, Spectral composition*

1.Introduction

The transition to renewable energy has become one of the most important global priorities, driven by both climate change concerns and the growing energy needs of modern societies. Among renewable sources, solar energy is often seen as one of the most promising solutions due to its scalability and decreasing costs (International Energy Agency [IEA], 2023). However, while much attention is given to improving solar technologies, less focus is placed on environmental factors that can directly affect how well these systems perform.

One of these factors is atmospheric pollution, especially in the form of haze and aerosols. As sunlight passes through the atmosphere, particles and gases can absorb and scatter radiation, reducing the amount of solar energy that reaches the Earth's surface. Research shows that this reduction can range from around 15% in moderately polluted conditions to more than 40% in heavily polluted areas (Li et al., 2017; Chudnovsky et al., 2013). In large urban or industrial regions, higher concentrations of fine particulate matter have also been linked to noticeable decreases in solar power generation, sometimes

reducing annual output by several percentage points (Bergin et al., 2017).

In addition to lowering the intensity of sunlight, atmospheric haze can also change its spectral composition. This means that some wavelengths of light are reduced more than others as sunlight passes through the atmosphere. Since solar panels are designed to convert certain parts of the light spectrum more efficiently, these changes can affect how much electricity they produce. In other words, even if sunlight is still available, it may no longer match the conditions under which solar panels perform best. As a result, the efficiency of solar systems can decrease not only because there is less light, but also because the quality of that light has changed (Gueymard, 2005).

These effects highlight the importance of understanding how environmental conditions influence solar energy systems, especially as their role continues to grow worldwide.

2. Atmospheric Pollution and Solar Radiation

While the impact of atmospheric pollution on solar energy is a global issue, its intensity and consequences vary depending on regional conditions such as urbanization, industrial activity, and air quality levels. Globally, air pollution remains a widespread challenge, with estimates suggesting that over 90% of the world's population is exposed to air quality levels that exceed recommended limits (World Health Organization [WHO], 2022). In many urban areas, PM_{2.5} concentrations frequently rise above 35 µg/m³, significantly exceeding recommended air quality limits.

These conditions have measurable effects on solar performance. Studies across different regions suggest that air pollution can reduce solar energy output by several percentage points annually, typically in the range of 5–10%, with significantly higher losses observed in heavily polluted environments (Li et al., 2017). This creates a gap between theoretical solar potential and actual energy generation. In regions with strong solar resources but higher levels of pollution, expected performance is not always achieved in practice. Air pollution and other environmental factors therefore need to be considered alongside technological improvements when evaluating solar energy systems.

Solar energy systems are installed in different environments, including rooftop panels on buildings and large-scale solar farms located outside cities. Rooftop systems are more directly exposed to local pollution, especially in urban areas where particulate matter can accumulate on panel surfaces and reduce efficiency. However, large solar farms are not completely unaffected. Atmospheric haze can spread over wide areas, reducing solar radiation even in relatively cleaner regions. In addition, dust accumulation in rural areas can also decrease panel performance (Mani & Pillai, 2010). This means that both urban and rural solar systems are influenced by air pollution, although through different mechanisms.

3. Case Study: Türkiye

Türkiye provides a useful example of the relationship between solar potential and real-world performance. The country has strong solar resources, with over 2,200 hours of sunshine annually and an average solar irradiance of around 1,500 kWh per square meter (Republic of Türkiye Ministry of Energy and Natural Resources, 2023). However, these figures represent potential conditions. In practice, air

pollution can reduce the amount and quality of sunlight that reaches solar panels.

Although national average PM_{2.5} levels are around 15–20 µg/m³, pollution tends to be higher in large cities and during certain periods of the year, particularly in winter (Organisation for Economic Co-operation and Development [OECD], 2022). These conditions can weaken solar radiation and increase the share of diffuse light, which may lower the efficiency of photovoltaic systems. In addition, transported dust particles can further reduce radiation and accumulate on panel surfaces. Even in countries with high solar potential, environmental conditions can influence how much of that potential is actually converted into usable energy.

Understanding these regional differences is therefore important for improving the performance and reliability of solar energy systems worldwide.

4. Effects of Haze on Different Solar Technologies

The effects of atmospheric haze on solar energy are not only about reducing the amount of sunlight, but also about changing its quality. As a result, different types of solar panels can be affected in different ways, depending on the materials they use.

Most solar panels today are made from silicon, which is widely used because it is relatively efficient, stable, and affordable. However, silicon panels are designed to work best under certain light conditions. When haze changes the spectrum of sunlight, their performance can be affected more than expected. In other words, it is not just how much light reaches the panel, but also what kind of light it is.

Newer materials, such as perovskites and gallium arsenide (GaAs), are being developed to improve efficiency and capture a wider range of light (Green et al., 2022). Compared to silicon, these materials can offer higher performance under ideal conditions. However, they may also react differently to changes in the light spectrum caused by atmospheric haze. Some studies suggest that under polluted conditions, their performance can vary more, which highlights the importance of considering environmental factors when choosing solar technologies.

5. Mitigation Strategies

To deal with these challenges, different solutions are being explored. Some solar cells are designed to absorb a wider range of wavelengths, while improvements in panel surfaces can help reduce reflection and dust accumulation. In addition, simple strategies such as adjusting panel angles or cleaning panels regularly can also improve performance (Mani & Pillai, 2010).

Overall, improving solar energy systems is not only about making them more efficient, but also about making them work better in real-world conditions. Understanding how materials react to environmental factors like haze is an important step in this process.

This topic is also explored in our own research at Hisar Okullari, where we examine how atmospheric haze, particulate matter, and dust affect solar panel performance and to what extent they reduce energy output under different conditions.

6. Conclusion

Overall, these findings highlight that evaluating solar energy systems requires going beyond ideal conditions and considering how they perform in real-world environments. Atmospheric pollution does not only reduce the quantity of sunlight reaching solar panels, but also changes its spectral composition, influencing how efficiently different solar technologies operate.

As solar energy continues to play an increasingly important role in the global energy transition, understanding the relationship between environmental conditions and photovoltaic performance will become even more important. Future improvements in solar technology should therefore focus not only on increasing efficiency under laboratory conditions, but also on improving resilience and adaptability under real-world atmospheric conditions.

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