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**Atmospheric Aerosol Concentrations and Solar Radiation Attenuation in
Urban Environments in Germany**



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Abstract

Purpose: The aim of this study was to investigate the atmospheric aerosol concentrations and solar radiation attenuation in urban environments in Germany.

Methodology: The study adopted a desktop research methodology. Desk research refers to secondary data or that which can be collected without fieldwork. Desk research is basically involved in collecting data from existing resources hence it is often considered a low-cost technique as compared to field research, as the main cost is involved in executive's time, telephone charges and directories. Thus, the study relied on already published studies, reports and statistics. This secondary data was easily accessed through the online journals and library.

Findings: The findings revealed that atmospheric aerosols reduce solar radiation in German urban environments through scattering and absorption, with an average radiative effect of -12.8 ± 5 W/m². Aerosol characteristics and meteorological conditions influence attenuation, highlighting the need for further comparative research across German cities.

Unique Contribution to Theory, Practice and Policy: Mie scattering theory, the beer–lambert law, radiative transfer theory may be used to anchor future studies on the atmospheric aerosol concentrations and solar radiation attenuation in urban environments in Germany. The study recommends that environmental monitoring agencies, urban planners, solar energy developers, and meteorological institutions in Germany strengthen the monitoring and assessment of atmospheric aerosol concentrations to improve the prediction and management of solar radiation attenuation. The study recommends that the German government strengthen the integration of atmospheric aerosol monitoring, air quality regulation, and renewable energy planning within national and municipal environmental policies.

Keywords: *Atmospheric Aerosol Concentrations, Solar Radiation Attenuation, Urban Environments*

INTRODUCTION

Solar radiation attenuation refers to the reduction in the intensity of incoming solar radiation as it passes through the atmosphere due to absorption and scattering by aerosols, gases, clouds, and other atmospheric constituents. It is an important atmospheric process that influences surface temperature, atmospheric energy balance, photovoltaic electricity generation, and climatic conditions. Atmospheric aerosols contribute to solar radiation attenuation by scattering sunlight away from its original direction and absorbing part of the incident radiation, thereby reducing direct solar irradiance at the Earth's surface. The magnitude of attenuation depends on aerosol optical depth, particle concentration, particle size distribution, chemical composition, atmospheric humidity, and solar zenith angle. In developed economies such as the United States and Japan, changes in industrial emissions, transportation-related pollution, and atmospheric aerosol loading have influenced patterns of solar dimming and brightening, making solar radiation attenuation an important subject of environmental and atmospheric physics research (Augustine & Hodges, 2021; Ma, 2022).

In the United States, Augustine and Hodges (2021) examined surface solar radiation trends from 1996 to 2019 and established that solar irradiance increased by 7.36 W/m^2 per decade between 1996 and 2012 before declining by approximately 3.90 W/m^2 per decade between 2013 and 2019, although the latter trend was uncertain. Their findings further revealed that aerosol optical depth declined by approximately 0.022 per decade, while cloud cover explained 62% of the observed variability in solar irradiance compared with only 3% attributable statistically to aerosol optical depth. In Japan, Ma. (2022) examined homogenised surface solar radiation records and identified an average brightening trend of approximately 0.9 W/m^2 per decade between 1961 and 2014, with an estimated positive aerosol-related contribution of 2.2 W/m^2 per decade and a negative cloud-cover contribution of 1.4 W/m^2 per decade. These findings demonstrate that declining atmospheric aerosol concentrations can contribute to increased surface solar radiation, although cloud variability and regional atmospheric conditions may modify the magnitude of the observed changes. Consequently, the experiences of the United States and Japan highlight the importance of long-term aerosol monitoring and atmospheric radiation modelling in understanding solar radiation attenuation in developed economies (Augustine & Hodges, 2021; Ma ., 2022).

Solar radiation attenuation is an important environmental and energy-related challenge in developing economies, particularly where rapid industrialisation, urbanisation, biomass burning, and transportation emissions increase atmospheric aerosol concentrations. In countries such as China and India, high particulate pollution levels can reduce incoming solar radiation through absorption and scattering, affecting photovoltaic electricity generation and regional atmospheric energy balances. Aerosol-related solar dimming can be particularly pronounced in densely populated industrial regions, where black carbon, sulfates, nitrates, and mineral dust contribute to atmospheric extinction. Yang . (2019) established that clear-sky surface solar radiation in China decreased by approximately $9.7 \pm 0.4 \text{ W/m}^2$ per decade between 1958 and 1999, compared with an all-sky decline of $7.4 \pm 0.4 \text{ W/m}^2$ per decade. These findings demonstrate how substantial changes in atmospheric transparency can accompany industrial development, highlighting the importance of pollution control and atmospheric monitoring in improving solar radiation availability (Yang ., 2019).

In China, Shi . (2021) established that surface solar radiation increased by approximately 0.70–1.16 W/m² annually between 2014 and 2019 across eastern and central regions, with declining aerosol radiative effects following air pollution control measures identified as a major contributor to this brightening. In India, historical observations indicate persistent solar dimming, particularly in heavily polluted regions, although its magnitude varies according to geographical location, aerosol composition, and cloud conditions. A global observational assessment published in the *Journal of Climate* (2021) identified persistent dimming across India, particularly during summer, while detecting increasing solar radiation in several other Asian regions. The contrasting experiences of China and India demonstrate that aerosol-related attenuation is not uniform across developing economies and may respond differently to pollution control, industrial emissions, and atmospheric circulation. Consequently, these findings emphasise the importance of investigating aerosol concentration, particle size distribution, chemical composition, and aerosol optical depth when assessing changes in solar radiation attenuation (Shi ., 2021; Yang ., 2019).

Solar radiation attenuation is particularly relevant in sub-Saharan African economies because atmospheric dust, biomass burning, industrial emissions, and urban particulate pollution can significantly influence the availability of solar energy. Countries such as Niger and Benin experience atmospheric aerosol conditions influenced by Saharan mineral dust, seasonal biomass burning, and anthropogenic emissions, which modify the absorption and scattering of incoming solar radiation. In Niger, Chaibou. (2020) investigated dust-related radiative effects across West Africa using the Weather Research and Forecasting model coupled with Chemistry and reported an average surface dust radiative forcing of –13 W/m², indicating a reduction in net radiation reaching the surface. The researchers further established atmospheric radiative forcing of approximately +23 W/m² and surface temperature reductions of up to 2°C, demonstrating the redistribution of atmospheric energy associated with mineral dust. These findings illustrate that atmospheric aerosol loading can influence both solar radiation attenuation and regional climatic conditions, with implications for agriculture, photovoltaic energy production, and environmental management (Chaibou ., 2020).

In Benin, Denjean . (2020) investigated aerosol optical properties across southern West Africa using aircraft observations from the DACCWA campaign and identified considerable differences in atmospheric absorption characteristics between mineral dust and biomass-burning aerosols. The researchers reported single-scattering albedo values ranging from 0.81 to 0.92 for mineral-dust-dominated layers, compared with 0.71–0.77 for biomass-burning aerosol layers, indicating stronger absorption by the latter under the observed conditions. In Niger, Chaibou . (2020) reported that dust-induced changes in the regional surface energy budget included reductions in sensible heat flux of up to 24 W/m², alongside the average surface radiative forcing of –13 W/m². These results demonstrate that aerosol composition, atmospheric transport, and particle optical properties influence the magnitude and mechanisms of solar radiation attenuation across sub-Saharan Africa. Consequently, improved aerosol monitoring, satellite observations, and radiative transfer modelling are necessary to quantify solar energy losses and support renewable energy planning in the region (Denjean ., 2020; Chaibou ., 2020).

Atmospheric aerosol concentrations refer to the quantity of suspended solid and liquid particles present in the atmosphere, commonly measured through particle mass concentration (µg/m³), particle number concentration (particles/cm³), and optical properties that influence atmospheric radiation transmission. These aerosols originate from natural sources, including dust, sea salt, and

wildfires, as well as anthropogenic activities such as industrial emissions, transportation, and residential heating. Conceptually, atmospheric aerosol concentrations can be examined through four key dimensions: aerosol particle concentration, particle size distribution, chemical composition, and aerosol optical depth, which collectively determine how aerosols interact with incoming solar radiation. Aerosol particle concentration represents the abundance of airborne particles, while particle size distribution describes their physical dimensions and influences the efficiency of light scattering at different wavelengths. Chemical composition determines the absorption and scattering characteristics of aerosols, whereas aerosol optical depth measures the integrated extinction of solar radiation through the atmospheric column, making these dimensions important for understanding variations in solar radiation attenuation (Witthuhn ., 2021).

Atmospheric aerosol concentrations influence solar radiation attenuation by modifying the amount of direct and diffuse solar radiation reaching the Earth's surface through absorption and scattering processes. Higher aerosol particle concentrations can increase atmospheric extinction when particle characteristics and meteorological conditions remain comparable, while particle size distribution determines the wavelength-dependent scattering efficiency of atmospheric aerosols. Chemical composition further influences radiation attenuation because light-absorbing components, particularly black carbon, absorb solar energy, whereas predominantly scattering particles such as sulfates redistribute incoming radiation (Senf ., 2021). Aerosol optical depth provides an integrated indicator of atmospheric extinction, with higher values generally associated with reduced direct solar irradiance under comparable solar and atmospheric conditions (Witthuhn ., 2021). Therefore, the four dimensions provide a conceptual framework for investigating how atmospheric aerosol characteristics influence solar radiation attenuation in German urban environments, while accounting for meteorological factors such as humidity, cloud cover, seasonal variability, and solar zenith angle.

Problem Statement

Atmospheric aerosol concentrations have become a significant environmental concern because of their influence on solar radiation transmission, urban climate, atmospheric visibility, and renewable energy performance. In Germany, urban environments experience varying aerosol concentrations arising from transportation, industrial activities, residential heating, and natural atmospheric processes, which influence the amount of solar radiation reaching the Earth's surface through scattering and absorption. Despite improvements in air quality across parts of Europe, the relationship between aerosol concentrations and solar radiation attenuation remains complex because of variations in particle size distribution, chemical composition, aerosol optical depth, humidity, and cloud cover. Witthuhn. (2021) established that aerosols produced an annual mean surface radiative effect of approximately $-12.8 \pm 5 \text{ W/m}^2$ across German monitoring stations, demonstrating their substantial influence on surface solar radiation availability. Similarly, Wild . (2021) identified multidecadal variations of approximately 10 W/m^2 in surface solar radiation over Potsdam, Germany, highlighting changes in atmospheric transparency associated with solar dimming and brightening. However, these findings do not fully establish how different aerosol characteristics individually and collectively influence solar radiation attenuation across Germany's diverse urban environments (Witthuhn ., 2021; Wild ., 2021).

Despite the growing body of research on aerosol–radiation interactions, significant conceptual, contextual, and geographical research gaps remain concerning the relationship between

atmospheric aerosol concentrations and solar radiation attenuation in German urban environments. Conceptually, existing studies provide limited integrated assessment of how aerosol particle concentration, particle size distribution, chemical composition, and aerosol optical depth jointly influence direct and diffuse solar radiation. Contextually, previous investigations have largely emphasised clear-sky atmospheric conditions and long-term radiation trends, with comparatively limited attention to the combined influence of urban emission sources, seasonal variations, humidity, and changing meteorological conditions. Geographically, the reviewed literature provides insufficient standardised comparative evidence across major German cities, including Berlin, Hamburg, Munich, Frankfurt, and Leipzig, where differences in urban activities and atmospheric conditions may influence aerosol-related radiation losses. Consequently, the central problem addressed by the proposed study is the insufficient integrated empirical understanding of how atmospheric aerosol concentrations and characteristics influence solar radiation attenuation across urban environments in Germany. The study therefore seeks to examine these relationships to provide evidence for improved atmospheric radiation modelling, urban environmental management, and solar energy planning (Witthuhn ., 2021; Wild ., 2021).

Theoretical Framework

Mie Scattering Theory

Mie Scattering Theory was developed by German physicist Gustav Mie in 1908. The theory explains how electromagnetic radiation interacts with spherical particles whose sizes are comparable to the wavelength of incident light. It establishes that particle size, refractive index, and wavelength determine the intensity and angular distribution of scattered radiation. Witthuhn. (2021) examined aerosol optical properties and their influence on solar radiation under clear-sky conditions in Germany. The theory underpins this study by explaining how aerosol particle size distribution and chemical composition influence solar radiation scattering and attenuation in German urban environments.

Beer–Lambert Law

The Beer–Lambert Law originated from the contributions of Pierre Bouguer (1729), Johann Heinrich Lambert (1760), and August Beer (1852). It explains the exponential reduction in radiation intensity as electromagnetic radiation travels through an absorbing or attenuating medium. In atmospheric physics, its application incorporates aerosol optical depth to quantify the extinction of direct solar radiation through absorption and scattering. Witthuhn. (2021) demonstrated the importance of aerosol optical properties in estimating clear-sky solar radiation attenuation across Germany. This theory supports the investigation of how increasing aerosol optical depth influences the amount of direct solar radiation reaching urban surfaces.

Radiative Transfer Theory

Radiative Transfer Theory was developed through contributions from Arthur Schuster (1905) and later formalised extensively by Subrahmanyan Chandrasekhar (1960). The theory explains how electromagnetic radiation propagates through the atmosphere while undergoing absorption, emission, and multiple scattering. Senf. (2021) demonstrated that absorbing aerosols influence atmospheric heating, cloud formation, and radiation fields over Germany.

Empirical Review

Witthuhn (2021) conducted a study to investigate the influence of atmospheric aerosol properties on solar radiation attenuation under clear-sky conditions across Germany, focusing on regional and seasonal variations in aerosol–radiation interactions. The researchers employed a quantitative modelling and observational approach using global and diffuse solar irradiance measurements collected from 25 German Weather Service monitoring stations, supplemented by aerosol optical properties from AERONET and atmospheric reanalysis data from the Copernicus Atmosphere Monitoring Service. The findings revealed that aerosols produced an average annual surface radiative effect of $-12.8 \pm 5 \text{ W/m}^2$ using clear-sky models, compared with approximately -11 W/m^2 from radiative transfer simulations, demonstrating measurable reductions in solar radiation reaching the Earth's surface. The study further established a correlation coefficient of 0.75 between the two estimation approaches, although discrepancies in aerosol absorption properties affected model accuracy. Based on these findings, improved characterisation of aerosol optical properties and the integration of observational measurements with radiative transfer models are recommended to strengthen solar radiation forecasting and atmospheric monitoring in German urban environments.

Wild (2021) investigated the contribution of atmospheric aerosols to long-term variations in surface solar radiation in Potsdam, Germany, with particular attention to distinguishing aerosol-related effects from changes in cloud cover. The researchers adopted a longitudinal observational design using daily solar radiation measurements covering 71 years, from 1947 to 2017, and applied two independent methods for identifying cloud-free atmospheric conditions. The findings demonstrated substantial periods of solar dimming and brightening under both all-sky and clear-sky conditions, with multidecadal changes in surface solar radiation of approximately 10 W/m^2 . The researchers concluded that variations in the cloud-free atmosphere, potentially driven substantially by anthropogenic aerosol pollution, contributed to the observed changes in atmospheric solar transmission. The findings support continued long-term monitoring of aerosol optical properties and solar irradiance to distinguish pollution-related attenuation from meteorological variability and strengthen renewable energy planning in Germany.

Senf (2021) investigated the effects of light-absorbing atmospheric aerosols on cloud formation and radiation fields over Germany, seeking to establish how aerosol absorption influences atmospheric heating and surface radiation. The researchers adopted a numerical experimental methodology involving high-resolution cloud-resolving simulations with horizontal grid spacings of 312 and 625 metres, comparing atmospheric conditions containing purely scattering aerosols with those containing realistic absorbing aerosols. The findings demonstrated that absorbing aerosols contributed to surface solar dimming and atmospheric heating, producing temperature increases and moisture reductions at atmospheric pressure levels between 800 and 900 hPa. These atmospheric changes reduced low-level cloud cover, cloud liquid water content, and precipitation, while direct and semi-direct aerosol effects contributed comparably to reductions in net radiation at the top of the atmosphere. The study supports further investigation of aerosol absorption properties and aerosol–cloud interactions when modelling solar radiation attenuation, particularly in German urban environments where particulate pollution and cloud variability may jointly influence surface irradiance.

Baars (2021) investigated the atmospheric optical properties of wildfire smoke transported from California to Leipzig, Germany, and to evaluate the ability of satellite-based lidar technology to characterise elevated aerosol layers. The researchers employed ground-based multiwavelength

Raman-polarisation lidar observations alongside measurements from the European Space Agency's Aeolus satellite during a major smoke event in September 2020. The findings revealed an exceptionally high smoke aerosol optical thickness exceeding 0.4, corresponding to an estimated aerosol mass concentration of approximately $8 \mu\text{g}/\text{m}^3$, while the lidar ratio at 355 nm was approximately 40–50 steradians. The study established that long-range aerosol transport can substantially alter atmospheric optical conditions over German urban areas, although it did not directly quantify the associated reduction in surface solar irradiance. The findings support further integration of ground-based lidar, satellite observations, and radiative transfer modelling to estimate the effects of transported aerosol plumes on solar radiation attenuation and improve atmospheric forecasting in German cities.

Witthuhn (2021) evaluated the reliability of aerosol optical properties obtained from atmospheric reanalysis datasets when estimating solar radiation attenuation across Germany. Using observational aerosol optical properties from AERONET, irradiance measurements from German Weather Service stations, and radiative transfer simulations, the researchers assessed discrepancies between modelled and observed atmospheric radiation. Their findings showed that the Copernicus reanalysis overestimated aerosol absorption by approximately 0.03, equivalent to about 30%, indicating that inaccurate representation of aerosol optical properties can introduce systematic errors into solar radiation attenuation estimates. The study also reported estimated uncertainty of $-1.5 \pm 7.7 \text{ W}/\text{m}^2$ for the simulated surface aerosol radiative effect, highlighting the importance of accurate aerosol characterisation. The findings support improved calibration of aerosol absorption parameters, validation against ground observations, and integration of multiple atmospheric datasets to enhance radiation modelling in German urban environments.

METHODOLOGY

This study adopted a desk methodology. A desk study research design is commonly known as secondary data collection. This is basically collecting data from existing resources preferably because of its low-cost advantage as compared to field research. Our current study looked into already published studies and reports as the data was easily accessed through online journals and libraries.

FINDINGS

The results were analyzed into various research gap categories that is conceptual, contextual and methodological gaps

Conceptual Research Gap

Existing empirical studies have examined various aspects of atmospheric aerosol concentrations and solar radiation attenuation without comprehensively establishing the individual and combined influences of aerosol characteristics on solar radiation transmission in urban environments. Witthuhn. (2021) primarily investigated aerosol optical properties and their radiative effects under clear-sky conditions, while Wild . (2021) examined long-term variations in surface solar radiation associated with atmospheric dimming and brightening. Similarly, Senf . (2021) focused on aerosol absorption and cloud interactions, whereas Baars . (2021) investigated the optical properties of long-range transported aerosols. Although these studies provided valuable insights into aerosol–radiation interactions, the reviewed evidence does not establish a unified empirical assessment of aerosol particle concentration, particle size distribution, chemical composition, and aerosol optical

depth as interconnected determinants of solar radiation attenuation. Furthermore, the relative contributions and potential interactions of these aerosol characteristics remain insufficiently examined within a single analytical framework. Therefore, the proposed study seeks to address this conceptual gap by developing and testing an integrated model that evaluates the individual and combined effects of these four aerosol dimensions on solar radiation attenuation in German urban environments.

Contextual Research Gap

Previous studies have investigated atmospheric aerosol behaviour under specific environmental and meteorological conditions, limiting the extent to which their findings explain solar radiation attenuation across diverse urban atmospheric settings. For instance, Witthuhn . (2021) concentrated on clear-sky conditions, while Wild . (2021) examined long-term atmospheric dimming and brightening in Potsdam. The Berlin studies published in 2018 and 2020 primarily investigated interactions between urban heat islands, particulate pollution, and meteorological variability, whereas Senf . (2021) employed numerical simulations to assess aerosol absorption and cloud-related processes. Although these studies demonstrated important relationships between aerosols, atmospheric conditions, and radiation, the reviewed evidence provides limited integrated analysis of how traffic emissions, industrial pollution, residential heating, seasonal changes, relative humidity, and cloud cover jointly influence aerosol-induced solar radiation attenuation. Additionally, Baars . (2021) investigated an exceptional long-range smoke transport event, whose atmospheric characteristics may differ substantially from routine urban pollution conditions. Consequently, the proposed study seeks to bridge this contextual gap by investigating aerosol–radiation relationships under varying urban pollution and meteorological conditions, distinguishing aerosol-related attenuation from changes associated with clouds, humidity, and seasonal atmospheric variability.

Geographical Research Gap

Although previous research has examined aerosol characteristics and solar radiation variations in Germany, the reviewed studies differ considerably in their geographical coverage, with several investigations concentrating on particular cities or broader national atmospheric conditions. Wild . (2021) focused on long-term solar radiation trends in Potsdam, while the studies published in 2018 and 2020 examined urban aerosol pollution and heat island interactions in Berlin. Similarly, Baars . (2021) investigated transported aerosol layers over Leipzig, whereas Witthuhn . (2021) analysed aerosol–radiation interactions across 25 German Weather Service monitoring stations without specifically establishing comparative relationships across different urban pollution environments. These studies provide important geographical evidence but do not collectively establish how aerosol concentration, particle size distribution, chemical composition, and aerosol optical depth influence solar radiation attenuation across multiple German cities under comparable measurement and analytical conditions. Consequently, the generalisability of city-specific findings to urban environments with different industrial activities, traffic densities, climatic conditions, and pollution sources remains uncertain. Therefore, the proposed study seeks to address this geographical gap by conducting a comparative investigation across selected German urban centres, potentially including Berlin, Hamburg, Munich, Frankfurt, and Leipzig, to establish spatial variations in aerosol characteristics and their influence on solar radiation attenuation.

CONCLUSION AND RECOMMENDATIONS

Conclusions

Atmospheric aerosol concentrations play a significant role in influencing solar radiation attenuation in urban environments through the absorption and scattering of incoming solar radiation, thereby affecting atmospheric visibility, surface energy balance, and solar energy generation. In Germany, urban activities such as transportation, industrial operations, construction, and residential heating contribute to atmospheric aerosol emissions, which may influence the transmission of solar radiation under varying meteorological conditions. The reviewed theoretical perspectives, particularly Mie Scattering Theory, Beer–Lambert Law, and Radiative Transfer Theory, provide a scientific foundation for understanding the relationship between aerosol characteristics and solar radiation attenuation. Aerosol concentration, particle size distribution, chemical composition, and aerosol optical depth are important factors influencing atmospheric radiative processes, although their effects vary depending on humidity, cloud cover, seasonal conditions, and solar zenith angle. Despite advancements in atmospheric monitoring and radiation modelling, further research is necessary to establish the relative and combined contributions of these aerosol characteristics to solar radiation attenuation across different German urban environments. Therefore, the proposed study seeks to address these knowledge gaps by examining the influence of atmospheric aerosol concentrations on solar radiation attenuation in Germany, with particular emphasis on aerosol optical properties, seasonal variability, and urban meteorological conditions. The anticipated findings could contribute to atmospheric physics by strengthening the understanding of aerosol–radiation interactions, while providing practical insights for solar energy forecasting, environmental monitoring, and urban air quality management. Furthermore, the study could generate empirical evidence to inform integrated environmental and renewable energy policies, supporting Germany's efforts to improve air quality, enhance solar energy utilisation, and promote sustainable urban development.

Recommendations

Theory

The study recommends the development of an integrated theoretical framework combining Mie Scattering Theory, Beer–Lambert Law, and Radiative Transfer Theory to explain the relationship between atmospheric aerosol concentrations and solar radiation attenuation in urban environments in Germany. Future researchers should investigate how aerosol particle concentration, particle size distribution, chemical composition, and aerosol optical depth influence the absorption, scattering, and transmission of solar radiation through the atmosphere. Particular emphasis should be placed on examining the individual and combined effects of these aerosol characteristics under varying meteorological conditions, including relative humidity, temperature, cloud cover, and atmospheric stability. Researchers should also employ quantitative atmospheric modelling and long-term observational datasets to establish how seasonal variations and urban pollution patterns influence solar radiation attenuation. The study's potential unique contribution to theory lies in developing and empirically testing a multidimensional framework that integrates aerosol microphysical properties, atmospheric optical processes, and urban meteorological conditions to explain variations in solar radiation attenuation. Such a framework could extend existing applications of atmospheric radiation theories by providing a more comprehensive explanation of how different

aerosol characteristics interact to influence solar energy transmission in highly urbanised environments.

Practice

The study recommends that environmental monitoring agencies, urban planners, solar energy developers, and meteorological institutions in Germany strengthen the monitoring and assessment of atmospheric aerosol concentrations to improve the prediction and management of solar radiation attenuation. Institutions such as the German Environment Agency (Umweltbundesamt) and the German Weather Service (Deutscher Wetterdienst) should consider integrating aerosol optical depth measurements, particulate matter concentrations, satellite observations, and ground-based solar radiation data into coordinated environmental monitoring systems. Furthermore, solar energy developers should incorporate aerosol-related radiation losses into photovoltaic site assessments, energy yield forecasting, and solar power system design, particularly in urban environments experiencing elevated particulate pollution. Municipal authorities should also encourage pollution reduction strategies, including cleaner transportation systems, industrial emission controls, and urban environmental management practices, to minimise atmospheric aerosol concentrations and improve air quality. The study's potential unique contribution to practice lies in developing evidence-based approaches for predicting aerosol-induced solar radiation losses, improving photovoltaic energy forecasting, identifying urban pollution hotspots, and supporting more effective solar energy infrastructure planning. These contributions could strengthen operational decision-making among environmental scientists, energy producers, and urban planners while improving the reliability of solar energy generation in German cities.

Policy

The study recommends that the German government strengthen the integration of atmospheric aerosol monitoring, air quality regulation, and renewable energy planning within national and municipal environmental policies. Policymakers should consider enhancing the implementation of existing European Union air quality requirements while supporting coordinated monitoring of particulate matter, aerosol optical properties, and surface solar radiation in major urban centres. In addition, the Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety and relevant energy authorities should promote research funding for atmospheric radiation modelling, aerosol monitoring technologies, and urban solar energy forecasting. Policy frameworks should also encourage data sharing between environmental agencies, meteorological institutions, research universities, and renewable energy developers to improve the accessibility and application of atmospheric observations. The study's potential unique contribution to policy lies in providing empirical evidence that could inform integrated air quality and renewable energy policies, strengthen environmental monitoring standards, and support the inclusion of aerosol-related solar radiation losses in urban energy planning. Such evidence could contribute to Germany's environmental sustainability objectives by supporting policies that simultaneously address atmospheric pollution, solar energy productivity, and urban climate resilience.

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