

**ASSESSING THE IMPACT OF AIR POLLUTION ON
SOLAR ENERGY RESOURCES IN INDIA IN PRESENT
AND FUTURE CLIMATE**

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by

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Submitted

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Dedicated to my grandmother

Certificate

This is to certify that the thesis entitled “**ASSESSING THE IMPACT OF AIR POLLUTION ON SOLAR ENERGY RESOURCES IN INDIA IN PRESENT AND FUTURE CLIMATE**” being submitted by **Mr Sushovan Ghosh** for the award of the degree of **Doctor of Philosophy**, is a record of the original bonafide research work carried out by his. He has worked under the joint guidance and supervisions and has fulfilled the requirements for the submission of this thesis. The results presented in this thesis have not been submitted in part or full to any University or Institution for the award of any degree/diploma.

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Abstract

Transitioning to renewable energy is essential for a sustainable future, and nations set ambitious targets to decarbonize their energy systems. Among the renewables, solar energy has seen remarkable growth, with India now ranking fifth globally in solar power capacity and aiming for 100 GW of installations.

Despite this progress, the solar photovoltaic industry faces several challenges pertaining to technology, economics, environments and installation. Effective photovoltaic deployment requires thorough resource assessments, as surface solar radiation—the key factor for photovoltaic system—is influenced by atmospheric aerosols. These aerosols can attenuate incoming solar radiation or accumulate on the panels, thereby reducing photovoltaic generation. Regions like China, India, and the Middle East, which have high particulate matter pollution, are witnessing booming investments in solar energy, making it crucial to address aerosol impacts on solar potential. Further, the solar radiation undergoes significant long-term variations through the change in aerosols and clouds, known as 'global dimming and brightening,' which affect photovoltaic production. Understanding these changes and their impact on the growing photovoltaic sectors is vital, especially for India's national-scale deployment, which must consider appropriate land type, ecosystem preservation, and environmental factors.

Additionally, the expansion of solar energy requires a thorough evaluation in the context of climate change to demonstrate its potential for a low-carbon economy. The electricity generated by photovoltaic panels is influenced by the amount of sunlight received on the surface, while the efficiency of the panels is affected by climatic factors including ambient temperature and surface wind speed. Furthermore, changes in cloud and aerosol patterns are

anticipated to modify the radiation, posing new challenges for the long-term planning and management of solar energy resources.

On the light of above research gaps, the current thesis aims to assess the impact of air pollution on solar energy resources over India as a case during present and future climates, using satellites, climate models, and in-situ data.

Firstly, the thesis identifies 60% of the Indian landmass as an effective solar-rich area based on the 18 years (2001–18) of annual global horizontal irradiance availability. However, India lost 29% of its resources due to the staggering air pollution between 2001 and 2018. Furthermore, the loss in photovoltaic output across the different panel configurations ranges from 12% to 41%, resulting in a loss of 245-835 million USD annually. Additionally, the successful implementation of clean air policies would allow India to generate 6–16 terawatts of surplus energy per year, translating to 325-845 million USD, equivalent to the cost of these policies. Furthermore, mitigating air pollution would accelerate India's progress towards achieving its solar energy target at a lower installation capacity, avoiding additional expenditure for solar energy infrastructure expansion. The 2nd part of the thesis also reports that 29.3% of the Indian landmass is suitable for effective photovoltaic deployments based on the appropriate land constraints on top of the radiation availability. However, this resource is declining at -0.21% per year due to aerosol-induced solar dimming, translating to a loss of 6,902 km² of land (considering India's total geographical area of ~3.287 million km²), leading to a cumulative loss of 50 gigawatts (GW) of solar potential (using the land-use photovoltaic factor of 7.5 MW km⁻²), equivalent to 75 terawatt-hours (TWh) of generation (using 1.44 GWh of generation per MW plant). Finally, this thesis explores the future potential of solar energy resources in India around mid-century, based on two plausible scenarios that account for varying degrees of air pollution mitigation and climate actions. Both scenarios predict a decline in photovoltaic

potential, with a national average decrease ranging from -2.3% to -3.3%. The reduction in potential is expected to be more pronounced in the scenario with moderate air pollutant mitigation and climate action compared to the scenario with strong air pollutant mitigation but weaker climate actions. This future decrease in potential is primarily attributed to changes in solar radiation, followed by changes in temperature and wind speed. Additionally, rising ambient temperatures in both scenarios will increase cell temperatures, thereby reducing cell efficiency and overall performance. Higher cell temperatures are projected under the weak climate action scenario compared to the intermediate climate action scenario.

This dissertation is an attempt to bridge the gap between atmospheric and renewable energy sciences by considering India as a case. Firstly, the thesis addresses the impact of air pollution on solar energy resources at Indian power grid scale and highlights the key benefits in-terms of surplus electricity India could have anticipated by implementing clean air policies with the solar expansions. This additional energy, coupled with health benefits from air pollution reduction, suggests a significant 'win-win' opportunity. Secondly, the thesis maps the Indian solar resources based on surface solar radiation and land availability criteria and estimates the impact from persistent dimming on photovoltaic generations. It also distinguishes key regions (and the existing solar parks) within the Indian landmass that are sensitive to either aerosols or clouds linked with the observed trend. Finally, the work investigates the promise of future photovoltaic potential during mid-century by considering two plausible future scenarios for India. It stresses the impact of change in radiation for the drop of potential and reports the negative influence of increasing temperature on cell efficiency and hence performances. Overall, these findings offer valuable insights for site selection, managing weather and climate variability, energy storage, and selecting cell materials, aiding energy planners and policymakers in maximizing power generation. However, the thesis can be extended to quantify the valuable information using high resolution spatio-temporal data to estimate

energy-surplus and deficit at desired scale. In conclusion, the outcomes of the thesis and the continued efforts in this field will be beneficial for transitioning to low carbon society in future.

सार

टिकाऊ भविष्य के लिए नवीकरणीय ऊर्जा में परिवर्तन आवश्यक है, और राष्ट्र अपनी ऊर्जा प्रणालियों को डीकार्बोनाइज करने के लिए महत्वाकांक्षी लक्ष्य निर्धारित करते हैं। नवीकरणीय ऊर्जा में, सौर ऊर्जा में उल्लेखनीय वृद्धि देखी गई है, भारत अब सौर ऊर्जा क्षमता में विश्व स्तर पर पांचवें स्थान पर है और 100 गीगावॉट की स्थापना का लक्ष्य रखा है।

इस प्रगति के बावजूद, सौर फोटोवोल्टिक उद्योग को प्रौद्योगिकी, अर्थशास्त्र, पर्यावरण और स्थापना से संबंधित कई चुनौतियों का सामना करना पड़ता है। प्रभावी फोटोवोल्टिक परिनियोजन के लिए संपूर्ण संसाधन मूल्यांकन की आवश्यकता होती है, क्योंकि सतह सौर विकिरण - फोटोवोल्टिक प्रणाली के लिए प्रमुख कारक - वायुमंडलीय एरोसोल से प्रभावित होता है। ये एरोसोल आने वाले सौर विकिरण को कम कर सकते हैं या पैनलों पर जमा हो सकते हैं, जिससे फोटोवोल्टिक उत्पादन कम हो सकता है। चीन, भारत और मध्य पूर्व जैसे क्षेत्र, जहां उच्च कण पदार्थ प्रदूषण है, सौर ऊर्जा में तेजी से निवेश देख रहे हैं, जिससे सौर क्षमता पर एरोसोल प्रभावों को संबोधित करना महत्वपूर्ण हो गया है। इसके अलावा, एरोसोल और बादलों में परिवर्तन के माध्यम से सौर विकिरण महत्वपूर्ण दीर्घकालिक बदलावों से गुजरता है, जिसे 'ग्लोबल डिमिंग और ब्राइटनिंग' के रूप में जाना जाता है, जो फोटोवोल्टिक उत्पादन को प्रभावित करता है। इन परिवर्तनों और बढ़ते फोटोवोल्टिक क्षेत्रों पर उनके प्रभाव को समझना महत्वपूर्ण है, विशेष रूप से भारत की राष्ट्रीय स्तर की प्रविस्तारण के लिए, जिसमें उचित भूमि प्रकार, पारिस्थितिकी तंत्र संरक्षण और पर्यावरणीय कारकों पर विचार करना चाहिए।

इसके अतिरिक्त, कम कार्बन अर्थव्यवस्था के लिए अपनी क्षमता प्रदर्शित करने के लिए सौर ऊर्जा के विस्तार को जलवायु परिवर्तन के संदर्भ में गहन मूल्यांकन की आवश्यकता है। फोटोवोल्टिक पैनलों द्वारा उत्पन्न बिजली सतह पर प्राप्त सूर्य के प्रकाश की मात्रा से प्रभावित होती है, जबकि पैनलों की दक्षता परिवेश के तापमान और सतह की हवा की गति सहित जलवायु कारकों से प्रभावित होती है। इसके

अलावा, बादल और एयरोसोल पैटर्न में बदलाव से विकिरण में बदलाव की आशंका है, जिससे सौर ऊर्जा संसाधनों की दीर्घकालिक योजना और प्रबंधन के लिए नई चुनौतियाँ पैदा होंगी।

उपरोक्त अनुसंधान अंतराल के प्रकाश में, वर्तमान थीसिस का उद्देश्य उपग्रहों, जलवायु मॉडल और इन-सीटू डेटा का उपयोग करके वर्तमान और भविष्य की जलवायु के दौरान भारत में सौर ऊर्जा संसाधनों पर वायु प्रदूषण के प्रभाव का आकलन करना है।

सबसे पहले, थीसिस वार्षिक वैश्विक क्षैतिज विकिरण उपलब्धता के 18 वर्षों (2001-18) के आधार पर 60% भारतीय भूभाग को एक प्रभावी सौर-समृद्ध क्षेत्र के रूप में पहचानती है। हालाँकि, 2001 और 2018 के बीच चौका देने वाले वायु प्रदूषण के कारण भारत ने अपने 29% संसाधनों को खो दिया। इसके अलावा, विभिन्न पैनल कॉन्फिगरेशन में फोटोवोल्टिक आउटपुट में हानि 12% से 41% तक है, जिसके परिणामस्वरूप 245-835 मिलियन अमरीकी डालर का नुकसान हुआ। सालाना. इसके अतिरिक्त, स्वच्छ वायु नीतियों के सफल कार्यान्वयन से भारत को प्रति वर्ष 6-16 टेरावाट अधिशेष ऊर्जा उत्पन्न करने की अनुमति मिलेगी, जो इन नीतियों की लागत के बराबर 325-845 मिलियन अमरीकी डालर है। इसके अलावा, वायु प्रदूषण को कम करने से कम स्थापना क्षमता पर अपने सौर ऊर्जा लक्ष्य को प्राप्त करने की दिशा में भारत की प्रगति में तेजी आएगी, जिससे सौर ऊर्जा बुनियादी ढांचे के विस्तार के लिए अतिरिक्त खर्च से बचा जा सकेगा। थीसिस का दूसरा भाग यह भी बताता है कि भारतीय भूभाग का 29.3% विकिरण उपलब्धता के शीर्ष पर उपयुक्त भूमि बाधाओं के आधार पर प्रभावी फोटोवोल्टिक तैनाती के लिए उपयुक्त है। हालाँकि, यह संसाधन प्रति वर्ष -0.21% की दर से घट रहा है, जिससे 50 गीगावाट सौर क्षमता का संचयी नुकसान हो रहा है, जो 75 टेरावाट-घंटे उत्पादन के बराबर है। अंत में, यह थीसिस मध्य शताब्दी के आसपास भारत में सौर ऊर्जा संसाधनों की भविष्य की संभावनाओं का पता लगाती है, जो दो संभावित परिदृश्यों पर आधारित है जो वायु प्रदूषण शमन और जलवायु कार्यों की अलग-अलग डिग्री के लिए जिम्मेदार हैं। दोनों परिदृश्य फोटोवोल्टिक क्षमता में गिरावट की भविष्यवाणी करते हैं, जिसमें राष्ट्रीय

औसत कमी -2.3% से -3.3% तक होती है। मजबूत वायु प्रदूषक शमन लेकिन कमजोर जलवायु कार्रवाई वाले परिदृश्य की तुलना में मध्यम वायु प्रदूषक शमन और जलवायु कार्रवाई वाले परिदृश्य में क्षमता में कमी अधिक स्पष्ट होने की उम्मीद है। क्षमता में भविष्य में होने वाली इस कमी का मुख्य कारण सौर विकिरण में परिवर्तन, उसके बाद तापमान और हवा की गति में परिवर्तन है। इसके अतिरिक्त, दोनों परिदृश्यों में बढ़ते परिवेश के तापमान से सेल तापमान में वृद्धि होगी, जिससे सेल दक्षता और समग्र प्रदर्शन कम हो जाएगा। मध्यवर्ती जलवायु कार्रवाई परिदृश्य की तुलना में कमजोर जलवायु कार्रवाई परिदृश्य के तहत उच्च सेल तापमान का अनुमान लगाया जाता है।

यह शोध प्रबंध भारत को एक मामला मानकर वायुमंडलीय और नवीकरणीय ऊर्जा विज्ञान के बीच अंतर को पाटने का एक प्रयास है। सबसे पहले, थीसिस भारतीय पावर ग्रिड पैमाने पर सौर ऊर्जा संसाधनों पर वायु प्रदूषण के प्रभाव को संबोधित करती है और अधिशेष बिजली के संदर्भ में प्रमुख लाभों पर प्रकाश डालती है जो भारत सौर विस्तार के साथ स्वच्छ वायु नीतियों को लागू करके प्रत्याशित कर सकता था। यह अतिरिक्त ऊर्जा, वायु प्रदूषण में कमी से स्वास्थ्य लाभ के साथ मिलकर, एक महत्वपूर्ण 'जीत-जीत' अवसर का सुझाव देती है। दूसरे, थीसिस सतही सौर विकिरण और भूमि उपलब्धता मानदंडों के आधार पर भारतीय सौर संसाधनों का मानचित्रण करती है और फोटोवोल्टिक पीढ़ियों पर लगातार मंद होने के प्रभाव का अनुमान लगाती है। यह भारतीय भूभाग के भीतर प्रमुख क्षेत्रों (और मौजूदा सौर पार्कों) को भी अलग करता है जो देखे गए रुझान से जुड़े एयरोसोल या बादलों के प्रति संवेदनशील हैं। अंत में, यह कार्य भारत के लिए दो संभावित भविष्य के परिदृश्यों पर विचार करके मध्य शताब्दी के दौरान भविष्य के फोटोवोल्टिक क्षमता के वादे की जांच करता है। यह क्षमता में गिरावट के लिए विकिरण में परिवर्तन के प्रभाव पर जोर देता है और सेल दक्षता और इसलिए प्रदर्शन पर बढ़ते तापमान के नकारात्मक प्रभाव की रिपोर्ट करता है। कुल मिलाकर, ये निष्कर्ष साइट चयन, मौसम और जलवायु परिवर्तनशीलता के प्रबंधन, ऊर्जा भंडारण और सेल सामग्री का चयन करने, ऊर्जा योजनाकारों और नीति निर्माताओं को बिजली

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Chapter 4

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List of Abbreviations

Aerosol optical depth (**AOD**)

Air Quality Guideline (**AQG**)

Baseline Surface Radiation Network (**BSRN**)

Black Carbon (**BC**)

Clouds and Earth Radiant Energy System Synoptic 1 degree (**CERES SYN1deg**)

Coupled Model Intercomparison Project Phase 6 (**CMIP6**)

December-January-February (**DJF**)

Deen Dayal Upadhyaya Gram Jyoti Yojana (**DDUGJY**)

Direct Normal Irradiance (**DNI**)

General Circulation Model (**GCM**)

Gigawatt (**GW**)

Global Energy Balance Archive (**GEBA**)

Global Horizontal Irradiance (**GHI**)

Global Human Settlement Layer (**GHSL**)

Goddard Earth Observing System (**GEOS**)

India Meteorological Department (**IMD**)

Indo Gangetic Plain (**IGP**)

Intergovernmental Panel on Climate Change (**IPCC**)

June-July-August (**JJA**)

March-April-May (**MAM**)

Moderate Resolution Imaging Spectroradiometer (**MODIS**)

Modern-Era Retrospective analysis for Research and Applications, Version 2 (**MERRA-2**)

Multi Model Ensemble (**MME**)

National Clean Air Program (**NCAP**)

Normalized Difference Vegetation Index (**NDVI**)

Organic Carbon (**OC**)

Particulate Matter (**PM**)

Pradhan Mantri Ujjwala Yojana (**PMUY**)

September-October-November (**SON**)

Shared Socio-economic Pathways (**SSPs**)

Solar Photovoltaic (**SPV**)

Terawatt-hour (**TWh**)

World Climate Research Programme (**WCRP**)

World Health Organization (**WHO**)

World Meteorological Organization (**WMO**)