学 位 論 文 内 容 の 要 旨/Dissertation Abstract

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India’s sustainable energy transitions: Analyzing agriculture land - water - solar energy nexus
（インドの持続可能なエネルギー転換：農地 - 水 - 太陽エネルギーネクサスの分析）


India's agricultural sector, which employs over 50% of its workforce and significantly contributes to its GDP, is challenged by the expanding solar energy sector. Solar energy projects converting agricultural lands raise food security concerns in a country where around 195 million people are already undernourished. Additionally, the growing water demand for cleaning solar panels and cooling solar plants strains India's already stressed water resources. Cleaning one solar module requires about two liters of water, and a medium-sized solar plant needs approximately 165,000 liters per month. This additional demand exacerbates water supply issues, impacting agriculture and domestic needs. This research paper explores the potential impacts of India's rapid solar energy expansion on its agricultural sector and water resources, emphasizing the need for sustainable practices to balance renewable energy goals with food security and water management.

Chapter two introduces the Solar Panel Index (SPI), an innovative algorithm for identifying and monitoring photovoltaic (PV) solar farms using multispectral satellite data. SPI utilizes six multispectral bands from optical satellite data to enhance solar panel area detection, reducing false positives. The study demonstrates SPI's application in India, enabling accurate identification and area estimation of solar plants. SPI provides precise location information, aiding energy generation estimation, performance optimization, and investment decisions. It supports grid operators and electricity market participants in managing the grid and tracking solar energy expansion. The algorithm's effectiveness varies with surface reflectance intensities from different locations. Testing various threshold values, a threshold of 0.16 achieved the highest accuracy of 97.8% at the Kamuthi solar farm, with an average accuracy of 91.9% across all locations.

The research introduces the Solar Energy Agriculture Water (SAW) nexus, emphasizing the interdependence of solar energy, agriculture, and water resources. This approach promotes integrated management and optimization across these sectors, addressing sustainability, food security, and climate change. Solar energy's role in the SAW nexus offers clean energy solutions while benefiting agriculture and water resources. Solar energy can power irrigation systems, reducing reliance on non-renewable resources and enhancing water efficiency. Adopting water-efficient irrigation techniques conserves water and reduces energy requirements, contributing to climate change mitigation. Conversely, agriculture can support solar energy by providing land for solar farms or integrating solar panels into farming operations, creating additional income for farmers and enhancing grid resilience. A case study at the Pavagadh solar power park analyzed the impact on agriculture and water management using Geospatial Land Use Land Cover (LULC) analysis and the Pearson Correlation Coefficient, revealing strong positive

correlations. A field visit to solar power plants in Maharashtra assessed the impact on soil microbial communities, showing significant differences beneath solar panels compared to agricultural farms, highlighting the need for further research on soil health. Water utilization in solar power plants was also investigated, focusing on cleaning methods. Some power plants rely on groundwater wells, while others use self-cleaning robots powered by solar energy, presenting a sustainable alternative to water-intensive methods. The study also explores agrivoltaics, where solar panels and crops mutually benefit, enhancing food production, conserving water, and generating additional revenue. However, converting agricultural land into solar farms could threaten food security, impact local water cycles, and exacerbate water shortages, necessitating careful planning and management.

Chapter four emphasizes the critical role of Geographic Information Systems (GIS) in sustainable SAW nexus management. Geospatial datasets identified solar farm locations and assessed land cover changes from their installation. The analysis revealed agricultural land as the predominant choice for solar farm expansion, supported by statistical data on land transformation. Groundwater level analysis using Gravity Recovery and Climate Experiment (GRACE) data assessed water resource availability and potential stress from solar power plants. Solar farm locations were overlaid with Night Time Light (NTL) data, indicating electrification trends from 2014 to 2020, a period of continuous solar industry growth. The chapter also presents a Land Suitability Map (LSM) for India, based on parameters like solar potential, power grid distance, land surface temperature, and water availability. The LSM aids decision-makers in promoting harmonious coexistence of solar energy production, agriculture, and responsible water management within the SAW nexus.

The concluding chapter summarizes the study's findings, emphasizing their significance and acknowledging limitations. Recommended policies can ensure sustainable solar energy growth while safeguarding agriculture and water resources, offering valuable lessons for other countries facing similar challenges, mitigating land encroachment, and addressing water scarcity concerns.