審 査 の 結 果 の 要 旨

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This study investigates the linkage between energy and water for future sustainability. Both of them are highly interconnected; we use water for energy and likewise, energy is needed for water. Freshwater scarcity is a global concern and cooling water withdrawals (CWW) by thermoelectric power plants (TEPPs) are further adding to such issues. The daily energy received by the earth from Sun is huge and with the help of solar photovoltaic (PV) it can be used to offset a substantial amount of electricity. This Energy-water nexus (EW-nexus) can lead to future sustainability in terms of energy and freshwater availability at a global scale.

Chapter 01 is on the significance of EW-nexus for future sustainability. It provides an insight into parameters and uncertainties involved in reducing the solar PV resource. Previous studies have demonstrated that meteorological parameters like temperature, dust, and snow, along with geomorphologic factors (tilt-angles) do affect the solar PV output. However, none of the previous studies has considered all such limiting factors together at a global scale. It also involves a detailed discussion on freshwater scarcity, components of water withdrawals, and explains how CWW is adding to such water scarcity. How the linkage between energy and water is significant in terms of limiting freshwater scarcity. Lastly, the electricity supply and demand-side relationship in the context of solar electric footprints of world megacities is discussed.

Chapter 02 describes the data and methodology to calculate final solar PV resources, PV economic analysis, water scarcity, and TEPPs credential mapping in addition to the EW-nexus scheme. First, global solar PV resource maps under different environments are produced using the solar irradiance available near the earth's surface and efficiency corrections for meteorological limiting factors. Then, freshwater withdrawals by TEPPs, a vital part of Industrial Water Withdrawals, are estimated for global 17 regions using the country-wise electricity generation data for different energy sources (coal, oil, gas, nuclear, and biomass), cooling technologies shares, once-through and wet tower type and water use intensity. Lastly, through EW-nexus, solar PV enhanced scenarios (PVenh) are established to see the PV area needed for each region to minimize the freshwater scarcity. In addition to the PV cost analysis, a novel methodology to know the solar electric footprints of world megacities is also established.

Chapter 03 is on the results and discussion of the energy section, solar PV. Global solar PV resource maps have revealed that a maximum annual loss of 20.1% is seen from snow covers during the season December-January (DJF) for the upper Northern Hemisphere. For Sub-Saharan Africa, the dust has the maximum power output drop of 6.5% during DJF. Also, temperature increase maximum cell efficiency reductions are recorded as 5.79% for the Middle East for June-August (JJA). Lastly, tilt angles are also proven to limit (1~8%) the solar PV outputs. The validation of our results shows a high value for the coefficient of determination (R2= 0.787) which demonstrates the better performance of our models. Likewise, future analysis up to 2100 by considering climate changes in terms of Representative Concentration Pathways (RCP2.6, RCP4.5, and RCP6.0) and socio-economic scenarios; Shared Socioeconomic Pathways (SSP1, SSP2, and SSP3) has revealed a slight difference (-4.72% to +4.23%) in the future PV resource. Cost analysis for solar PV has demonstrated that it is competitive with conventional electricity in regions like Sub-Saharan Africa and Australia.

Chapter 04 is on the results and discussion of the water section, water scarcity, and TEPPs credentials mapping. The water scarcity index, withdrawal-to-availability is used to map the global freshwater scarcity. Results have shown that China has the maximum population (0.11 billion) under severe water stress situations. The cooling water withdrawals (CWW) by TEPPs is adding to such stresses as most of it is not available to the downstream areas because of being polluted and raised temperatures. Among global 17 regions, available in Asia-Pacific Integrated Model, USA has the maximum electricity demand and withdrawing maximum freshwater (218 km3) to cool the TEPPs. Comparison of our results with the existing study shows a high value for the coefficient of determination (R2= 0.94) and demonstrates the better performance of our method. Future analyses have confirmed the variations in CWW among various regions for RCP and SSP scenarios which are mainly attributed to the technology shifts and efficiency changes.

Chapter 05 deals with the results and discussion of EW-nexus. Keeping in view the technology improvement for solar PV and country-wise policy to limit the greenhouse gases emission, three solar PV scenarios (PVenh) namely Low, Medium, and High are established for the future, 2050 and 2100. Region-wise solar PV areas needed by PVenh scenarios have revealed that these areas are very small (<0.1%) as compared to the total available land area in each region. Significant savings in terms of freshwater water withdrawals are seen for all regions with a maximum saving of 289 km3 is witnessed for China for 2100 under the SSP3-RCP6.0 (High) scenario. This saving could help to improve the anticipated number of populations under severe stress in the region.

Chapter 06 is on the results and discussion of electricity demand maps and case studies of megacities. Global gridded electricity demand maps have revealed that megacities are consuming maximum electricity due to bigger population and economic activities. For 2010, Shanghai has the maximum solar electric footprints (1383 km2) among other megacities. However, most of the megacities like 11 out of 24 offer a reasonable roof-top area to fulfil whole of such massive demands. Other megacities can fulfil ~40% of their electricity demands from roof-top PV schemes.

Chapter 07 is on the conclusion and recommendations of this study. This research has proven that solar PV has a great potential to offset a considerable amount of renewable electricity to the system and can help to minimize freshwater scarcity. With improving technology, and decreasing costs, it is believed to have a large impact on the energy system in the near future. In addition, it will help in achieving the United Nations Sustainable Development Goal No. 6–Water and Sanitation, Goal No. 7–Clean and Affordable Energy, Goal No. 11–Sustainable Cities and Communities and Goal No. 13–Climate Action.

よって本論文は博士（工学）の学位請求論文として合格と認められる。