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Land use Potential and Related Effect of Power Generation Technologies in India: A Sustainability Perspective

***Aqsa Anjum, **Jahangir Chauhan**
*Research Scholar, Department of Commerce, Aligarh Muslim University, Aligarh(UP),India.
**Assistant Professor, Department of Commerce, Aligarh Muslim University, Aligarh (UP),India.

Abstract
The increasing population and its growing energy demands impose significant pressure on land use, compelling a fundamental shift to meet the escalating demand sustainably. In contrast to conventional belief, the detrimental impact on land quality is contingent upon how the land is utilized rather than being solely determined by population density. Sustainable land management is pivotal, and in alignment with this, India aims to restore 26 million hectares of degraded land by 2030.Acknowledging that all energy sources necessitate land for installation and operation, this study delves into the intricate relationship between power generation technologies and the country's limited land cover. This comprehensive review examines the potential uses of land and the effects of diverse power generation technologies in India, emphasizing renewable energy sources such as solar and wind power. It includes a comparative study with coal-based technologies, approaching the analysis from a sustainability standpoint that considers environmental, economic, and social aspects of land utilization. Notably, there is a dearth of studies scrutinizing this facet of energy sustainability, rendering this research a significant and timely addition to the field. Findings reveal that the Solar PV cycle has the smallest land footprint among renewable energy sources, followed by wind energy. Among conventional sources, coal-fired power plants emerge as the most land-intensive, disturbing soil equilibrium and rendering the land infertile.
Keywords: Coal plants; Energy sustainability; Land requirement; Land footprint; Renewable energy.

1. Introduction

Land use cover in India for different purposes comprises livestock (27%), forests (26%), barren land (19%), glaciers (10%), shrub (8%), cropland (7%), and freshwater (1%) (UNECE,2021). In addition to the effects of the 1.4 billion population on land cover, the land acquired by energy technologies is also a significant factor in land degradation and climate change. According to the United Nations Convention to Combat Desertification (UNCCD), land quality dilapidation directly affects over 250 million people (Sivakumar,2007). Goal 5 of sustainable development goals (SDGs) emphasizes preventing land degradation induced by energy supply and consumption. Energy generation technologies are critical for the country's economic development and improved living standards. However, they impact the land during its life cycle, from raw material extraction to transportation, from the supplier to the final consumer. According to Kumar et al. (2010), "Lack of land use planning results in land degradation". Using conventional sources for power generation requires a vast land area, impacting biodiversity and human life.The installation of an energy system encompasses not only the physical footprint of the infrastructure but also entails consequences for soil quality. The primary manifestation of this impact on land use is the appropriation of significant land areas, often at the expense of the natural ecosystem. This process invariably results in land and soil deterioration. Indian Space Research Organization (ISRO), in a study entitled "Desertification and Land Degradation Atlas," reported that 97.85 million hectares (mha) of land area degraded in 2019 due to different land use practices. Such practices for installing power generation technologies affect air quality besides land degradation by modifying emissions and atmospheric conditions and diverting and disrupting groundwater flow (Foley,2005).

Although this land degradation due to electricity generation is prolonged, it might not be visible in a short span. The land use intensity of power generation technologies differs, ranging from 0.1 to 500 m^2/MWh, in which hydropower covers the maximum area (as shown in Table 1).Moreover, the land demand associated with power generation technology extends beyond the installation phase; it fluctuates throughout the entire lifecycle of a power plant, encompassing stages from material procurement to disposition, as demonstrated in Figure 1. The demand for land use has increased due to economic and population expansion; therefore, a well-balanced mix of all three dimensions of sustainability is required (Wiggering et al., 2006). In accordance with the Intended Nationally Determined Contributions (INDC) scenario, the land requirement is projected to be 96 percent, while under the business-as-usual (BAU) scenario, it exceeds 120 percent. This underscores that the shift toward a low-carbon economy is intricately linked to a substantial demand for land (Rej & Nag,2021).Renewable energy technologies have the advantage of utilizing the same land on an annual basis, eliminating the need for extensive total land area (Jacobson & Delucchi,2011).

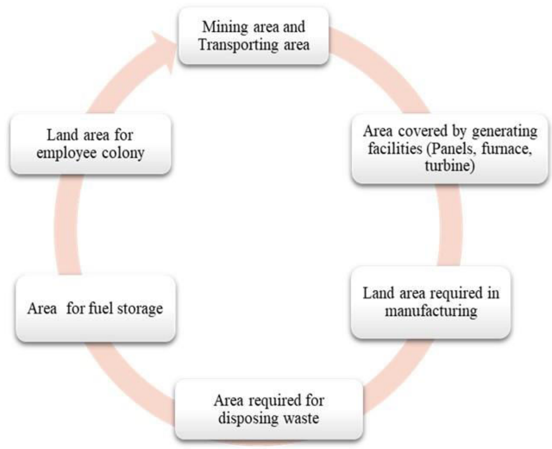

Figure 1. Land use requirement during power plant lifecycle.

Table 1. Land use intensity of energy sources.

Technology	Land use intensity (m^2 annum per MWh)
Hydropower (small to medium) (<360MW)	33
Hydropower (large plants) (>660MW)	14
Solar (CSP)	22
Solar (PV silicon) (Ground-mounted)	19
Coal Power	15
Gas Plant	1
Nuclear power	0.3
Onshore Wind (excluding spacing area)	0.4

Source: UNECE (2021)

2. Methodology adopted

This study's main goal is to find existing studies on energy generation. In this situation, the following research questions were chosen: RQ1: How much land area is acquired by power generation technologies, and what is their impact on land quality? RQ2: What are the important research and study loops in energy generation sustainability that have been noted for this subject? RQ3: What new lines of inquiry are suggested by the body of existing research? The search process involved querying Google Scholar using specific terms such as 'Land requirement by power generation technologies,' 'Impact of power generation technologies on land,' 'Electricity generation impact on Land,' and 'Impact and land use of renewable technologies,' along with 'Impact of coal power generation. During the exploration, terms associated with the subject under investigation were identified, and these are provided in Table 3.

3. Results

3.1 Solar power generation technologies

Renewable energy technologies have the potential to outperform conventional energy sources in various aspects. Within the spectrum of renewable power generation options, the solar photovoltaic (PV) cycle demands the least land area, while biomass involves the most (Fthenakis& Kim, 2009). Adding perspective to this, it is noteworthy that the Earth receives an abundant 120,000 terawatts per hour, a potential energy source capable of meeting global power needs for a substantial period of 20 years (Morton, 2006). The amount of land required to generate electricity from solar energy is determined by the plant site and the type of solar technology used (Horner & Clark,2013; Tahri et al.,2015&Paktinat et al.,2014). Site selection for installing solar power plants is crucial for better plant performance, reduced transport losses, minimized operation and maintenance costs, and reduced environmental impacts (Carrion et al.,2008). According to Ramachandra (2011), nearly 58% of the region could be the country's solar hotspots, with an average global insolation of more than 5 $kWh/m^2/day$ available annually.

Solar PV plants exhibit minimal land disturbance throughout their lifecycle compared to traditional sources and other renewable power technologies (Groesbeck & Pearce, 2018). The land area needed for solar PV is significantly less than that required for coal-based plants. Furthermore, climate change is expected to have a negligible impact on solar irradiance, while land use intensity will introduce more significant variability (Gunderson et al., 2015).Solar photovoltaic (PV) technology showcases versatility in applications and locations, ranging from rooftops to parking areas and ground-mounted systems. Its advantageous feature lies in the ability to be installed on poor-quality land, demonstrating compatibility with diverse uses (Denholm & Margolis, 2008). Despite the minimal land usage on rooftops, solar panels still require land for mining materials, contributing to their production (UNECE, 2021). In India, solar PV utilizes 1.7-2.5 percent of the landmass for energy provision, with projections indicating an uptake of 50,000 to 75,000 square kilometers by 2050 (Gupta, 2021).

Unused land, without any productive purpose, becomes an ideal candidate for solar panel installations. Panels can be strategically placed in agricultural areas, unutilized locations, along field boundaries, edges of irrigation areas, and on the rooftops of barns or sheds. This approach minimizes the impact on crop yield and serves additional agricultural functions, such as powering machinery, electric barricades, irrigation pumping, crop drying and storage, and farmhouse electricity (Bazen & Brown, 2009).Hoffacker et al. (2017) highlighted the potential of judicious siting of renewable energy to mitigate environmental trade-offs associated with land and water use in agricultural areas. Additionally, lakes, ponds, and reservoirs occupy just over three percent of the planet's surface, providing ample opportunities for deploying floatovoltaics (Brauman et al., 2013; Downing et al., 2006; Samo et al., 2017). Installing solar panels on water reservoirs (Floatovoltaic) can reduce evaporation, decrease algae growth, lower water temperature, and enhance efficacy through the refrigeration effect. The incorporation of solar systems into agricultural fields, commonly known as agrivoltaic systems, along with the integration of wind systems, serves to further minimize the land footprint associated with renewable energy systems (Goetzberger& Zastrow, 1982; Dinesh & Pearce, 2016; Ravi et al., 2016; &Amaducci et al., 2018). Solar PV systems hold the most long-term potential, but their implementation necessitates significant adjustments to the existing energy infrastructure (Nonhebel, 2005).

The economic benefits of utility-scale solar photovoltaic systems make them an appealing option compared to other sectors (Majumdar & Pasqualetti, 2019). Solar developers typically seek to lease land near transmission lines and power grids, necessitating landowners to consider factors such as long-term commitment, land impact, and neighbors' relations. Decommissioning a plant before its intended lifespan poses challenges due to high costs for solar developers. Studies indicate that heavily populated regions with high per capita energy demands may require a considerable share of domestic land, equivalent to the current built-up space, for a high contribution of solar energy generation. Potential conflicts over land allocation can be mitigated by prioritizing underused agricultural regions for renewable energy generation in energy policies (Gazheli& Di Corato, 2013). Segregation of land use can raise awareness, reduce land degradation rates, and prevent land use conflicts, as illustrated in Table 2.Planning and regulating new installations in a coordinated manner is essential to avoid a substantial increase in life cycle emissions by solar PV systems stemming from the loss of carbon dioxide from terrestrial sources and to prevent land use conflicts.

Table 2. Land suitable/unsuitable for solar photo voltaic installation

Category	Land Use
Favorable	Land along railway lines, Mines, Junkyards, Burnt Areas, Mineral extraction sites, Bare rocks, and Motorways.
Suitable -Conflict	Productive land, Pastures.
Possible- Conflict	Fruit and Berry plantations.
Unfavorable	Non-rural areas, Forest land, Wetland.

Source: Sliz-Szkliniarz (2013)

3.2 Wind power generation technologies

The expansion of the wind sector has resulted in a healthy ecosystem, projected operating capacities, and a production base of approximately 10,000 MW per year. With an installed capacity of 40.357 GW, India ranks fourth in the world regarding wind installed capacity in 2022 (MNRE,2022). Wind energy projects require much space for power generation, clearing potentially massive sections of forest or other extensive vegetation for the turbines and accommodating roads. A lifecycle analysis of land requirements by wind plants would include the turbine pad area, access roads, and transmission and distribution for grid connection. However, wind energy uses less land than other renewable energy sources. Furthermore, compared to biomass or solar power plants, the space beneath a wind farm can be used for agricultural purposes because turbines only occupy a small portion of a farm’s area (Sliz-Szkliniarz,2013). Wind power generation offers significant environmental benefits. Not only does it refrain from releasing pollutants into the atmosphere, but it also eliminates the need for water in the cooling process, with exceptions being rare. Additionally, offshore wind turbines exhibit a reduced environmental footprint compared to their land-based counterparts. Wind farms can be installed in the agricultural sector on moderate to high-quality arable land, where solar farm installation may exacerbate existing tensions (Sliz-Szkliniarz,2013). All power generation technologies impact the environment and ecosystems; wind turbines pose a few environmental issues, such as aesthetic concerns when people see them in the landscape, leading to accidents. Further, a few fire incidents have been caught by wind turbines, and some cases of leaked lubricating fluids have occurred, but this is uncommon. Wind energy projects cause significant noise pollution and can also kill birds and bats (Pimentel et al.,2002). Each wind turbine covers an average area of three acres, resulting in land acquisition issues primarily aimed at common and forest properties, which are easier to acquire but result in conflict. A few instances are the Suzlon project in Maharashtra, which caused various land conflicts, and Andhra Pradesh wind energy companies (Gawande & Chaudhry,2019). The limited land resources for onshore wind projects are becoming a key barrier to wind power generation. The existing body of research reveals a notable gap in examining land use aspects related to the deployment of renewable energy. Furthermore, this research focus is predominantly confined to developed nations, where studies have primarily concentrated on estimating land area requirements. Consequently, there is a clear need for qualitative research that delves into the intricacies of land use in deploying renewable energy, emphasizing conducting comprehensive investigations in developing countries.

3.3 Coal power generation technologies

Coal contributes 60 percent of India's commercial power needs, and its estimated demand is expected to reach 1.75 million tonnes by 2030. The cumulative consumption of coal to date stands at approximately 200 billion tonnes. However, the extensive use of land for mining and storage and the evacuation of raw coal sites by coal power plants raise environmental concerns. The negative impact encompasses pollutants released during extraction, construction, and power generation.Currently, 340 square kilometers of land are dedicated to coal electricity generation, which is projected to escalate to 1295 square kilometers by 2050 (Gaeatlholwe et al., 2022). Notably, coal plants require 5 to 13 times more land than solar photovoltaic plants and emit greenhouse gases at 13 to 18 times higher (Groesbeck and Pearce, 2018). Beyond environmental consequences, challenges related to resettlement, rehabilitation, internal river water disputes, and flooding are further associated with coal-based power generation.

The Intergovernmental Panel on Climate Change (IPCC) underscores the urgency of restricting coal power plant production by 2050 to mitigate global warming (IPCC, 2022). Within 2-31 years, the land requirement for coal power is projected to equal or surpass that of renewable energy, raising viability concerns (Trainor et al., 2016). Pollution, ash, and solid waste from coal power generation exploit vast land areas for storage, leading to land quality degradation and rendering it unusable for irrigation and rehabilitation, necessitating population displacement.Rehabilitating degraded land for greenhouse gas (GHG) emission control and disease regulation is time-intensive, varying across ecosystems (as shown in Table 4). Notably, retrofitting plants with Carbon Capture and Storage (CCS) technology to control coal emissions demands 361 kha of land area, surpassing that required for solar PV plants (~27 kha). While studies extensively discuss the environmental impacts of coal power generation, few focus on the associated land use impacts (Mishra, 2004; Munawer, 2018; Oberschelp et al., 2019; Zhang et al., 2020; Fthenakis& Kim, 2009; Li et al., 2019).

Despite progress in estimating global warming potential, many land effects and obligations indicators remain in the early development stages. As the transition towards more renewable-based systems gains momentum, attention to land-related considerations becomes paramount. Failure to address these issues adequately may introduce unforeseen challenges in the energy transition. Given the expanding population, rising energy needs, and connections to biodiversity, thorough land use analysis assumes critical importance. Examining land footprint draws attention to end-of-generation technologies, waste disposal requirements, and the potential for land reuse, necessitating a comprehensive and balanced strategy to tackle the evolving land use issue.

Table 3. Terms found in the existing literature.

Source	Relevant Terms	Definition
Denholm and Margolis (2008)	Solar electric footprint	Land required for electricity generation from solar PV lifecycle.
Saunders (2020)	Space Impact	The amount of land that a specific project directly occupies.
Ftehnakis and Kim (2009); Rej and Neg (2020); Pimental et al. (2002)	Land transformation	It is transforming a land area from one form of occupation process to another (Forest to roads).
Ftehnakis& Kim (2009)	Land occupation	The period over which a given piece of land returns to its original state.
Cai et al. (2020)	Land use efficiency	It is an increase in a unit land area's output due to social and economic activities.
Burley (1961)	Land cover	It is the installation covering the land surface.
Burley (1961)	Land utilization	It is the employment of land

		surface through the medium of the land cover.
Ong et al. (2013); Gagnon et al. (2002)	Direct land use	It comprises solar arrays, transportation facilities, power stations, and infrastructural facilities.
Ong et al. (2013); Gagnon et al. (2002)	Indirect land use	It includes land required for manufacturing equipment, the establishment of an employee colony, and waste disposal.
Schmidt et al. (2012)	Indirect land use change	It implies the relationship between land demand in one area and deforestation in another.
Lovering et al. (2021)	Footprint land	It is the surface area occupied by a power plant's physical components (natural gas and wind).
Fischer et al. (2008); Green et al. (2005)	Land sparing	Land sparing conserves some land while other parts are used intensively to produce agricultural commodities.
Ristic et al. (2019)	Land use footprint	The total amount of land used to produce a product or generate electricity.
Trainor et al. (2016)	Energy sprawl	Land and water use by energy generation development.
Mead and Willey (2008)	Land equivalent ratio	The ratio of the area required for cropping to the intercropping area provides an equal output at the same management level.
Trainor et al. (2016)	Land use equivalency time	The time required for conventional energy production to cover the same area as renewable energy.
Lovering et al. (2021)	Spacing area	It is the land between physical components at an electricity plant (natural gas and power plant) or fuel extraction area.

Table 4. Estimated land restoration time for various ecosystem types.

Ecosystems	**Time to restore (Yrs)**
Agricultural land	>5
Species-rich forests or Shrubs	50-200
Old growth forests	1000-10000
Species-rich Marshlands, Grasslands	25-50
Species poor Grasslands	5-25
Old dry Grasslands	200-1000

Source: Scholz (2007)

4. Discussion and Conclusion

This review synthesizes numerous findings from previous research on land requirements associated with power generation technologies, aiming to enhance transparency in data utilization and land estimations. The literature shows that each power generation technology exerts distinct impacts, creating a competition between renewables and conventional power technologies.Existing studies underscore the significance of scrutinizing land requirements, revealing that the actual amount of land needed for power-generating technologies is substantially less than the environmental effects they pose. Notably, conventional plants contribute to higher land acquisition and degradation than their renewable counterparts, emphasizing the imperative for transitioning towards renewable energy sources.The rapid expansion of renewable energy systems in recent years has significantly shaped landscapes and environmental dynamics. Although the impact of renewables may seem comparatively minor when juxtaposed with thermal plants, their cumulative effect on the overall environment should not be underestimated. Investigating the long-term adverse implications becomes crucial to developing solutions that ensure the continued sustainability of wind and solar power, safeguarding landscapes, ecosystems, human health, and finite fossil fuel reserves.

While recognizing that selecting energy technologies solely based on land use impact is insufficient for informed policy decisions, it remains a crucial factor. Future studies should extend their considerations beyond land use and degradation, encompassing parameters such as land use intensity, health impacts, and greenhouse gas emissions to provide a holistic perspective on generation technologies and facilitate informed comparisons.The necessity for a fundamental shift in land use and planning to achieve sustainable development goals by 2030 is emphasized. Policymakers must identify regions where conservation attributes are at risk due to the proliferation of renewable energy and where immediate planning interventions are necessary. This holistic approach is essential for steering the nation toward sustainable development.

5. Implications

5.1 Theoretical implications

In terms of conceptual implications, this study adds theoretical improvement to the corpus of knowledge by critically analyzing energy sustainability literature. This study adds to the literature on energy and sustainability by expanding theoretical evidence on the link between energy-producing technology and land utilization to bring energy and sustainability closer. This is an essential addition to the literature because only some studies have covered this dimension of energy generation technologies. Further, this study is critical for low-carbon transitions but has mixed effects on social equity due to unequal socio-spatial patterns.

5.2 Practical implications

Although the future of energy sustainability appears bright, environmental challenges such as land degradation undercut the global sustainability goal and must be addressed by governments. Regulators could use the findings of this study to design guidelines and legislation to assist sustainable energy generation. Policymakers could create enhanced economic, social, and environmental goal-balancing strategies by including the opinions of energy generation technology professionals and stakeholders. As a result, by emphasizing this component, the research might contribute to achieving sustainability.

5.3 Limitations and Future Scope

The study also emphasizes sustainability among individuals, encouraging them to be more environmentally sensitive while meeting their energy demands and contributing to the country's economic success in responsible and sustainable ways. Every study includes limits that pave the way for future research endeavors, including this one. This research is based on theoretical evidence from the literature and is limited to a few energy generation technologies, considering one crucial aspect for an in-depth analysis. Future research could experimentally explore these links between the undertaken aspect and other aspects.

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