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Challenges in meeting all of India's electricity from solar: An energetic approach

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ABSTRACT

India's electricity requirements will continue to grow with its increasing population and urbanization. Climate change, increased carbon emissions, and the depletion of nonrenewable energy resources have forced India to shift to renewable energy resources. India's solar potential is large enough to provide 100-percent of its current electricity requirements if photovoltaic arrays and energy storage infrastructure of sufficient size is deployed. In this paper, we modeled the dynamics of net electricity input and output from a photovoltaic electricity (PV) system as it is built out to provide the entire electricity demand by 2050. The results showed that building a PV system large enough to meet the nation's entire electricity demand by 2050 is possible; however, it will require a rapid increase in the deployment of solar PV and the associated storage infrastructure over the next few decades. Such rapid expansion of the PV system will require substantial electricity allocation away from general societal use and towards building the photovoltaic system equipment and integrating it with existing infrastructure. This will lead to a short-term lack of electricity supply for general use by society.

1. Introduction

1.1. Background

The Indian government is pushing for the adoption of renewable energy technologies to reduce the carbon emissions from electricity generation. Under the Paris Agreement, India committed to having at least 40% of its total installed capacity from renewable resources by 2030 [1]. Subsequently, the share of electricity from renewable resources is projected to increase from 15% in 2016 to 24%, and the carbon intensity of generating a single unit of electricity is expected to be reduced by 29% by 2026–2027 [2]. However, under the existing policy scenario, India's carbon emissions from the electricity sector will only be reduced on a per kWh basis rather than in absolute terms, as shown in Fig. 1. The carbon intensity of electricity generation is expected to decrease from 0.732 kg CO2/kWh in 2015-16 to 0.522 CO2/kWh by 2026-27; however, the total emissions will increase to 1113 million tons from 810 million tons during the same period.

However, more ambitious policy objectives must be adopted to reduce carbon emissions. Limiting the global temperature rise to between 1.5–2 °C will require significant cuts in global carbon emissions by 2050 IPCC, [3,4]. As India is the third-largest carbon emitter [5] and electricity generation accounts for almost 40% of its total carbon emissions [6], decarbonizing electricity generation will be crucial to global climate change mitigation.

1.2. Renewable electricity potential in India

India has vast potential for renewable energy generation, particularly from solar resources. A substantial amount of decarbonization of India's electricity sector must come from electricity derived from solar resources. While India's potential for renewable resources, such as wind, is considerable, it is insufficient to meet the country's electricity demand. India's maximum wind potential is estimated to be 300 GW [7] and wind turbine capacity factors range from 0.13 to 0.19 in states with high wind potential [8]. Assuming an average capacity factor of 0.16, the maximum electricity that can be generated from 300 GW of wind resources will be less than 15% of the projected electricity demand in 2050 [9]. However, India has vast potential for solar resources. Barren and non-arable land accounts for 5% of India's total area, equal to 170,000 km 2 [10]. Assuming that it requires five acres of land to install 1 MW of solar PV [Central Electricity Regulatory Commission (CERC),

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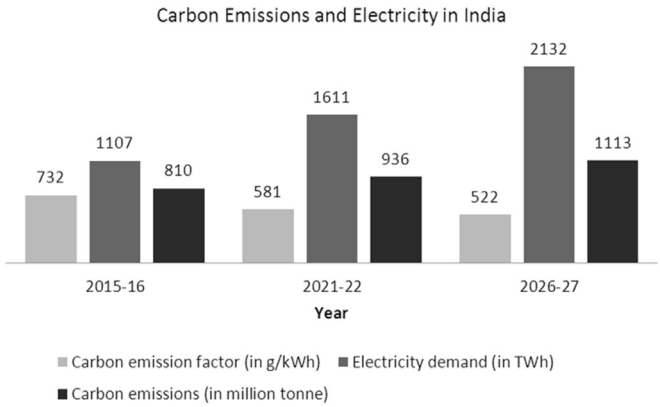

Fig. 1. Current and projected carbon emissions from electricity generation in India [2].

[11]], theoretically, 8500 GW of group-mounted solar PV can be installed using only the barren land. Solar PV can also be complemented with 352 GW of rooftop PV [12]. By using economically and commercially viable solar energy technologies [13,14], India's entire present and future electricity demand can be met through solar PV, as shown in Table 1.

1.3. An overview of challenges in rapid deployment of solar in India

Several authors have reviewed challenges in deployment of solar technology on large scale in India. Moallemi et al. reviewed the historical transitions on the development of on-grid solar and concluded that there is a need for favorable government interventions and political support for meeting 100 GW solar PV target by 2022 [15]. Hairat and Ghosh evaluated techno-economic challenges of adding 100 GW solar power in India by 2022 [18]. Goel indicated that a lack of consumer awareness, effective net-meter policies, skilled-workforce, and innovative business models will make it difficult to meet the policy goal of 40 GW of rooftop solar PV by 2022 [19]. NITI Aayog, a government policy think-tank in India, and Manju and Sagar highlighted higher financial and investment risks and lack of expertise in financial institutions for funding renewable energy projects make it commercially risky to start large scale renewable energy projects in developing countries such as India [7,20]. NITI Aayog also pointed out that lack of demand due to unwillingness of utilities to purchase renewable electricity from generators may slow down rapid deployment of renewable energy including solar PV [7]. In addition to these soft challenges, several reports argue that without the expansion and upgrading of India's transmission and distribution grid, the pace of integration of solar PV is likely to be limited size by the existing grid [19,21]. The temporal scope of these studies was limited to 2022 and these studies focused on overall deployment capacity of 100 GW, far smaller than what is required for decarbonization of the grid.

Decarbonization of electricity sector by 2050 will require deployment of clean energy technologies on a terawatt scale [22–24], which will likely pose additional challenges. These challenges include lack of political-will to transform electricity system [25], high investment costs of solar PV and lack of storage technologies [20], which may make electricity unaffordable, poor grid reliability due to increased share of renewables [26], and possibly shortage of certain materials [27,28].

1.4. Energetic challenge in rapid deployment of solar

Some researchers have pointed out that most challenges discussed in literature ignore physical constraints to terawatt scale deployment of renewable energy technologies and have examined the challenges associated with a large-scale deployment of solar, along with other renewables, through an energetic lens [24,29]. Energetic analyses model energy inputs and outputs through an energy system over the energy system's entire lifespan. A viable energy system should be able to deliver more energy than the energy required in its manufacturing and maintenance over its lifetime [30–32]. If an energy system is a net energy sink, the energy system cannot be a source of energy for society because the system itself requires more energy from external sources than it can provide. Thus, energetic analyses are more insightful for understanding the challenges in transitioning to a different energy system because these approaches use information in physical units [33,34].

Through this type of energy lens, solar energy systems are energetically viable; i.e. these systems generate more energy than the energy required for manufacturing and maintaining them over their useful lifetime. However, a significant portion of the system's energy investment in manufacturing them is front-loaded [35–37] causing the PV system to only become net energy positive in the later part of its life cycle. Depending upon the deployment rate, a national scale solar energy system may require substantial external energy allocation to support its expansion during the initial years before the energy system becomes a net energy surplus [38]. These points have been raised in earlier studies, and the phenomenon is called ‘energy cannibalism’ [29,39–41].

Furthermore, the inherent intermittency of renewable resources makes the large-scale integration of solar into the grid difficult [42]. However, building long and geographically dispersed transmission lines [43], designing an appropriate mix of solar and wind [44], and energy storage [45,46] can potentially overcome technical challenges to certain extent. Moreover, simulation results show that energy storage is absolutely necessary for electricity generation exclusively from intermittent renewable technologies [45]. Thus, the deployment of solar large enough to meet entire electricity demand must be supplemented by a large-scale deployment of storage technologies.

Energy storage technology will also require energy investment and further decrease the solar energy system's net energy surplus [47,48]. Under a rapid-growth scenario, such external energetic support would create short-term energy scarcity for society, making decarbonizing politically and socially challenging. Studies have focused on energetics to assess the feasibility of low-carbon energy technologies; however, to the best of the author's knowledge, no study has quantified the implications energy cannibalism of transitioning to a low-carbon energy system which integrates energy storage. This paper quantifies these

Table 1
Solar PV-based electricity potential in India.

Technology	Electricity demand (TWh)[a]	Capacity factor	Required PV capacity to meet electricity demand (in GW)[c]	Available capacity (in GW)[d]
Electricity demand in 2015–16	1100	0.18[b]	700	8850
Projected electricity demand in 2050	4000		2540	

[a] Based on information and projections in [2,9].
[b] There is enormous geographical diversity in distribution of the solar potential in India [15,16]; Average values were assumed to be representative of all India. The capacity factor was found to vary between 0.16 and 0.20 for most locations in India [17], and it was assumed to be equal to the average (0.18) for this study.
[c] Demand/(capacity factor*8760).
[d] Total 8500 GW ground-based PV on barren land and 350 GW rooftop PV.

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