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Renewable Energy and Land Use in India by Mid-Century

Careful Planning Today Can Maximise the Benefits and Minimise the Costs of India's History-Making Energy Transition

Executive Summary

Whether or not India commits to a formal mid-century net-zero emissions goal this year, it will continue adding very substantial solar and wind generation capacity over the next three decades. Part of this capacity will replace thermal generation, but some will be required to meet population and economic growth.

This report considers the land-use implications of India's unfolding energy transition and the important choices about where these resources should be located. It reviews current land-use studies and then outlines likely future requirements based on the mid-century scenarios presented in recent reports, including those published by the Council on Energy, Environment and Water (CEEW),[1] The Energy and Resources Institute (TERI) and Shell,[2] and the International Energy Agency (IEA).[3]

Analysis of these reports shows that some have exaggerated land-use requirements while other projections under-estimate them. Uncertainties in future electricity demand accounts for most of the variation in estimated land use.

A precautionary, high-side land use estimate for net zero in 2050 is between 50,000 and 75,000 km² for solar, and for wind 15,000-20,000 km² (total project area) or 1,500-2,000 km² (direct impact).

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The quantity of land required for different types of power generation is arguably of much less importance than what impacts they have. The widespread solar resource

[1] Chaturvedi V. Peaking and Net-Zero for India's Energy Sector CO2 Emissions An Analytical Exposition. Council on Energy, Environment and Water. March 2021.
[2] TERI and Shell. INDIA: Transforming to a Net-Zero Emissions Energy System. 2021.
[3] IEA. India Energy Outlook 2021. February 2021.

in particular gives India the opportunity to locate solar generation in a widely distributed pattern, and base decisions about location on multiple economic, social and environmental criteria. By contrast, coal can only be mined where it exists, and any new coal would be heavily concentrated in some of India's most important forests such as the Hasdeo Arand. Properly managed renewable generation can co-exist with other land uses, and, unlike coal-based power, it does not fundamentally change land during use or following its ultimate de-commissioning.

The quantity of land required for different types of power generation is arguably of much less importance than what impacts they have.

While a net-zero India in 2050 is likely to require less land for renewable generation than some estimates have suggested, the total land area is nevertheless still large and such a major transition should not proceed without policies to optimise land use. Recommendations are presented in three categories and can be summarised as:

1. **Minimising total land use requirements for renewable energy.**

   Measures include the promotion of offshore wind, rooftop solar, and solar on (mostly artificial) water bodies where net environmental benefits can be assured.

2. **Optimising the identification and assessment of land for renewable generation.**

   Measures include developing clear environmental and social criteria for rating potential sites; comprehensive assessments and ranking of potential sites against these criteria in advance and independent of tenders or project proposals; incentivising the selection of the highest ranked locations in tenders; limiting undue regional concentration and supporting widely distributed renewable generation at a range of scales.

3. **Increasing the stock of potentially suitable land for renewable generation.**

   Protection of farmland is essential, but nurturing an Indian agrivoltaics sector could secure benefits to farmers and reduce pressure on other types of land. Measures include supporting a major expansion of agrivoltaics research and incentivising agrivoltaics uptake where crops, soils and conditions are suitable and yields can be maintained or improved.

Introduction

A recurrent issue raised in discussions of renewable energy is land use – the amount of land occupied by solar and wind generation facilities, where these are located, and the extent to which using such land for power generation conflicts with alternatives such as human habitation, farming, or the conservation of natural resources.

The question of renewable energy's land use is far from new. As early as 1979 it was explicitly outlined as a potential problem in a report for the U.S. Department of Energy,[4] and it has subsequently emerged as an issue in several countries, leading, for example, to the Netherlands introducing restrictions on large-scale solar parks in 2019 because of concerns over competition with agriculture.[5] In the Asian region it has been debated in Indonesia,[6] and in Japan several aspects of land use for power emerged as concerns in a recent survey of local governments.[7]

It is the broad public debate over net-zero emissions targets for mid-century, however, that has reignited land use as a significant question. With net-zero targets pledged by many countries and under consideration by others, it is forcing an evaluation of the energy landscape, literally as well as figuratively, 30 years hence.

A critical case is that of the United States. Following an earlier report that U.S land changes were being driven primarily by trends in energy production,[8] a landmark Princeton University study, 'Net-Zero America',[9] explored multiple energy scenarios and presented detailed data and maps depicting their land use implications.

In contrast to the 330,000 km^2 currently used to generate the nation's power, it reported that the most land-intensive plan would quadruple that required land area to be approximately equivalent to the whole of the state of Iowa. This has sparked debate about the degree to which land use may constrain the clean energy transition, reported by, amongst others, the New York Times,[10] Bloomberg,[11] and globally, The Economist.[12]

[4] Neff, TL. Social cost factors and the development of photovoltaic energy. Report MIT-EL79-026, MIT Energy Laboratory, 1979.
[5] PV Magazine. Netherlands introduces soft restrictions for solar parks on agricultural land. 29 May 2019.
[6] Kennedy S, The Conversation. Research: land use challenges for Indonesia's transition to renewable energy. 3 July 2020.
[7] Akita N. et al. Managing Conflicts with Local Communities over the Introduction of Renewable Energy: The Solar-Rush Experience in Japan. Land, 9, 290, 2020.
[8] Trainor, AM et al. Energy Sprawl Is the Largest Driver of Land Use Change in United States. PLOS ONE. 8 September 2016.
[9] Larson, E et al. Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report. Princeton University. 5 December 2020.
[10] New York Times. Where Wind and Solar Power Need to Grow for America to Meet Its Goals. 28 May 2021.
[11] Bloomberg Green. The U.S. Will Need a Lot of Land for a Zero-Carbon Economy. 29 April 2021 (updated 4 June 2021).
[12] The Economist. Missing ingredients: The bottlenecks which could constrain emission cuts. 12 June 2021.

India's Energy-Related Land Use Outlook Has Unique Features

India has unique characteristics that call for a better understanding of land-use requirements. Some areas of very high population density, as yet incomplete electrification, low levels of electricity consumption and climatic differences are some of those features.

For the purposes of any mid-century estimates, increased demand from economic and population growth are stand-out features which distinguish the India land use outlook from those for Europe and North America. This was highlighted in a media release from the CEEW suggesting that renewable energy for net zero by 2050 would require a 55-fold increase in India's renewable electricity generation,[13] implying a substantial increase in land requirements.

Environmental and Social Aspects of Renewable Energy Land-Use Decisions

Electricity generation must compete with possible alternative uses for land, especially food production, ecological conservation and human habitation, including increased urbanisation. Avoidance of productive agricultural land appears to be a broadly accepted principle, although solar parks such as the giant Pavagarda facility have been credited with providing local farmers with an income stream.[14] The initial roll-out of solar generation has tended to favour less fertile regions with a high solar resource. Gulagi and colleagues, for example, wrote that "*solar PV is expected to be mainly placed in zero impact areas… such as rooftops, landfills, contaminated industrial and mining sites and further barren land*."[15]

The terms "zero impact areas", "barren land", "unused land" or the official designation of "wasteland" imply that such areas have no value. This has been strongly contested both by groups who claim ownership of or rights to use such land, as in the case of the Charanka solar park in Gujarat[16] or of farmers in Assam opposing a solar installation,[17] as well as by advocates for environmental conservation who point out that supposed 'wasteland' areas may actually be fragile and home to unique ecosystems.[18]

The potential for renewable energy installations to conflict with conservation values even in sparsely populated areas has been highlighted by a recent decision of the

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[13] Council on Energy, Environment and Water. Renewables in Electricity Must Increase 55-fold for India to Achieve net-Zero Emissions by 2050: CEEW (press release). 22 March 2021.
[14] Renew Economy. A 2GW solar farm – for farmers: India launches "world's largest" solar park. 6 March 2018.
[15] Gulagi A, et al. Electricity system based on 100% renewable energy for India and SAARC. PLOS ONE 12(7): e0180611, 2017.
[16] Yenneti, K. et al. Spatial justice and the land politics of renewables: Dispossessing vulnerable communities through solar energy mega-projects. Geoforum 76, 90-99, 2016.
[17] The Wire. In Assam, a 'Green' Energy Plant Is Bulldozing Claims of Small and Marginal Farmers. 3 January 2021.
[18] The Hindu. Wasteland conversion threatens livelihoods, ecological balance. 17 November 2019.

Supreme Court. The Court has called for transmission lines evacuating solar energy in Rajasthan to be laid underground, in response to claims that overhead transmission lines may further threaten the small remaining population of the iconic Great Indian Bustard,[19] a decision that is being appealed by the proponents.

Madhusudan and Vanak have recently pointed to the significance of such lands, which include deserts, rock and boulder fields, grasslands and savannas,[20] which they label 'Open Natural Ecosystems'. They observe that their ecological value is frequently under-rated, as is their capacity to sustain hundreds of millions of people and to provide about half the fodder for India's 500 million livestock. They specifically note the threat from large-scale solar parks, and the high resolution on-line mapping resource they have developed[21] shows, for example, part of Rajasthan's Bhadla Solar Park occupying land which they classify as an Open Natural Ecosystem.

Supposed 'wasteland' areas may actually be fragile and home to unique ecosystems.

As renewable generation grows, these social and environmental considerations are likely to become more prominent, especially as there has been a steady decline in common land.[22] Choosing locations that optimise benefits and avoid such costs as much as possible requires some consensus to be developed about the likely future land requirements of renewable energy.

This report first considers currently available studies that have attempted to estimate land use needs directly, and then outlines indirect estimates that follow from several independent electricity demand scenarios for 2050.

To provide context, these mid-century land requirements (predominantly or entirely met by renewable energy, depending on the scenario) are compared to the impacts of continued use of coal for power generation, in qualitative as well as quantitative terms.

Finally, three groups of recommendations on approaches to optimise land-use for renewable generation are presented.

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[19] Business Standard. A giant poor-sighted bird stands in the way of India's green energy goals. 15 June 2021.
[20] Madhusudan, MD, Vanak, A. Mapping the distribution and extent of India's semi-arid open natural ecosystems. Earth and Space Science Open Archive, 25 July 2021.
[21] Madhusudan, MD, Vanak, A. Mapping India's Open Natural Ecosystems (ONE)(Google Earth Engine Apps), 2021.
[22] Malghan, D, Mukherji A, Thapliyal S. Declining common lands in India: Role of economic inequality. Ideas for India. 14 January 2021.

How Much Land will Renewable Energy Occupy by 2050?

Direct Land-Use Studies

Estimating how much land will be needed for renewable energy generation three decades from now necessitates combining information from the small number of specific land-use studies with various outlooks for the country's future generation requirements.

Although there are many reports of India's renewable resource potential (e.g.[23]), only a few have included specific estimates of land-use requirements. These are summarised in Table 1.

Table 1: Direct Estimates of Land Use for Renewable Generation

Study	RE Types	Land Use (km^2)	Nominal Forecast Year
Mitavachan et al.[24]	Solar, Wind, CSP	28,840	2070
Kiesecker et al.[25]	Solar, Wind	55,000-125,000	2022
Van der Ven et al.[26] (78% solar penetration)	Solar	30,000-41,000[a]	2050

[a] *Excludes desert and dry scrubland for which 11.5-12% of solar capacity expected.*

There are several important caveats to these widely varying estimates that prevent them being taken at face value.

Mitavachan and Srinivasan's study was published at a very early stage of India's renewable energy roll-out (2012) when there was only limited on-ground evidence about land use. It used an assumption of two hectares per MW of solar capacity, an arbitrary allowance for efficiency improvements over the four hectares per MW assumed by the study on which it was based.[27]

Its outlook for 2070's generation requirement of 3,400 TWh was also borrowed directly from the earlier study. In turn, this applied an allowance of 2,000 kWh per person, a goal that the earlier author described as "*frugal*" and chosen on the grounds that "*it would be wise for the nation as a whole to plan for a simple lifestyle*". Because the ensuing land-use estimate of 28,000 km^2 is not based on any forecast of

[23] Mahtta, R. et al. Solar power potential mapping in India using remote sensing inputs and environmental parameters. Renewable Energy, 71, 255-262, 2014.
[24] Mitavachan H et al. Is land really a constraint for the utilization of solar energy in India? Current Science 103, 2,: 163-168. 25 July 2012.
[25] Kiesecker J et al. Renewable Energy and Land Use in India: A Vision to Facilitate Sustainable Development. Sustainability. 12, 1: 1-14, 30 December 2019.
[26] van de Ven D-J et al. The potential land requirements and related land use change emissions of solar energy. Scientific Reports. 11:2907, 3 February 2021.
[27] Sukhatme, S.P. Meeting India's future needs of electricity through renewable energy sources. Current Science. 101, 5: 624-630. 10 September 2011.

actual demand and uses an arbitrary forecast year, it should not be given undue weight. Demand growth in the decade following publication suggests that this outlook, and therefore the estimated land area, is unrealistically low.

By contrast, the land-use estimates from the Kiesecker et al. study are argued to be far too high, as was noted (but not fully accounted for) by Chakravarty and Somanathan.[28] The study was primarily a detailed presentation of the potential land available for renewable energy (RE), options for its location by state, and possible impacts on forest and agricultural land under different scenarios. Its estimates of the land use needed to meet the stated 175GW target for 2022 (shown in Table 1) follow from this analysis as a secondary step.

These figures appear to have been seriously over-estimated, by a multiple of about 4 or 5. Given that the range of 55,00-125,000 km^2 has already been cited as an example of "*socio-environmental impacts and risks of utility-scale solar*" in an influential report,[29] it is important to substantiate this claim of over-estimation in some detail. This is provided separately in an End-Note, and for the reasons outlined there, adjusted estimates for the 2022 target of 100 GW of solar (using the same assumption that the remaining roll-out is all ground-mounted) are closer to 3,600 km^2 for solar and 30,000 km^2 for wind, for a total upper limit value of 33,600 km^2 for the combined 175GW target, instead of the stated 125,00 km^2.

In addition, the study's large area for wind reflects the use of total project area, rather than land area directly impacted by pads, sub-stations, roads and buildings. This is entirely valid when identifying possible locations, given minimum spacing requirements for turbines, but if the land area estimate is used to consider co-location of wind with appropriate types of agriculture, for example, it greatly over-states the impact. The direct land impact would be closer to 3,000 km^2, based on an assumption of 50 MW/km^2, in line with other published reports.

The final study, by van de Ven et al., compares the 2050 land-use outlook for Europe, India and a combination of Japan and South Korea and considers only solar generation. Three different levels of solar penetration (30-78%) were modelled through to mid-century. Table 1 shows just the highest of these as it comes closest to a net-zero scenario. The estimates are based on well-specified methods and assumptions, although they appear to use relatively high expectations for generation per unit of land (6.4-8.8 km^2 per TWh), based on expected technical improvements in the 2020-2050 period, and they anticipate 11.5–12% of solar energy to be generated on deserts and dry scrubland that is not included in the estimates shown in Table 1.

[28] Financial Express. Is land a constraint for Modi govt's ambitious expansion programme for renewables? 31 January 2020.
[29] WRI India, TERI, Forum for the Future, Landesa, WWF. Renewable energy to responsible energy: A call to action. March 2021.

Mid-Century Land Use from Capacity Projections

In Table 2 a set of electricity outlooks for 2050 are used as the basis for estimating land requirements from potential installed capacity. Solar and wind generation and capacity values for 2050 are either directly presented in each report or are extrapolated from data for periods ending in 2030 or 2040.

Land requirements are estimated as a range. For solar, the higher value applies a ratio of 25 km^2/GW to the capacity estimate, based on the average for India's three largest existing solar parks (Bhadla in Rajasthan, Pavagada in Karnataka, and Kurnool in Andhra Pradesh), and the lower value allows for a 30% decrease in the land/capacity ratio, to account for efficiency improvements in coming decades.

For wind, direct land use is estimated rather than total project area, as their purpose is not to inform the choice of possible areas but to illustrate the extent of potentially conflicting land use. A value of 3 km^2/GW from a report by the U.S. National Renewable Energy Laboratory (NREL)[30] provides the higher estimate, with the lower number also illustrating the effects of a 30% improvement in efficiency. Based on average values reported by NREL, multiplying these numbers by ten provides an estimate of total project area.

Although there are many reports of India's renewable resource potential, only a few have included specific estimates of land-use requirements.

The wide range of land-use values in Table 2 is attributable mostly to the large differences in electricity generation estimated for 2050, but the share of renewable energy by that date, the split between wind and solar, and the assumptions about issues such as the density of solar panels also influence the land-use estimates.

The lowest values are from the Central Electricity Authority (CEA) Optimal Generation Capacity Mix report. This did not extend beyond 2030, and the extrapolation from that date under-estimates new solar capacity because it causes all capacity to increase between 2030 and 2050, including coal, a highly unlikely scenario. Even if coal only plateaued in 2030, an additional 300GW of capacity would likely be added to solar, increasing its low land-use estimates. If coal were scaled back after 2030 as part of any net-zero goal, the land-use range would be closer to those provided for the three IEA scenarios in Table 2.

[30] Denholm, P; Hand, M; Jackson, M; Ong, S. Land Use Requirements of Modern Wind Power Plants in the United States. U.S. Department of Energy NREL/TP-6A2-45834. August 2009.

Table 2: Estimates of Land Use for 2050

Report	2050 Generation (TWh)			2050 Capacity (GW)		2050 Land Use (km²)	
	Total	Solar	Wind	Solar	Wind	Solar	Wind (Direct)
CEA[31] [a]	5,072	1,265	726	732	329	14,054-18,300	757-987
IEA STEPS[32] [b]	4,968	1,745	722	1,033	298	19,384-25,825	685-894
IEA SDS	4,551	1,996	1,119	1,176	476	22,579-29,400	1,095-1,428
IEA IVC	5,467	1,895	951	1,135	393	21,792-28,375	904-1,179
Gulagi[33] [c]	7,212	4,441	501	2,220	200	42,624-55,500	460-600
TERI/Shell[34] [d]	10,934	3,909	3,930	2,300	1,680	44,163-57,504	3,865-5,041
CEEW[35] [36] [e]	10,602	6,336	2,464	3,728	1,053	71,580-93,204	2,423-3,160

[a] *2050 generation and capacity extrapolated from 2019, 2022, and 2030 (Tables 1,2,5, Exhibit 9)*
[b] *2 STEPS: Stated Policy Scenario, SDS: Sustainable Development Scenario, IVC: India Vision Case. 2050 generation and capacity extrapolated from 2019, 2030, and 2040 (Table 3.2)*
[c] *2050 generation and capacity from Figs. 6 and 7. (Solar: PV single axis + tilted; Wind: onshore only)*
[d] *2050 generation from TERI/Shell's Fig. 5, capacity values estimated using 19.4% and 26.7% Capacity Utilization factors (CUFs) from IEA India data.*
[e] *2050 generation and capacity values estimated from stated 55-fold increase in renewable generation from 2019, and 83% generation from non-hydro renewable sources and same CUFs as in* [d]

The greatest land-use values follow from the CEEW outlook, which incorporates the highest outlook for electricity generation of all the reports, and has a high renewable energy penetration of 83%.

Land use implied by the TERI/Shell outlook is distinguished by the relatively large expectation for wind generation in comparison with the other reports, as well as by the high expectation for total electricity generation.

Overall, Table 2 shows that the direct impact of wind generation is very much lower than for solar (averaging about 4.4% of solar land use), and these estimates are far more variable, mostly because of widely differing assumptions about wind's future share of generation. Even when the much larger total project area is considered, at an average of between 14,500 and 19,000 km^2, it is less than half the quantity of solar land, and about one-third if the Teri/Shell outlook, with its exceptionally high wind outlook, is excluded.

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[31] Government of India, Ministry of Power, Central Electricity Authority. Report on Optimal Generation Capacity Mix for 2029-30. January 2020.
[32] IEA. India Energy Outlook 2021. February 2021.
[33] Gulagi A et al. The Demand For Storage Technologies In Energy Transition Pathways Towards 100% Renewable Energy For India. Energy Procedia 135, 37-50. October 2017.
[34] TERI and Shell. INDIA: Transforming to a Net-Zero Emissions Energy System. 2021.
[35] Chaturvedi V. Peaking and Net-Zero for India's Energy Sector CO2 Emissions An Analytical Exposition. Council on Energy, Environment and Water. March 2021.
[36] Council on Energy, Environment and Water. Renewables in Electricity Must Increase 55-fold for India to Achieve net-Zero Emissions by 2050: CEEW (press release). 22 March 2021.

One recent study[37] has identified 29,457 km^2 as "highly suitable for wind farms", which could accommodate this level of wind penetration.

Another consideration for wind is that it can often be co-located with agriculture on cultivatable land, as is the case for 70% of wind farms in Tamil Nadu,[38] for example, which, along with the potential for future offshore wind development suggests that demand for solar land will be a much more significant issue.

Reconciling Direct Land Use Studies and Estimates from Installed Capacity Outlooks

There can be no uniform approach to choosing from a range of different estimates, especially if they are highly variable, use different data sources and are based on different assumptions.

However, planning for such a large and important roll-out of critical infrastructure that may be in place for decades demands that policy-makers have a plausible notion of possible land requirements at the outset. This could inform the adoption of strategies to prevent unnecessary land-use conflicts as much higher generation capacity is rolled out in future. A precise estimate today is neither possible nor necessary, and all such estimates will improve as data and experience accumulate over the next 30 years.

Such a large and important roll-out of critical infrastructure that may be in place for decades demands that policy-makers have a plausible notion of possible land requirements at the outset.

In that context, it is helpful that there is some convergence of the direct land use study estimates (Table 1) and those from possible installed capacity (Table 2), which point to an approximate range that could be used as a guide. Some of the estimates have already been noted as being unrealistically low or high, so the focus is on those which do not have apparent shortcomings in terms of assumptions or methods.

From Table 1, van de Ven's 30,000-41,000 km^2 range, for solar only, appears the most credible. It specifically estimates a value for 2050, and is based on well-explained and justified methods. It is not strictly a net zero estimate as it is based on an expectation of 78% penetration of solar generation, given factors such as the longevity of other sources that already exist, and it does not count the expected

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37 Saraswat K. et al. MCDM and GIS based modelling technique for assessment of solar and wind farm locations in India. Renewable Energy, 169, 865-884, May 2021.

38 Mercom India. India's Cultivable Land Has Wind Generation Potential of 347 GW: Report. 27 February 2020.

11.5-12% of generation on deserts and dry scrubland. These should be included, because they may still represent important Open Natural Ecosystems, as discussed earlier. Approximate adjustments for both factors (dividing the values by .78 to approximate 100% penetration, and adding in the desert and scrubland generation gives a range of about 49,000-67,000 km^2.

This range is in line with the indirect estimates in Table 2 based on the outlooks from Gulagi and TERI/Shell, which have mid-points of about 50,000 km^2. In order to apply the 'precautionary principle' and allow for the possibility of higher electricity use than is actually likely (given the history of over-optimistic demand outlooks), erring on the higher side of these estimates is reasonable for planning and policy development. Therefore it is suggested that a range of 50,000 to 75,000 km^2 for solar, with wind using an additional 15,000-20,000 km^2 for total project area (or 1,500-2,000 km^2 for direct impact), be considered.

Comparisons with Land Use for Coal

It is instructive to compare these land-use estimates with those for alternative forms of generation. While nuclear, hydro and other sources will continue to be part of India's generation mix, the fundamental choice is between renewables (principally solar) and coal. As demand grows, it could in principle be met by additional coal or more renewables, and their relative trajectories will largely determine how land for energy is deployed in India.

Statistics on overall land use by coal in India (mines, transport, power plants) are not readily available, and recent studies focus on specific sectors such as individual mines (e.g. Jharsuguda)[39] and coastal coal infrastructure[40] rather than the whole mining sector.

Land-use reports from other countries generally show that solar is substantially more land-intensive than coal,[41] but many of these comparisons do not include the full fuel life-cycle, which should account for all land use from mines through coal's share of transport corridors to power plants, as well as land used for disposal of fly-ash.

In addition, while there is no further change in land use once a renewable generation plant is in operation, a coal-fired plant requires continued mining (and therefore additional land use) throughout its life. For the U.S, Fthenakis and Kim calculated that the 1 million acres of land being prepared for coal mining, in use, or under reclamation for electricity generation could produce 40% more power if used for solar, leading them to conclude that "*PV [photovoltaic – solar] uses land more*

[39] Ranjan A et al. Quantitative assessment of landscape transformation due to coal mining activity using earth observation satellite data in Jharsuguda coal mining region, Odisha, India. Environment, Development and Sustainability, 23, 4484–4499. 24 May 2021.
[40] Oskarsson, P et al. India's new coal geography: Coastal transformations, imported fuel and state-business collaboration in the transition to more fossil fuel energy. Energy Research & Social Science. 73, 101903. March 2021.
[41] van Zalk, J. et al. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. Energy Policy, 123, 83-91. December 2018.

efficiently than coal to generate electricity".[42] In India the relatively low calorific value of thermal coal would likely mean that more land is used than in the U.S per unit of electricity generation. But even if coal occupies less land, comparing only the surface area provides a very incomplete portrayal of land use.

When wind turbines or solar panels are installed, they do not fundamentally transform land in the way that large open-cut mines such as Korba, Gevra and Dipka do, nor do they produce the large quantities of waste that occupies coal plants' fly-ash ponds and during floods or because of inadequate containment, periodically contaminates neighbouring land and waterways.

More importantly, renewable generation is viable in many parts of the country, and India is in a position to decide, using its preferred combination of economic, environmental and social criteria, where it should be located.

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If the equivalent additional power were to come from coal, then it would be constrained to further expand existing mines in districts such as Korba, or exploit new coal blocks that are concentrated in forest land with high biodiversity and conservation values, such as the Hasdeo Arand,[43] where displacement of Adivasi peoples is an additional concern. When the land use consequences of renewables and coal are fairly compared, solar may potentially occupy a larger surface area, but its impact on that land is much smaller, easily reversed after de-commissioning, and its location can be decided as a matter of public policy rather than being determined by geography.

A final consideration in contrasting a principally renewable as opposed to coal-fired energy pathway is that not only are their choices about the location of renewable power, there is the capacity to choose how concentrated or distributed those locations should be.

Even though thermal power stations are found across India, their fuel supply is heavily concentrated in the eastern coalfields, and their transport networks are fixed. By contrast, India can elect to build a highly distributed network of renewable generation facilities of varying size, placing many close to load centres and existing transmission infrastructure. This would limit the requirement for new power lines

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[42] Fthenakis, V. and Kim, V. Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews. 13, 1465–1474, 2009.
[43] Hindustan Times. Coal mine auction opens up vast stretches of forests in central India for mining, show documents. 18 June 2020.

and sub-stations, which also occupy land, as well as potentially reducing overall system costs.

Recommendations

This analysis shows that even with a mid-century net-zero target, India has sufficient land available for all of its renewable energy generation requirements. Nevertheless, the amount of land needed is still substantial, ranging from 1.7% to 2.5% of the country's surface area for solar if the 50,000-75,000 km^2 suggested for the purposes of planning is used, and a much smaller direct impact from wind.

To safeguard India's ecologically important regions, prevent or minimise conflict over social impacts, and maintain agricultural productivity, it is imperative that Union and State governments develop a policy and planning framework that optimises decisions about land use for renewable energy in coming decades, rather than by proceeding with such decisions on an ad-hoc basis. Recommendations to assist the development of such an approach fall into three categories.

1) Minimise total land use requirements for renewable energy by:

- Supporting the development of offshore wind, as envisaged, for example, in the identification of 71GW offshore wind capacity in eight zones off Gujarat and Tamil Nadu.[44]

- Maximising the uptake of rooftop solar, especially commercial and industrial premises. The current 7GW of rooftop capacity[45] falls well short of even the current 40GW goal. Enhancing this uptake will require resolving issues such as the appropriateness of net-metering costs, and mechanisms to ensure that benefits to residential consumers do not accrue unfairly across different social sectors.

- Making use of appropriate water bodies for solar. India has already experimented with panels above irrigation canals, but identifying water bodies where the appropriate coverage with floating solar produces net benefits (e.g. reducing evaporation, preventing algal blooms)[46] outweigh any potential harms (e.g. reduced oxygenation, lower photosynthesis, leaching).[47] [48] Artificial water bodies where water quality is often sub-optimal should be the focus.

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[44] Ministry of New and Renewable Energy. Offshore Wind. Accessed 12 August 2021.
[45] PV Magazine. India closing in on 7 GW of rooftop solar. 12 April 2021.
[46] Kumar M, Kumar A. Experimental characterization of the performance of different photovoltaic technologies on water bodies. Progress in Photovoltaics. 5 November 2019.
[47] Matthijssen D et al. Potential impact of floating solar panels on water quality in reservoirs; pathogens and leaching. Water Practice and Technology. 15, 807–811. 2020.
[48] Mongabay. Solar projects on water could come at a cost to the environment, alert experts. 12 March 2021.

2) Optimise the identification of land for renewable generation by:

- Developing clear environmental and social criteria for rating the suitability of potential renewable generation locations.
- Undertaking comprehensive, independent assessments of all potential locations against these criteria before any specific projects or tenders are considered. Ideally, states would develop publicly available land inventories listing the renewable resource potential as well as these assessment scores.
- Incentivising the use of the highest ranked locations (those of least environmental and social concern) in the development of tenders, through the adoption of appropriate bidding rules and procedures. For example, eligibility to bid could include a bidder's meeting minimum "fleet-wide" land-use scores.
- Limiting undue concentration of generation in single regions and incentivising widely distributed generation at different scales.

3) Increase the stock of potentially suitable land for renewable generation by:

Nurturing an Indian agrivoltaics sector. Farmland makes up 60.4% of India's total surface area (2018 data),[49] a far higher proportion than most countries. Various configurations of solar panels above crops can, in the right conditions, see maintained or increased yields, and reduce soil moisture loss, but India has only about 20 small-scale projects in progress.[50] A major research effort to establish optimal conditions and lay-outs for India's various regions, climates and crops, and the right incentives, could see agriculture host a much larger proportion of renewable generation and add income streams in the rural economy, while alleviating pressure on other land.

End-Note

This end-note outlines the rationale for assessing the 55,000-125,000 km^2 land requirement estimate for India's 2022 175 GW target by Kiesecker et al.[51] as being unrealistically high. As shown from the paper's Supplementary Information Table S2, the lower figure for renewable land use (55,000 km^2) is for the remaining RE from 2017, about 100GW (175GW target – ~60GW installed by 2017 – ~15GW of other RE). The higher value from the study (125,000 km^2) is for the full 160GW of wind and solar, assuming all remaining solar capacity is ground-mounted. Both are disaggregated into solar and wind components in the paper's Supplementary Information (Table S2).

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[49] World Bank. Agricultural land data. Accessed 12 August 2021.

[50] NSEFI. Agrivoltaics in India: Overview of operational Projects and relevant Policies. January 2021.

[51] Kiesecker J et al. Renewable Energy and Land Use in India: A Vision to Facilitate Sustainable Development. Sustainability. 12, 1: 1-14, 30 December 2019

When the solar and wind components from Table S2 ("Full goals") are considered separately, their stated land areas (18,271 km^2 for ground-mounted solar, and 105,782 km^2 for wind) correspond to capacity/land ratios of only 5.34MW/km^2 and 0.57MW/km^2 respectively – many times lower than the respective 26MW/km^2 and 2MW/km^2 stated in the methods section, or the 40MW/km^2 already achieved by existing solar parks in India, or, for wind, the 3MW/km^2 for total project area reported by NREL[52]

It appears that the land area calculations may have used figures for expected 2022 solar and wind generation from Table S1 that omitted consideration of their capacity utilisation factors (CUFs) (about 19.4% and 26.7% respectively from IEA data, though wind CUF has fallen significantly since 2019). Table S1 suggests solar and wind generation in 2022 would total 1,408TWh – more than India currently generates from all sources and unrealistically high, but a value that could follow if generation values were estimated from total capacity without taking CUFs into account.

The descriptions of these calculations in Tables S1 and S2 also suggest that the CUFs may have been overlooked*: "Goals were converted from MW to GWh by multiplying by 8760 hours per year and dividing by 1000 (MW/GW)"* and the resulting generation (and thus land area) estimates therefore exceed realistic values by amounts that correspond very closely to those factors (x4.9 for solar, x3.5 for wind).

It should be stated that this analysis was a secondary part of what is otherwise an extremely thorough and detailed study which presents a valid and important discussion of land-use issues.

[52] Denholm, P; Hand, M; Jackson, M; Ong, S. Land Use Requirements of Modern Wind Power Plants in the United States. U.S. Department of Energy NREL/TP-6A2-45834.
August 2009.

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