Is land really a constraint for the utilization of solar energy in India?

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This article compares the land use in solar energy technologies with conventional energy sources. This has been done by introducing two parameters called land transformation and land occupation. It has been shown that the land area transformed by solar energy power generation is small compared to hydroelectric power generation, and is comparable with coal and nuclear energy power generation when life-cycle transformations are considered. We estimate that 0.97% of total land area or 3.1% of the total uncultivable land area of India would be required to generate 3400 TWh/yr from solar energy power systems in conjunction with other renewable energy sources.

Keywords: Land occupation, land transformation, land use, photovoltaic, renewable energy, solar energy.

IN a recent article, Sukhatme[1] has assessed the potential of different renewable energy sources in India. While assessing the potential of solar energy, he has stated, 'However, it is fairly clear that the real issue is not the availability of solar radiation as much as the availability of open land. This is going to be the real constraint limiting the use of these sources.' In this article, we argue that solar energy differs from other energy sources in terms of land use. We first compare the land-use pattern of three primary energy sources: coal, nuclear and hydro with solar energy. Then, we calculate the percentage of India's land area that would be required to meet the future projected energy demand, based on the present solar energy technology. Finally, an attempt has been made to answer the question: will availability of land become a limiting constraint for solar energy to become a major player in India's future electricity power generation mix? We have not considered roof-top PV systems in this study as this issue has been addressed recently by Chokshi[2].

Technically, the land-use type of any energy technology can be accounted for by two terms – land transformation and land occupation. *Land transformation* is the overall land footprint of the technology across its lifetime which includes, but is not limited to, directly transformed land area for setting up the power plant, mining fuel, fuel transportation, waste disposal and provision of space around the plant. In addition, it also accounts for indirect land transformations the land area that goes into upstream processes and secondary land disturbances, i.e. land degradation due to pollutants and effluents from the fuel and material cycles. In our analysis, we have considered only the direct land transformations. We have used the parameters 'm^2/MW' and 'm^2/GWh' to compare the land transformations associated with different energy sources. The parameter 'm^2/MW' accounts for land area required to set up a typical power plant for each of the energy sources considered; it is the ratio of the area occupied by a typical power plant to its capacity of generation (nominal capacity). The parameter 'm^2/GWh' accounts for life-cycle land transformations, which include the area that goes into setting up a power plant, fuel mining (coal and nuclear), transportation (coal only) and waste disposal (nuclear only) across the lifetime of the power plant; it is the ratio of life-cycle land area transformed by a typical power plant to its lifetime energy generation. *Land occupation* is a measure about how a certain energy source affects the land qualitatively. An approximate calculation for the land transformation and occupation associated with each of the energy sources is discussed in the following sections.

Land transformation

Coal

A typical coal power plant requires 2023 m^2 of land area per MW for plant installation[3]. Coal power plants not only transform land around the power plant, but they also require land for mining coal and transportation of the extracted fuel from the mines to the plant location. Table 1 gives the break-up of land area transformed by a typical coal power plant in USA. We have used the same values in our study as no data are available for India. Apart from these direct land requirements, coal plants also transform and affect the land indirectly; for example, operating coal mines and building infrastructure require additional land during the upstream processes. In addition, there are secondary land disturbances, such as

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Table 1. Break-up of land area transformed by a typical coal power plant in USA[3]

Category	Area (m^2/GWh)	Area (m^2/MW)	Included	Not included
Mining				
Surface	400		Only direct land usage	Indirect land use
Underground	200			Secondary land disturbances
Power plant operation	9.1	2023		Area that goes into waste storage
Rail transportation attributed to coal	30–80			

Table 2. Land area transformed by a typical nuclear power plant

Category	Area (m^2/GWh)	Area (m^2/MW)	Reference
Mining uranium	30		3
	15		4
Power plant		1180–4725	4
Power plant including	48		3
buffer zone	65	16,057–23,140	4
Fuel disposal	29		3
Total land area	120		3
(including buffer zone)	85		4

contamination of water, land acidification and deterioration of forests, caused by pollutants from coal-fuel cycle.

Nuclear

The direct land footprint of a nuclear power plant includes power plant area, buffer zone, waste disposal area and the land that goes into mining uranium. Table 2 summarizes the values for land area transformed by a nuclear plant from two international studies[3,4].

Hydro

The direct land footprint of hydroelectric power plants varies significantly depending on the geographic location and the primary purpose of the plant. At present, there are around 5100 large dams in India. To assess the land area required for power generation from hydroelectric power generation, we have chosen 9 out of 61 dams which were built mainly for power generation, from the National Register of Large Dams[5]. Table 3 provides the details of these nine dams. Assuming a plant load factor of 37% and an average lifetime of 50 years, the area required per MW and GWh of electricity produced for a typical dam turns out to be 222,698 and 1374 m^2 respectively.

Solar

The literature suggests that the land area required per MW of installed solar power is around 20,234 m^2 (approx. 2 ha)[6,7]. Due to recent advances in solar technologies, especially the efficiency of solar cells, some authors[4,8] give land requirements as low as 12,000 m^2/MW. However, in this article, we take the direct land footprint of solar technologies, both solar thermal and photovoltaic power generation, as 20,234 m^2/MW. Then, the corresponding land area required per GWh of life-cycle electricity produced would be 385 m^2, assuming a plant load factor of 20% and the lifetime of the plant as 30 years.

Figures 1 and 2 compare the land area required to set up a typical power plant (m^2/MW) and the area transformed across its life cycle (m^2/GWh) for different energy sources.

Land occupation

Land occupation is calculated by multiplying the transformed land area with the time taken to recover to its initial state and hence is a measure of how a certain energy source affects the land qualitatively. Therefore, this term accounts for functional degradation of the land as well. Defining a reference recovery state of land is not an easy task as it depends on the type of vegetation and the local environment interrupted. In their seminal study, Fthenakis and Kim[3] have calculated a range of land occupation values for different electricity generation technologies based on life-cycle approach for USA. Figure 3 summarizes the land occupations for the four energy sources in m^2 yr/GWh from their study. Further, Fthenakis and Kim[3] also argue that the land occupation for photovoltaic decreases with increasing the time that a certain land area is used for generating solar energy, which is contrary to the relatively independent land occupation times of nuclear and other fossil fuel-based energy sources. In the present study, we assume that the values suggested by Fthenakis and Kim[3] will hold true for the Indian region as well. More detailed information and discussion about land occupation values, including their calculations, can be found in ref. 3.

Comparative assessment

As shown in Figures 1 and 2, although the land area required to set up a solar power plant is more compared to a coal plant, the same does not hold true when we compare it with nuclear and hydro power plants. When we take into account the land area transformed across its life cycle, solar power is next to nuclear and is comparable

Table 3. Details of large dams considered in this analysis[5]

Name	Year	River	Reservoir area (sq. km)	Storage capacity (km^3)	Installed capacity (MW)
Srisailam	1984	Krishna	616.4	4.25	1,670
Chamera-I	1994	Ravi	9.5	0.11	540
Salal	1986	Chenab	9.4		690
Baglihar	2009	Chenab	8.1	0.15	450
Linganamakki	1965	Sharavathy	316.6	4.29	1090
Supa	1987	Kalinadi	123	3.76	970
Koyna	1964	Koyna	115	2.64	1960
Rihand	1962	Rihand	468	8.90	300
Totladoh	1989	Pench	77.71	1.09	160

Only dams that were primarily built for hydroelectric power generation are included.

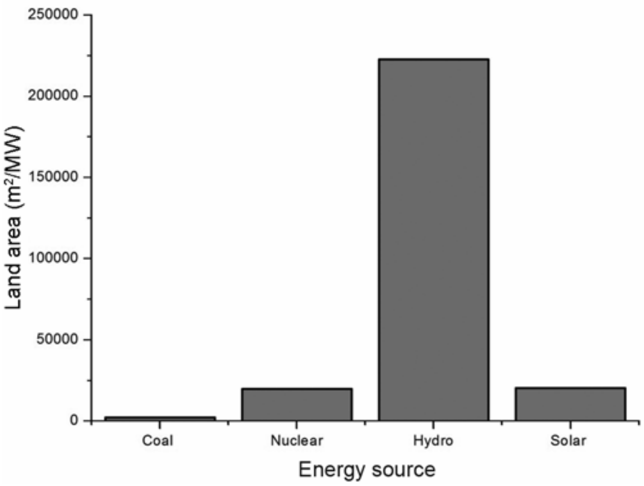

Figure 1. Mean values of land area required to set up a typical power plant for different energy sources.

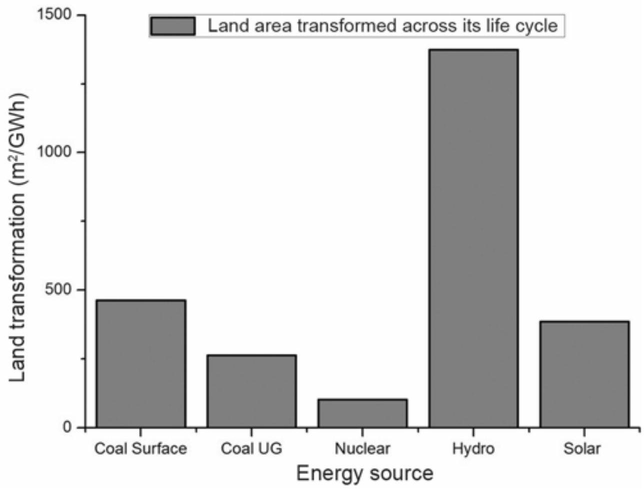

Figure 2. Mean values of direct land transformation associated with coal, nuclear, hydro and solar energy sources.

with coal. In fact, the land required for a solar power plant is small compared to hydro power. It should also be noted here that the values considered for coal are US average values. As Indian coal is inferior in quality compared to US coal and, around 70% of coal in India is surface-mined[9], the life-cycle land use will go up for this energy source if we take these factors into account. Even though nuclear power is effective in terms of land transformation (life-cycle value), it is the highest when it comes to land occupation (Figure 3). In addition, the recent estimation of required land area for Indian nuclear power plants by Chokshi[2] is higher than the one we have assumed here. Hence, there is a need for further work in this direction.

How much of India's land would be required to meet the future electricity demand by solar energy?

The percentage distribution of India's land area by land-use type according to the Ministry of Agriculture, New Delhi, is given in Table 4. As India is a densely populated country, the agricultural land and forest cover are necessary for food production and maintaining the ecological balance. Hence, it would be judicious to consider only the waste lands for installing the solar electricity generation systems. Table 4 shows that the total area occupied by waste lands and the 'land not available for cultivation' in India is around 951,860 sq. km, i.e. 31.1% of the total land area.

As suggested by Sukhatme[1], it would be wise for a densely populated country like India to target at a simple lifestyle pattern with an annual per capita electricity consumption of around 2000 kWh, i.e. 3400 TWh per annum for the country as a whole by 2070. Assuming that the installation of a solar power plant, both photovoltaic (PV) and thermal technologies, requires around 2 ha of land area and redoing the calculations by keeping all other assumptions the same as that by Sukhatme[1], we determine that 38,813 sq. km of land would be required to meet the projected annual demand of 3400 TWh. That is, 1.3% of the total land area or 4.1% of the total uncultivable land area, excluding forests and net area sown, is enough to meet the projected demand by solar energy alone. This is less than the land that has been covered by permanent pastures and other grazing land (Table 4).

Table 4. Distribution of India's geographic land on the basis of land-use types[10]

Land-use type	Percentage of total land	Land area (sq. km)
Forests	22.8	696,260
Land not available for cultivation	14.1	432,180
Permanent pastures and other grazing land	3.4	103,880
Land under tree crops (not included in net area sown)	1.1	33,110
Cultivable waste land	4.3	131,210
Fallow land	8.2	251,480
Net area sown	46.1	1,408,610
Total	100	3,056,740

Source: Directorate of Economics and Statistics, Ministry of Agriculture, New Delhi.

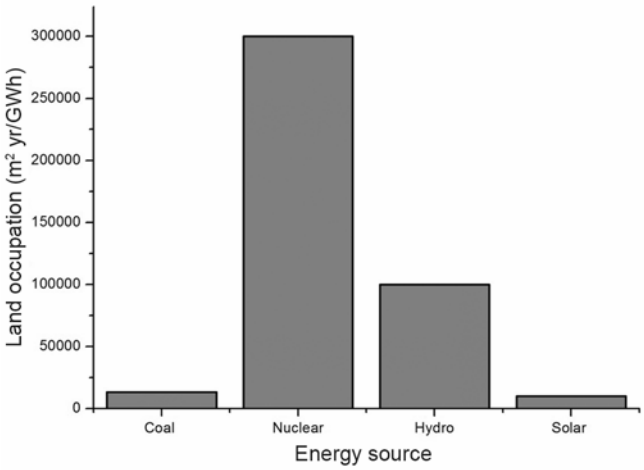

Figure 3. Mean values of land occupation for coal, nuclear, hydro and solar energy sources to produce 1 GWh of electricity. Land occupation involves the duration over which the transformed land area returns to its original state, measured as a product of land area and time[3].

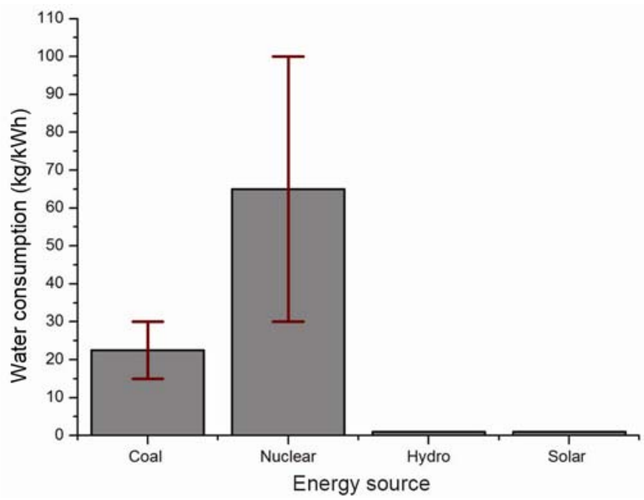

Figure 4. Water consumption by the four energy sources for their power plant operations[13].

If we bring the other potential renewable energy sources of India into picture, then the land area required by solar technologies to meet the projected annual demand collectively would reduce to around 29,783 sq. km, using the projections for other renewable energies by Sukhatme[1]. Hence, we estimate that 0.97% of the total land area of India or 3.1% of the total uncultivable land area would be required for solar energy to meet India's future electricity needs in conjunction with other renewable energy sources. It should be noted here that these calculations do not include higher efficiencies achieved by new solar cells. Recently documented efficiencies for different types of solar cells and modules can be found in Green *et al.*[11]. The role of concentrated PV technology, which has undergone tremendous development in recent years with its cell efficiencies reaching 40% and higher, is completely ignored in these calculations (see ref. 12 for more information on these technological developments).

Discussion

Although we have not accounted for all the land transformations associated with an energy source in our analysis, it is obvious that considering only the land area required to set up the power plant will not give the real picture and hence such an analysis may lead to misconceptions about an energy resource. For example, the solar power plant, which requires more land area (m^2/MW) than a coal power plant, transforms less land area than coal power plant with surface-mining option when compared on the basis of life-cycle direct land transformations and is effective in terms of land occupation. It should also be noted that the solar technologies use land statically compared to coal and nuclear energy sources. That is, apparently there is no need for further extraction of resources once a solar power plant has been set up, whereas nuclear and fossil fuel-based technologies must continuously transform some land to extract the fuels or dispose the hazardous waste.

Figure 4 shows the water consumption of PV technology in comparison with other technologies[13]. As PV technology requires minimal amount of water for operation, it provides an opportunity to make use of dry/waste lands to generate power, which otherwise would be left untouched. In addition, PV technology also

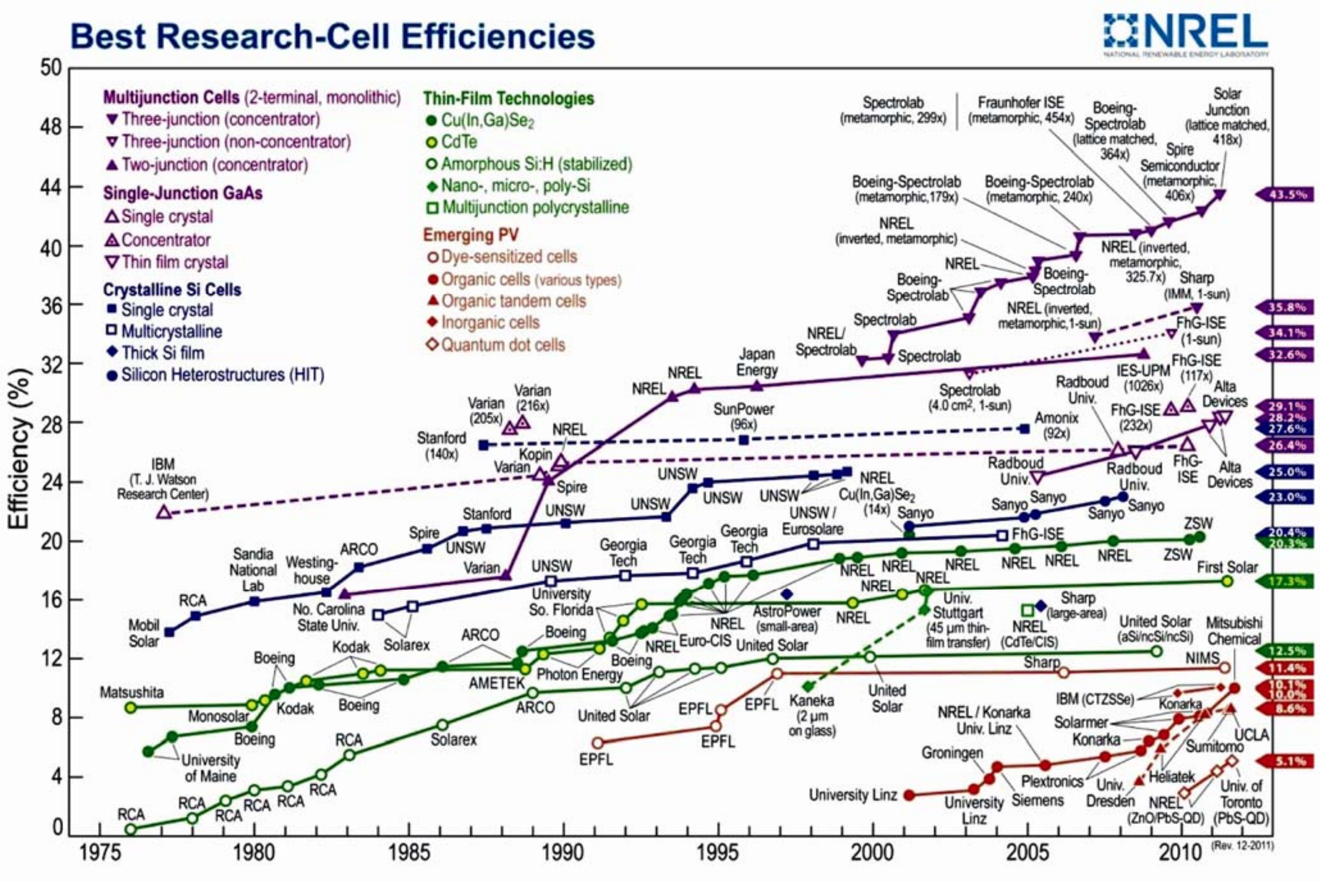

Figure 5. Historic summary of the best research cell efficiencies for various photovoltaic technologies[14].

Figure 6. A concentrator PV power plant installed by Concentrix Solar. This shows that the technology can support multiple land usage. (Credit: Soitec[15]).

promises the usage of land for multiple purposes, i.e. the same land can be utilized for grazing, power generation and shading purposes.

Further, as cell and module efficiencies increase, even less land will be required for solar power plants. Figure 5 summarizes the efficiency learning curves over the past few decades for various PV technologies. The efficiency of the PV cells has increased from 8% in 1976 to around 43% in 2011 (ref. 14). These newly developed high-efficiency multi-junction solar cells are being used in conjunction with concentrators because of their high cost. The concentrators necessitate that the whole system should track the sun accurately. So, the concentrator PV systems have to be mounted on the two axis-tracking towers, as shown in Figure 6 (ref. 15). Notably, this also provides more opportunity to make use of the same land for multiple purposes. Moreover, there is a possibility in the near future that one can lease only the land required for the tracking tower instead of acquiring a large amount of land from farmers (Figure 6).

Lastly, land issues are multi-dimensional in nature, which involve societal, political and economical aspects associated with a particular developmental project or energy source in this context. Hence, we cannot assume that the land issues which are affecting the growth of any other energy source will also affect the solar energy source in a similar way. For example, the World Commission on Dams estimates that dam construction submerged 4.5 m ha of Indian forest land between 1980 and

2000, and an average dam displaces 31,340 persons and submerges 8748 ha of land[16]. Because of these issues, land acquiring may be a difficult proposition for hydro power, but these factors cannot play any major role in solar technologies. Similarly, acquiring land to set up a nuclear power plant may be an issue because of the potential risk involved in the technology. For example, the Chernobyl accident contaminated around 300,000 sq. km of land with radio nucleotides[17]. The same cannot hold true for solar power.

Conclusion

The present study shows that solar power plants require less land in comparison to hydro power plants, and are comparable to other energy sources including nuclear and coal when life-cycle land transformations are considered. In addition, an attempt has been made to show how solar source differs from other energy sources in the way it uses the land. Because of its unique type of land usage, it has been argued that land availability may not be a limiting constraint for the solar source. Moreover, it should also be noted that viability of solar power vis-à-vis other forms of power depends on the trade-offs between many factors, such as capital cost, cost of generation, carbon footprint, land area, potential risk involved in the technology, environmental friendliness and many others, but not just on one measure.

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