Multi-criteria sustainability assessment of coal and solar power generation in India

About 70% of total electricity generation in India in 2015–16 came from thermal power plants that burn coal[1]. Further, coal power plants still dominate the planned power capacity additions under the 12th and 13th five-year plans[2]. The coal-based thermal power plants are considered to be least expensive and more reliable in the present electricity grid infrastructure. Here, we present a holistic overview of coal and solar photovoltaic (PV) power generation options. The former is dominant in today's power grid and the latter is expected to play a major role in future low-carbon grid. These power supply options are evaluated with respect to a set of seven sustainability criteria. This study examines the two power generation options based on techno-economic and environmental indicators.

All the environmental criteria considered in this study are assessed from life-cycle perspective, that is, the estimated values account for all the major impacts across the life-cycle stages of the power generation options, such as mining raw materials and fuels, fuel transport, power plant installation, power production and decommissioning. Brief descriptions of the seven sustainability criteria – global warming, air pollution, water footprint, energy return on investment (EROI), land footprint (land transformation and land occupation), reliability and costs associated with power generation (levelized cost of electricity (LCOE) and external costs) – are given below, along with India-specific assumptions and estimations.

Global warming: This accounts for the amount of greenhouse gases (GHGs) emitted by a power source across its life cycle, and is expressed in gCO_2eq./kWh. Coal power generation emits 1010–1350 gCO_2eq./kWh in India during power plant operation phase[3]; we assume upstream and life-cycle emissions of coal power are negligible. Solar power generation leads to 16–57 gCO_2eq./kWh GHG emissions across its life-cycle stages[4,5], and has zero emissions during operation stage.

Air pollution: This accounts for emissions of the following gases and particulates across the life cycle of a power source: nitrogen oxides, sulphur oxides and particulate matter (<10 um), and is expressed in $mgPM_{10}$eq./kWh. It is estimated that coal power plants emit 1030–3750 $mgPM_{10}$eq./kWh during their operation phase[2,6,7]. The life-cycle air pollution impacts due to solar power generation are between 36 and 121 mg PM_{10}eq./kWh (ref. 5).

Water footprint: Here we account for life-cycle water consumption of a power source (water lost) and it is expressed in L/MWh. For coal power generation, the water consumption during coal fuel cycle, that is, mining, processing and transportation of coal accounts for 83–220 L/MWh (ref. 8); the power plant construction phase, raw materials manufacturing and decommissioning of the plant consume 4–95 L/MWh (ref. 8). The power plant operation phase consumes between 3500 and 4000 L/MWh for cooling tower make-up, ash disposal, servicing, sludge removal and dust suppression[9], since most Indian coal power plants use wet-tower cooling systems[10]. The life cycle of solar PV power plants consumes 20–107 L/MWh for raw materials extraction, manufacturing, construction, transportation, plant operation and decommissioning stages[8,11].

Energy return on investment: This is the ratio between electricity delivered by a power source across its lifetime and the amount of primary energy invested in capturing and delivering this electricity. It is a dimensionless parameter, and indicates whether a power source is a net energy generator or consumer over its life cycle. The EROI estimates in this study are for electric power generation ($EROI_{el}$), so there will be differences between the estimates from the present study and the other popular studies that account for primary energy returns, not electricity returns (see Raugei *et. al.*[12] for more details). Based on global average values, it is estimated that coal power plants have $EROI_{el}$ in the range 11–14 (refs 13–15). Further, we estimate that present solar PV plants have $EROI_{el}$ in the range 4–12 in India, depending on the type of solar PV technology – mono/poly-crystalline or thin films.

Land footprint: This has two categories – land transformation and land occupation.

Land transformation is the land area transformed from its natural state by a technology across its lifetime which includes, but is not limited to, directly transformed land area for setting up a power plant, mining fuel, fuel transportation, waste disposal and provision of space around the plant. In addition, it also accounts for indirect land transformation, that is, the land area that goes into upstream processes and secondary land disturbances such as land degradation due to pollutants and effluents from the fuel and material cycles, among others.

In this study, we have expressed land transformation in 'm^2/GWh' which is the ratio of life-cycle land area transformed by a typical power source to its lifetime electricity generation. Based on Fthenakis and Kim[16], we estimate that coal power life cycle transforms 6–18 m^2/GWh during power plant operation and 432–491 m^2/GWh during mining, transportation and disposal of coal. We estimate that solar power life cycle transforms 346–528 m^2/GWh during operation phase and 23–26 m^2/GWh during upstream processes to manufacture PV modules and balance of system components.

Land occupation is a measure of how long a power source affects and occupies a certain piece of land. It is calculated by multiplying the amount of transformed land area with the lifetime of the power plant and is expressed in m^2.year/GWh. Coal power life cycle occupies 13,140–20,400 m^2.year/GWh during its lifetime[5,16], and we estimate that solar power occupies 9710–15,855 m^2.year/GWh across its lifetime.

Reliability: This indicator is expressed as capacity utilization factor (CUF) in the present study. It is the ratio of actual electricity output from a power plant with respect to its rated capacity. Based on the available historical data of Indian power plants, we estimate that coal power plants have a CUF of 50–74% and solar PV plants in India have CUF in the range 16–24% (refs 1, 17, 18).

Cost of power generation: This has two categories – Levelized cost of electricity (LCOE) and external costs.

LCOE is the ratio between overall costs of power generation (capital and operating costs) and the lifetime electricity delivered by a power source. In this study, we account for levelized tariff based on recent bids in India that take into account internal rate of return along with standard LCOE; these figures are indicative of the power purchase agreements (PPAs) between power producers and power distribution companies (DISCOMs). The recent levelized long-term bids indicate that LCOE for coal power plants in India is INR 3.6–5.84/kWh (refs 19–21), and average harmonized LCOE for solar PV plants is INR 4.34–5.85/kWh (refs 22–26).

The present electricity pricing method ignores the social, environmental and energy security costs of power generation that will be incurred by the society directly or indirectly. The power generation technologies cause various negative impacts on air (e.g. global warming, air pollution), water (surface and groundwater pollution, underground water table depletion), land (degradation, forest cover loss, loss of biodiversity and wildlife) and socio-economic aspects (health impacts, infrastructure and livelihood impacts, agriculture crop loss, energy security issues, additional infrastructure requirements) across their life cycle value chains. These are called 'externalities' or 'external costs' as the present market prices are insensitive and do not account for these costs because of their limited operational economic boundaries. It is estimated that coal power generation leads to INR 4.99–13.56 additional cost to the society for every kilowatt hour of electricity it delivers[27,28], and solar power incurs additional INR 0.13–0.88/kWh of electricity it delivers to the society[29,30]. A study by Pudjianto *et. al.*[31] estimates that the cost of grid integration of solar power is INR 1.44–1.87/kWh, and this estimate includes costs of maintaining the adequacy of generation capacity for security purposes, upgrading grid main transmission system, reinforcing distribution network, losses attributed to PV and having more operating reserve requirements due to increased PV generation. If we add this estimate to the external costs of solar PV, then the total external costs become INR 1.57–2.75/kWh.

Table 1 provides a brief summary of all the nine indicators (within the seven sustainability criteria) along with their India-specific estimations and corresponding references[32–42].

Figure 1 shows the comparative performance of coal and solar power generation with respect to nine sustainability indicators. It can be seen that solar PV is superior to coal power generation in global warming, air pollution, water consumption and external cost criteria. It has been found that coal power plants emit approximately 23 times (63 on the higher end) more GHGs emissions, cause 28 (31) times more air pollution, grab 40 (180) times more water and lead to 15 (38) times more external costs to society than solar PV plants in India. Further, both the power sources are comparable when seen from land transformation, land occupation and LCOE perspectives. Coal plants return 11–14 times of their invested energy ($EROI_{el}$) to the society, slightly better than solar PV technologies which have $EROI_{el}$ in the range 4–12. It is only in reliability criterion that solar plants with 16–24% CUF lose out dramatically to coal plants which have 50–74% CUF.

The above results indicate that irrespective of the technology improvements that can happen in the near future, it can be said that coal plants will always be inferior to solar PV plants by a factor of 10s or more when it comes to global warming, air pollution and water consumption impacts. Energy returns criterion ($EROI_{el}$) clearly shows that there is room for improvement with regard to solar technologies in the coming years in terms of developing power plants with higher performance efficiencies and innovating low energy intensive manufacturing processes. In land-use criteria, it becomes evident that the land footprint of solar power plants is not high as generally perceived by the decision makers; here we underscore the necessity of looking at the footprints of power sources from life-cycle perspective (see Mitavachan and Srinivasan[43] for a more elaborate discussion on land footprint of solar energy). Though solar power performs on par with coal power generation from life-cycle perspective, it should be noted that the placement of solar power plants shall be prioritized on waste lands and rooftops because of their higher operating land-use requirements, unlike coal plants.

The cost results clearly highlight that the era of inexpensive coal is over and solar power is already cost competitive with coal power generation, even when considered without environmental concerns. This implies that (i) the legacy of coal as a low-cost power generation option in India is coming to an end; and (ii) the cost of solar power generation has reduced dramatically in the recent years and the solar market is not like what it used to be few years back. With coal prices coming up and solar prices coming down, solar power will be more competitive in the future. In fact, this is a typical characteristic behaviour of most of the renewable energies and the fossil fuels-based power sources; that is, the more the renewable energies get deployed the cheaper they become, while the more the fossil fuels are used the costlier they become because of their limited resource base. Furthermore, when we account for externalities of power generation on health (direct impacts on society) and environment (indirect impacts on society), coal power becomes costlier than solar power generation by a factor of 2–3. On the other hand, even after accounting for grid-integration costs of solar power, its external cost estimates (INR 1.57–2.75/kWh) are significantly lower than coal power generation (INR 4.99–13.56/kWh).

Further, the lower reliability (CUF) is the inherent characteristic feature of solar PV plants because of the diurnal and seasonal variation of solar radiation. Therefore, it becomes necessary to integrate solar with other renewable energies and storage technologies as the penetration of solar energy increases in the grid. This can be done by interconnecting the power systems via large grid-networks and smartly managing both the demand and generation profiles; such efforts are presently underway in Germany because its national grid has high penetration of solar and wind power generation[44,45].

The main objective of this study was to compare coal power vis-à-vis solar power generation, and also highlight the necessity to account for multiple criteria in the decision-making process in the country. For instance, through our study, a decision maker can clearly realize that the water footprint of coal power plants is extremely high and hence placing these technologies in high water stress areas will be disastrous, as these plants will start competing with freshwater needs of the local population. In fact, it has been found that a significant number of coal power plants are located in the drought-prone regions of India[46,47]; the underperformance of five out of eight

Table 1. Data summary of the seven sustainability criteria for coal and solar power generation in Indian context

Sustainability criteria	Indicator	Units	Coal	Solar	References
Global warming	Greenhouse gases (GHGs)	gCO_2eq./kWh	1010–1350	16–57	Coal – CEA[3] Solar – Hertwich[5], Frischknecht[4]
Air pollution	PM_{10}, NO_x, SO_x	$mgPM_{10}$eq./kWh	1030–3750	36–121	Coal – Own estimations based on Guttikunda[2], CSO[6], CSO[7] Solar – Hertwich[5]
Water footprint	Life cycle water consumption	L/MWh	3587–4314	20–107	Coal – Own estimations based on Meldrum[8], CEA[9], IEA[10] Solar – Macknick[11], Meldrum[8]
Energy return on investment	$EROI_{el}$	Ratio	11–14	4–12	Coal – White[15], Neumeyer[14], Dale[13] Solar – Own estimations based on Ramachandra[32], Edalati[33], Vasisht[34], Kumar[35], Bhandari[36], Wild-Scholten[37], Ito[38]
Land use	Land transformation	m^2/GWh	438–509	372–551	Coal – Fthenakis[16], Gautam[39] Solar – Own estimations based on Mitavachan[43], Turney[40], Hernandez[41], Fthenakis[16], Murphy[42], MNRE[18]
	Land occupation	m^2 year/GWh	13,140–20,400	9,710–15,855	Coal – Fthenakis[16], Hertwich[5] Solar – Own estimations based on Mitavachan[43], Hertwich[5]
Reliability	Capacity utilization factor (CUF)	Percentage	50–74	16–24	Coal – CEA[17], CEA[1] Solar – MNRE[18]
Cost	Levellized cost of electricity	INR/kWh	3.60–5.84	4.34–5.85	Coal – CERC[19–21] Solar – BridgeToIndia[22], CERC[23,24], PVTech[25], Business-Standard[26]
	External costs	INR/kWh	4.99–13.56	0.13–0.88 (1.57–2.75)	Coal – Wang[28], Epstein[27] Solar – Fthenakis[29], Roth[30], Pudjianto[31]

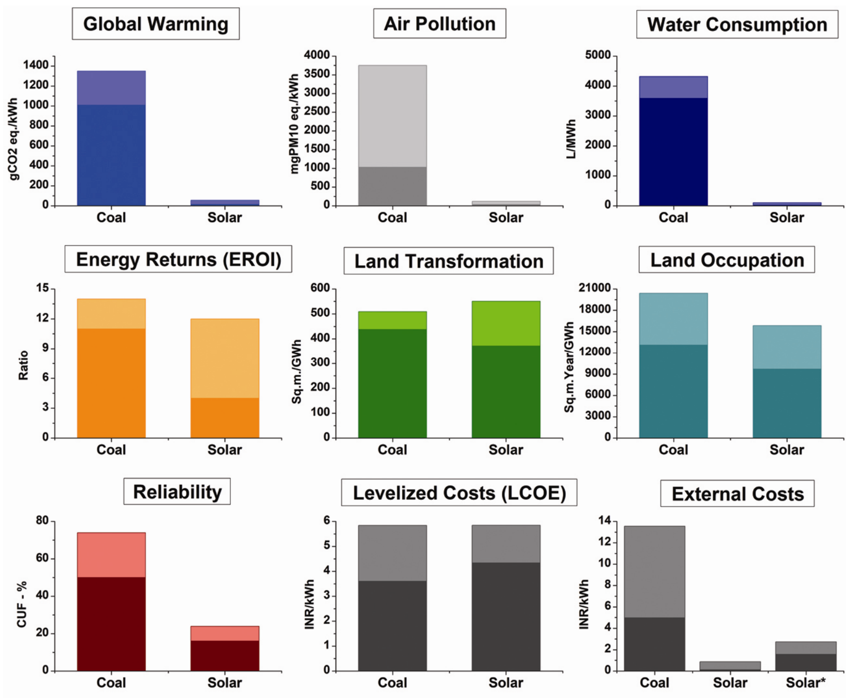

Figure 1. Comparative performance of coal and solar power generation with respect to nine sustainability indicators in the Indian context. The lighter shades represent higher bound values.

units at the Raichur coal power plant in Karnataka owing to water shortages in 2016 can be noted as a specific example here[48]. The same arguments hold true in the context of air pollution as well, and the shutting down of the Badarpur power plant in recent months owing to severe air pollution issues in Delhi is a good example[49,50]. Thus, it becomes self-evident that the future energy system planning of the country should be made based on multi-criteria assessments from a life-cycle perspective. This point has also been highlighted by Khosla *et al.*[51] in the context of Indian development policy-making arena by taking specific examples from the cooking and buildings sectors. There are various multi-criteria techniques available in the literature[52] and 'multi-criteria decision analysis' (MCDA) is a well-recognized framework that can aid decision makers to account for multi-objectives during the policy-framing process[53,54]. In this study we compared only two power generation options, and hence the application of a standard multi-criteria technique was not required. However, this is not the case when we compare more than two power sources with respect to a series of sustainability indicators. The application of MCDA techniques to assess present and future Indian power systems will be headed, and this will be the subject of our future work.

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Dolomitic carbonatite from the Chotanagpur Granite Gneiss Complex: a new DARC (Deformed Alkaline Rocks and Carbonatite) in the Precambrian shield of India

The Chotanagpur Granite Gneiss Complex (CGGC) of the East Indian Shield records a protracted geological history ranging from Palaeo- to Meso- to Neoproterozoic time[1,2]. It is commonly believed that the whole of the CGGC behaved as a unified crustal block at least from 1600 Ma (ref. 3). The E–W to ENE–WSW trending North Purulia Shear Zone (NPSZ) dissects and geographically divides the CGGC into the northern and southern blocks[4]. The NPSZ exposes diverse rock types, including khondalite, biotite gneiss, charnockite, mafic granulite and nepheline syenite. This rock association is distinctly different from the gneissic rocks exposed on its shoulders. Towards the central part of the NPSZ, near the village Chalania (23°27.03′N, 86°21.82′E), coexisting carbonate-rich rocks (CRR) and apatite–carbonate-rich rocks (ACRR) are identified that are enclosed by migmatitic felsic rocks and augen gneiss having a gneissic banding of amphibolite facies assemblage trending E–W to ENE–WSW defining the dominant fabric of the NPSZ[5]. The host rock is frequently traversed by bands of CRR and ACRR which are extensively brecciated and the angular fragments of CRR and ACRR are welded together by silica-rich veins. The strike of the brecciated bands is parallel with the gneissic banding of the enclosing rocks.

Here we present preliminary data on petrography, mineral chemistry, trace element and stable isotope composition of the CRR and ACRR and discuss their significance. Detailed study on the rock suites are in progress.

Original fabric and mineralogy of the studied CRR and ACRR are virtually