Supplementary information to “Solar energy as an early just transition opportunity for coal-bearing states in India”

1 Mapped capacity

The mapped capacity represents the capacity marked as data points in Figure 3 in the main text and Figure S1 below. The location and capacity data for the different technologies has been taken from different data sources – i) coal power plants and coal mines (operating and under-construction/planned) from the Global Energy Monitor 2021; ii) solar, wind, biopower and co-generation, small hydro power plants from Renewable Energy Project Monitoring Division 2020; iii) gas, oil, nuclear, and large hydro[1] from World Resources Institute et al. 2018.

Power plant locations in i) and iii) were available at unit/plant level and were generally exact. Other relevant notes are on corresponding webpages[2]. Power plant locations in ii) are generally accurate at a district level, however, data is generally of poor quality. The addresses available as part of the report were cleaned and then geocoded using Google Maps API, followed by again checking for inconsistencies. The result is that the mapped capacity is much lower than reported plant-wise capacity (Solar ~ 25 GW mapped vs. 29.9 GW reported, Wind 34.2 GW mapped vs. 37.4 GW reported)

State	Biopower	Co-gen	Coal	Gas	Hydro	Nuclear	Oil	Solar	Wind
Andhra Pradesh	489.81	0	12961	4671.284	3648.4	0	0	3987.78	4072.89
Arunachal Pradesh	0	0	0	0	411	0	0	3.68	0
Assam	0	0	750	610.45	375	0	0	0	0
Bihar	0	0	6400	0	20	0	0	0	0
Chandigarh	0	0	0	0	0	0	0	17.545	0
Chhattisgarh	0	0	26845	0	120	0	0	0	0
Dadra and Nagar Haveli and Daman and Diu	0	0	0	0	0	0	0	16.74	0

[1] The hydro column Table 1 represents sum of small hydro (<25 MW) and large hydro (>25 MW) taken from two different data sources.
[2] https://datasets.wri.org/dataset/globalpowerplantdatabase and https://globalenergymonitor.org/projects/global-coal-plant-tracker/

Delhi	0	0	0	2066	0	0	0	147.16	0
Goa	0	0	0	48	0	0	0	0	0
Gujarat	0	0	17355	7683.161	1995	440	0	2613.18	7237.45
Haryana	0	0	5980	431.586	62.4	0	0	0.13	0
Himachal Pradesh	0	0	0	0	10714.17	0	0	0	0
Jammu & Kashmir	0	0	0	0	2989.4	0	175	0	0
Jharkhand	0	0	5876.5	0	214	0	0	0	0
Karnataka	134.32	1731.61	9750	406.5	4580.21	880	106.6	5944.06	4778.67
Kerala	0	20	0	515	2080.09	0	177.84	91.53	51.88
Ladakh	0	0	0	0	96.75	0	0	0	0
Madhya Pradesh	0	0	22415	75	2319.1	0	0	265	515.4
Maharashtra	215	2485.7	26312	3489.88	3548.73	1400	1009.7	377.6	4782.13
Manipur	0	0	0	0	105	0	0	0	0
Meghalaya	0	0	0	0	333.2	0	0	0	0
Mizoram	0	0	0	0	60	0	0	2	0
Nagaland	0	0	0	0	75	0	0	0	0
Odisha	0	0	17799.5	0	2011.5	0	0	315	0
Puducherry	0	0	0	32.5	0	0	0	0	0
Punjab	0	0	5680	0	1187.65	0	0	768.95	0
Rajasthan	114.3	0	11025	1054.83	440.86	1180	0	3772.55	4296.56
Sikkim	0	0	0	0	2177	0	0	0	0
Tamil Nadu	986	0	14226	1018.18	2236.7	2440	411.7	2295.27	8378.73
Telangana	216.6	0	7756.5	0	657.61	0	0	3497.47	126
Tripura	0	0	0	1103.1	15	0	0	0	0
Uttar Pradesh	1905.11	0	23357.7	1468.4	471	440	0	849.12	0

Uttarakhand	0	0	43	225	3656.75	0	0	0	0
West Bengal	0	0	14715	0	1372.7	0	0	0	0
Total	**4061.14**	**4237.31**	**229247.2**	**24898.87**	**47974.22**	**6780**	**1880.84**	**24964.77**	**34239.71**

Table S1 Capacity mapped in Figure 1 of main text.

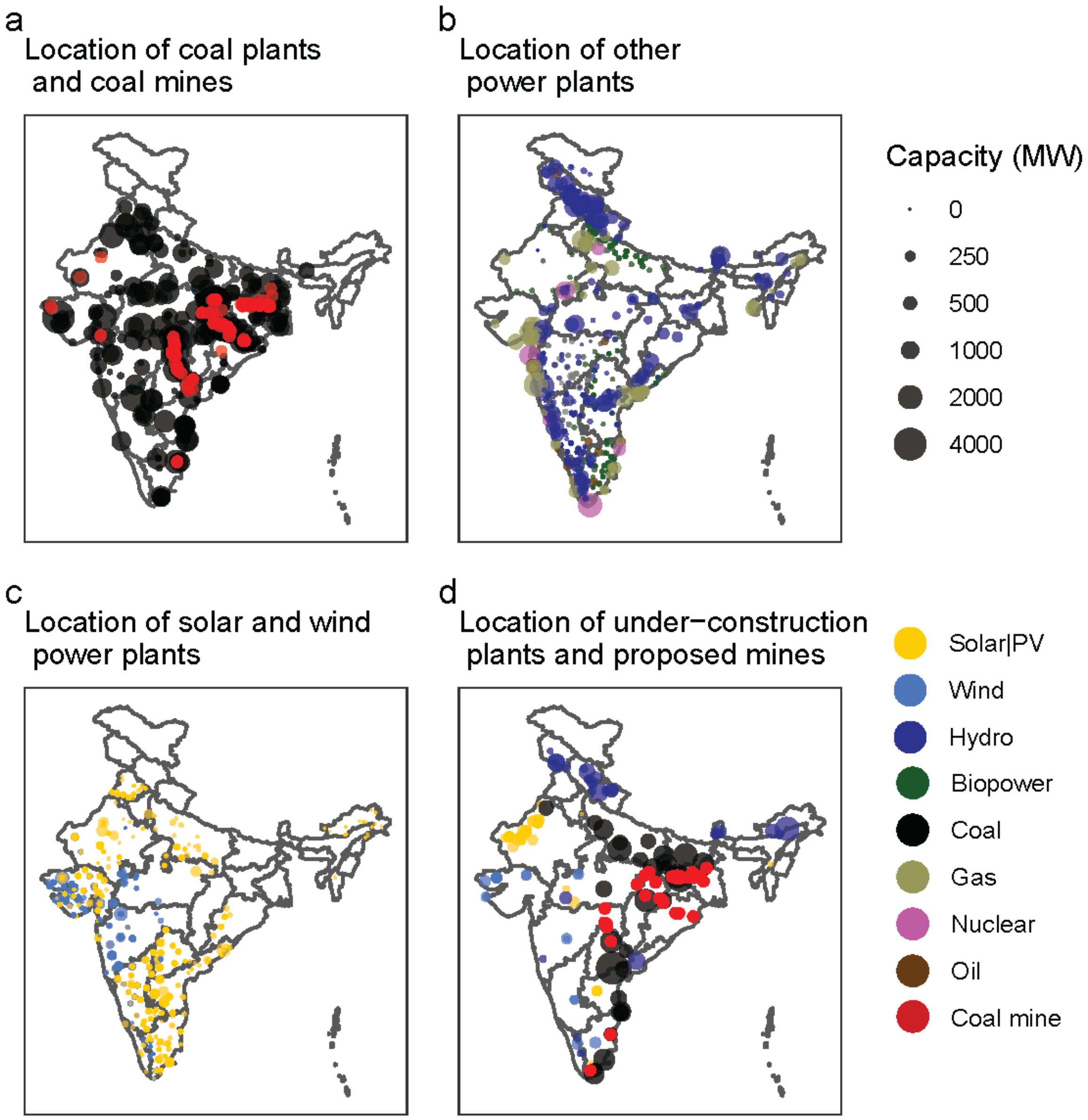

Figure S1 Location of power plants and mines in India, compiled from various sources - a) coal power plants in black, mines in red, b) Location of other power plants – gas, hydro, nuclear and oil c) location of solar and wind power plants, d) location of under-construction power plants – solar, wind, and coal, and proposed coal *mines (red). Note that i) for conventional power plants, capacity represents plant-level capacity (sum of units). For solar and wind, this may or may not be the case, ii) location of solar and wind plant data is approximate. Solar implies only Solar PV.*

2 Commissioned and pipeline capacity

Bridge to India's RE Navigator (https://india-re-navigator.com/utility) contains aggregate up-to-date information on state-wise, commissioned and pipeline installations. However, locational data is unavailable. Table S2 contains data for selected states. Note that solar only includes solar PV utility, i.e., excludes solar rooftop. Wind is wind onshore.

State	Type	Commissioned (GW)	Pipeline (GW)	Total (GW)
Rajasthan	Solar	5.1	27.5	32.6
Rajasthan	Wind	4.1	0.4	4.5
Gujarat	Solar	2.6	3.9	6.5
Gujarat	Wind	7.8	4.8	12.6
Andhra Pradesh	Solar	4	7.5	11.5
Andhra Pradesh	Wind	3.8	0	3.8
Karnataka	Solar	7.6	0.5	8.1
Karnataka	Wind	4.8	1.2	6
Tamil Nadu	Solar	3.9	1	4.9
Tamil Nadu	Wind	6.5	0.4	6.9
Maharashtra	Solar	1.9	2.9	4.8
Maharashtra	Wind	4.4	1	5.4
Madhya Pradesh	Solar	2.4	0.3	2.7
Madhya Pradesh	Wind	2.6	0.6	3.2
Odisha	Solar	0.4	0	0.4
Chhattisgarh	Solar	0.2	0	0.2
Jharkhand	Solar	0	0.1	0.1
Odisha	Wind	0	0	0
Chhattisgarh	Wind	0	0	0
Jharkhand	Wind	0	0	0
Telangana	Solar	3.5	0.2	3.7
Telangana	Wind	0.3	0	0.3
West Bengal	Solar	0.1	0	0.1
West Bengal	Wind	0	0	0

Table S2 Capacity Commissioned and in pipeline for different states from Bridge to Solar (update 15 March 2021)

3 Calculation of solar and wind technical potential

Solar potentials were calculated using the NREL RE-Data Explorer (https://www.re-explorer.org/re-data-explorer/technical-potential), using parameters in the **High constraint** scenario, see Table S3. The resulting potentials (Table S4 and resulting map, see Figure S2-left panel) should be considered conservative, as the allowed land use types were restricted to “wastelands” and “shrublands”. In comparison, the government authorised report on *India’s Wind Potential Atlas at 120m agl* from the National Institute of Wind Energy (NIWE) allows for much broader land-use types (next paragraph). Furthermore, soon to be commissioned floating-solar in India[3] shows the versatility of solar PV installations.

Only for eastern states of Chhattisgarh, Jharkhand, and Odisha, sensitivity analysis for other constraints (Medium and Low, see Table S3) were performed; results are in Table S5.

Wind technical potentials were taken from NIWE at 120m height (National Institute of Wind Energy, 2019) with the following parameters/constraints – i) Power density of 5 MW/km^2 , ii) Excluded areas - roads, railways, protected areas, airports; land area with elevation more than 1500m; land with slope more than 20 degrees, iii) capacity utilisation factor (CUF) more than 25%, iv) Suitable land areas – Waste land (80%)[4], Cultivable land (30%), Forest land (5%). See Figure S2, right panel for resulting map of suitable areas with CUF.

Criteria	**High Constraint**	**Medium Constraint**	**Low constraint**
Resource Type	Solar	Solar	Solar
Technology Type	Fixed tilt PV system	Fixed tilt PV system	Fixed tilt PV system
Limit by Solar Resource (kWh/m^2/day):	Min 4 Max 9	Min 4 Max 9	Min 4 Max 9
Power Density (MW/km^2):	100	100	100
Limit by Distance to Roads:	None	None	None
Limit by Distance to Transmission:	None	None	None
Exclude Protected Areas	Yes	Yes	Yes

[3] https://www.hindustantimes.com/india-news/indias-largest-floating-solar-power-plant-to-be-commissioned-by-ntpc-in-may-101615410322573.html
[4] Waste land includes grassland, other waste land, scrubland, and Rann (National Institute of Wind Energy, 2019).

Exclude Land Use Types:	All except – • Barren or Sparsely Vegetated • Shrubland	All except – • Barren or Sparsely Vegetated • Shrubland • **Dryland Cropland/Pasture (5%)**	All except – • Barren or Sparsely Vegetated • Shrubland • **Dryland Cropland/Pasture (10%)**
Limit by slope (%):	Max 5	Max 5	Max 5

Table S3 Criterion and constraints used to calculate solar technical potential using NREL's RE-Data explorer tool. The differentiating assumptions are highlighted in bold.

State	**Code**	**Solar technical potential (GW)[5]**	**Wind technical potential (GW)**	**Weighted average solar capacity factor for suitable areas in high constraint scenario**
Rajasthan	RJ	15179	128	0.182
Gujarat	GJ	3469	143	0.181
Madhya Pradesh	MP	108	15	0.176
Maharashtra	MH	3114	98	0.180
Karnataka	KN	1486	124	0.180
Tamil Nadu	TN	148	69	0.179
Andhra Pradesh	AP	718	75	0.180
Telangana	TG	111	25	0.177
Odisha	OR	182	8	0.166
Jharkhand	JH	22	0	0.168
Chhattisgarh	CT	13	0	0.172
West Bengal	WB	85	1	0.162

Table S4 Solar and Wind technical potential (in GW) for selected states in India, along with potential weighted capacity factors. Solar potential and capacity factors from NREL's technical potential tool (for high constraint), while wind potentials are from the National Institute of Wind Energy 2019.

[5] Potential considers only solar utility.

State	**Solar potential (GW)**		
	High constraint	**Medium constraint**	**Low constraint**
Chhattisgarh	13	115	218
Jharkhand	22	141	260
Odisha	182	313	445

Table S5 Potentials for utility scale solar for various assumptions on land constraints for the eastern states of Chhattisgarh, Jharkhand, and Odisha

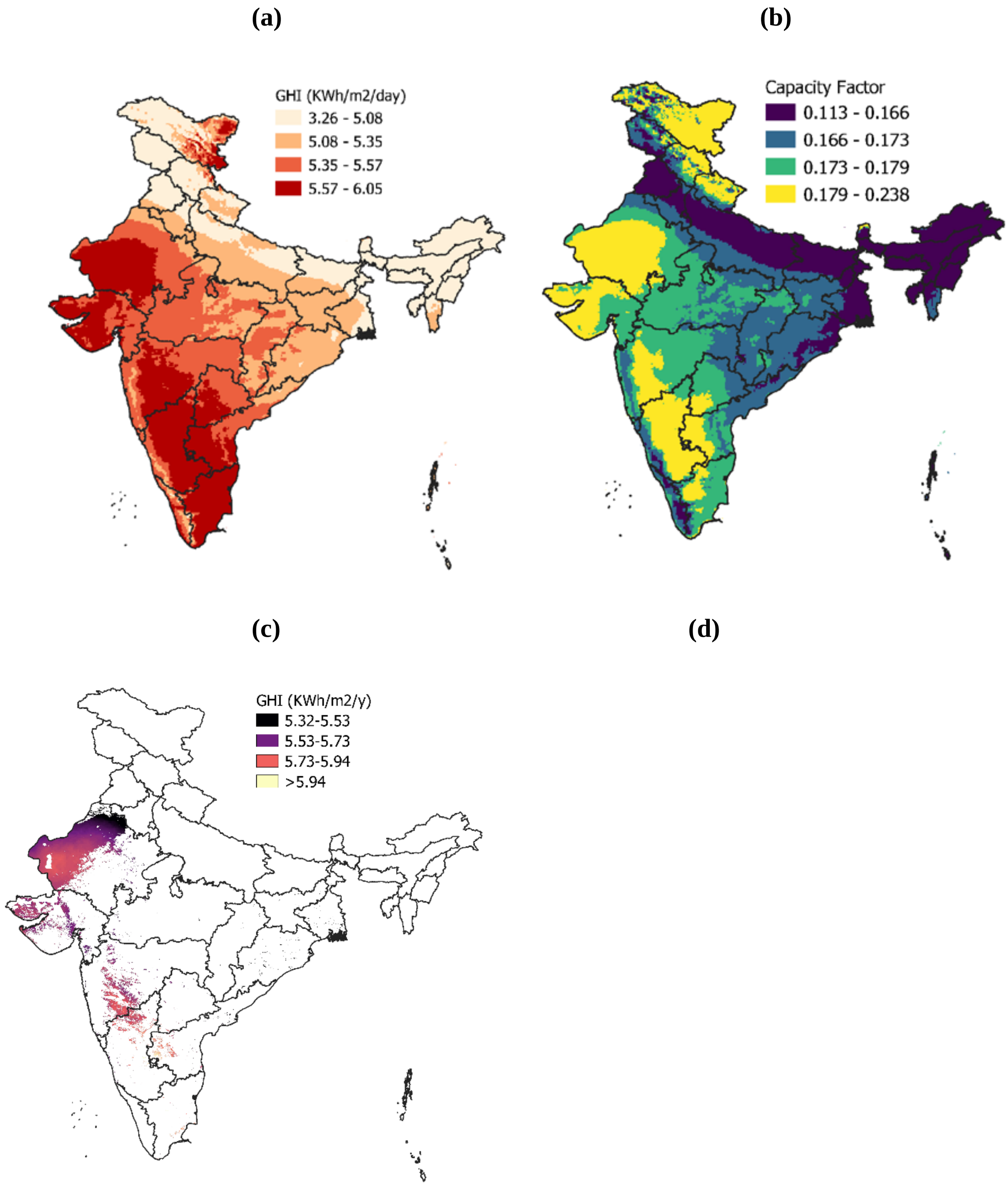

Figure S2 a) All-India Global Horizontal Irradiance (GHI) (Kwh/m2/day) b) All-India capacity factor for solar c) Map showing GHI for suitable areas in the high constraint scenario from NREL d) Wind potential according to Capacity Utilisation Factor (CUF) for India from National Institute of Wind Energy 2019 (For original figure see Figure 9 in report. The figure has not been included for copyright reasons). All maps (a-c) produced on QGIS with data from NREL's RE-data explorer.

4 Manufacturing locations of solar components

Item	Company	Location (Town/city)	State	Capacity/ yr	Status
module and cell production	Adani solar	Mundra Special Economic Zone	Gujarat	1.5 GW	operating
module production	Emvee	Bangalore	Karnataka	500 MW	operating
module production	Gautam solar	Haridwar	Uttar Pradesh	250 MW	operating
module production	Goldisolar	Surat	Gujarat	500 MW	operating
module production	Insolation Energy (INA)	Jaipur	Rajasthan	200 MW	operating
module production	Premier Energies	Hyderabad	Andhra Pradesh	500 MW	operating
module and cell production	Premier Energies	Hyderabad	Telengana	1.5 GW	operating
module production	Rayzon solar	---	Gujarat	300 MW	operating
module production	RenewSys	Patalganga	Mahashtra	750 MW	operating
module production	Saatvik	Ambala	Haryana	500 MW	operating
cell production	Tata Power Solar	Bengaluru	Karnataka	530 MW	operating
module production	Tata Power Solar	Bengaluru	Karnataka	580 MW	operating
module production	Vikram	Indospace Industrial Park, Oragadam	Tamil Nadu	1.3 GW	operating
module production	Vikram	Falta	West Bengal	1.2 GW	operating
module production	Waaree	Tomb	Gujarat	1 GW	operating
module production	Waaree	Surat	Gujarat	1 GW	operating

module and cell production	Adani solar	Mundra Special Economic Zone	Gujarat	2 GW	Planned/under-construction
module production	Emvee	Dobaspet	Karnataka	3 GW	Planned/under-construction
module production	First Solar	---	Tamil Nadu	3.3 GW	Planned/under-construction
module production	Goldisolar	Navsari	Gujarat	2 GW	Planned/under-construction
module production	Insolation Energy (INA)	Jaipur	Rajasthan	500 MW	Planned/under-construction
module production	Jakson Group	Noida	Uttar Pradesh	500 MW	Planned/under-construction
module and cell production	Premier Energies	---	---	1 GW (cell) + 1 GW (module)	Planned/under-construction
module production	Rayzon solar	---	---	1.2 GW	Planned/under-construction
module production	RenewSys	Dholera Special Industrial Region	Gujarat	2 GW	Planned/under-construction
module production	Solex	Surat	Gujarat	1 GW	Planned/under-construction

Table S6 Location of operating and under-construction/planned solar PV manufacturing plants in India. Gathered from various sources.

5 Evolution of capacity, production, and new capacity in REMIND scenarios

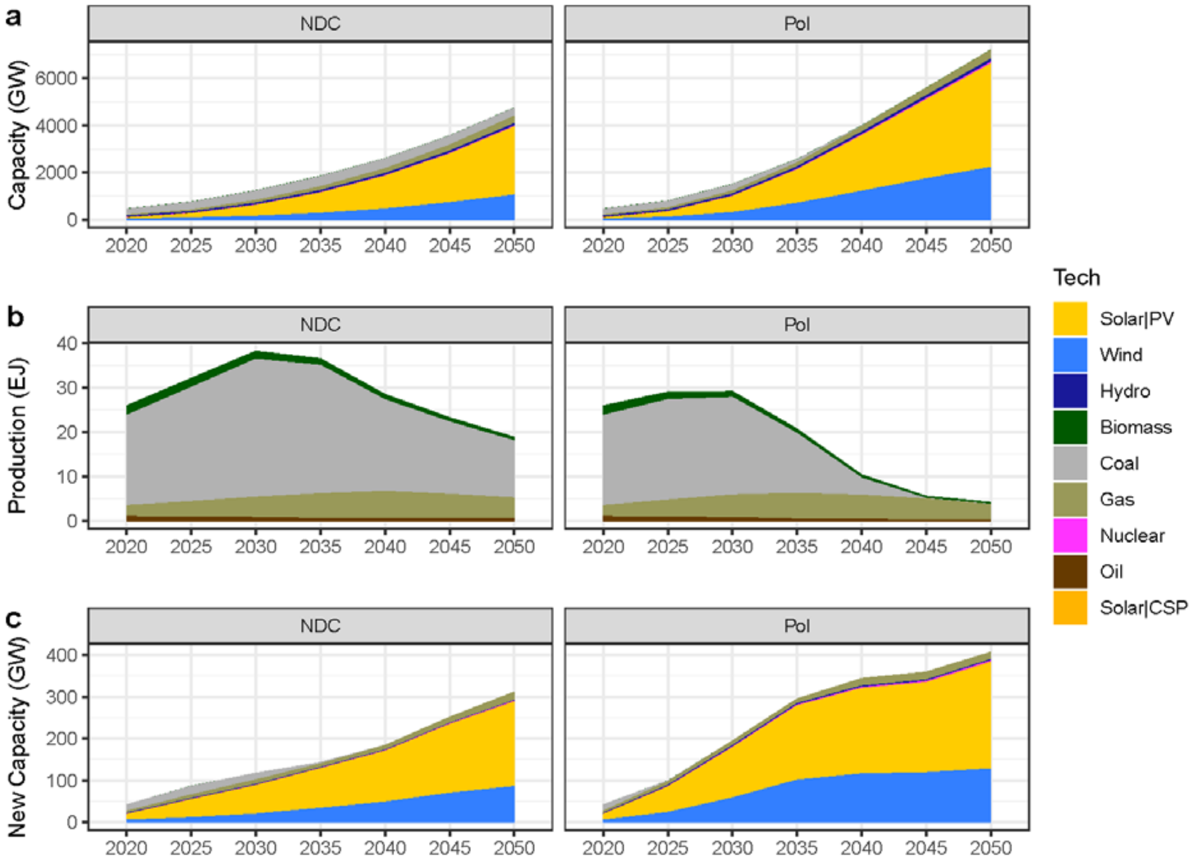

Figure S3 Capacity (GW), Production (EJ) and New Capacity (GW) for different technologies, for the two policy scenarios - NDC and Pol (1.5C-compatible)

6 Replacing coal mining jobs with solar jobs

Year	Average Employment factor – solar utility (EF_{SU}) (FTE/MW)		Average Employment factor – solar rooftop (EF_{SR})(FTE/MW)	
	O & M	**C & I**	**O & M**	**C & I**
2020-2025	0.4	1.8	0.4	4.88
2025-2030	0.25	1.25	0.25	3.2

Table S7 Average employment factor for the different time steps for solar utility and rooftop, for the two activities – O & M and C & I.

Calculation for Case I: Coal jobs only replaced by O & M jobs in solar-utility

In this case the solar capacity required to replace coal mining jobs during that particular year is:

$$\textit{Solar capacity required} = \textit{Coal jobs lost/Employment factor}_{O\,\&\,M}$$

This calculation is identical for both time steps.

Calculation for Case II: Coal jobs replaced by both O & M and C & I jobs in both solar utility and solar rooftop (20% of total)

Unlike operation and maintenance (O & M) jobs which are created for the lifetime of a power plant, construction and installation (C & I) jobs are concentrated for a limited time at the start of a power project; e.g., solar PV-utility the average is approximately 1 year. However, in an economy, where many projects are being built (and replaced) every year, people employed in C & I could in principal, continue having jobs much longer than the initial period. To consider C & I jobs as long-term jobs, we assume: i) that in 5-yr time step, the total C & I jobs resulting from the installed solar capacity are divided by 5, because assuming constant yearly installations the same number of people are employed during each of those years; ii) in the next time step, people from the previous time step need to be re-employed, however because of the decreasing employment factor / increasing labour productivity, higher capacity needs to be installed for a given amount of jobs.

<u>For the first time step (2020-2025), the required solar capacity to replace coal jobs is:</u>

Total solar capacity to be added/replace coal jobs= x

Of that, solar utility is assumed to provide 80%, and solar rooftop 20%

Coal jobs to be replaced = y

Coal jobs to be replaced = Jobs in O & M solar utility + Jobs in O & M solar rooftop +

Jobs in C & I solar utility + Jobs in C & I solar rooftop

$$y = EF_{O\&M\_SU} * (0.8x) + EF_{O\&M\_SR} * (0.2x) + \left(EF_{C\&I\_SU} * (0.8x)\right)/5 + \left(EF_{C\&I\_SR}(0.2x)\right)/5$$

$$x = y/\left[EF_{O\&M\_SU} * (0.8) + EF_{O\&M\_SR} * (0.2) + \left(EF_{C\&I\_SU} * (0.8)\right)/5 + \left(EF_{C\&I\_SR}(0.2)\right)/5\right]$$

Note that the employment factors correspond to those of 2020-2025; see Table S7.

<u>For the second time step (2025-2030), the required solar capacity is:</u>

In this time step, people in C & I from the last time step need to be re-employed in the same sector. This requires a certain capacity addition:

Total solar capacity to be added = X

Of that, solar utility is assumed to provide 80%, and solar rooftop 20%

People in C & I from last time step = Z

$$X = 5 * Z/ \left(EF_{C\&I\_SU} * (0.8)\right) + \left(EF_{C\&I\_SR} * (0.2)\right)$$

Note that the employment factors correspond to those of 2025-2030; see Table 8.

Additionally, the installation of X creates long-term jobs in O & M (W):

$$W = X* \left(EF_{O\&M\_SR} * (0.2) + EF_{C\&I\_SU} * (0.8)\right)$$

Thereby reducing the number of coal jobs to be replaced in the time step:

Jobs to be replaced = Coal jobs lost in the time step – W

Jobs to be replaced = y_2

Solar capacity to be added/replace coal jobs: x_2

Jobs to be replaced = Jobs in O & M solar utility + Jobs in O & M solar rooftop +

Jobs in C & I solar utility + Jobs in C & I solar rooftop

$$y_2 = EF_{O\&M\_SU} * (0.8x_2) + EF_{O\&M\_SR} * (0.2x_2) + \left(EF_{C\&I\_SU} * (0.8x_2)\right)/5 + \left(EF_{C\&I\_SR}(0.2x_2)\right)/5$$

Total solar capacity to be installed in the time step: X + x_2

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