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An Assessment of Solar Power Potential and Prospects in India

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Abstract: Among all the developed and developing countries, India is actively contributing to providing clean, affordable and sustainable energy to the citizens and making pace to achieve the UN Sustainable Development Goals 7 till 2030. In this regard, tremendous growth in solar energy generation has been observed in the Indian energy sector. The National Solar Mission targets to attain the goal of 100 GW upto 2022. The country's solar power potential is 748.99 Gwp. The total on-grid installed capacity is 47112.55 MW, with ground-mounted (i.e., solar power plants) accounting for 41001.49 MW and solar roofs accounting for the remaining 6111.06 MW. Solar power contributes a substantial share (41.68%) in the total annual (June 2020 to May 2021) electricity generation (147678.3 MU) from renewable sources. The rise in the overall solar installed capacity (25 MW to 48556.65 MW) in the last decade represents a massive growth in solar power in the country. India is located in the tropical and sub-tropical region, receives high intensity of solar radiation (200MW/km^2) and hence possesses more potential for energy to be harnessed. The present study provides insights into the country's existing solar energy potential, installed capacity and solar power generation to achieve goals in this sector. The potential states are categorized based on installed capacity (commissioned) through the atlas and statistical computation. Solar energy policies/schemes initiated by the Government of India are reviewed concerning the progress in the energy sector.

Keywords: Solar energy potential; Solar installed Capacity; Solar atlas; National Solar Mission.

1.1. Introduction

The biosphere is endowed with diverse ecosystems[1] providing innumerable goods and services to humankind (Glavič & Lukman, 2007), so-called natural resources. Renewable resources vary in location, quantity, quality, and sustainability and are considered inexhaustible (Lele, 2019). The clean energy resources (that emits concentration of hazardous gases) and long-lasting (sustainability) like solar energy, wind energy, geothermal energy, biomass energy, etc., are regarded as an alternative source of energy (Rathore &. Panwar, 2007). Solar energy is the viable renewable energy source derived from the Sun that has been recently promised to trim down global warming (Ramachandra et al., 2011; Hosseini, 2014). The consistent nuclear fusion reactions produce solar energy, which manifests the earth's surface in the form of heat and radiation (Shaikh et al., 2017). Humans have been utilizing solar energy to meet their energy requirements since time memorial. But, the cradle of civilizations has resulted in the development of techniques and devices to harness solar energy to use it as electricity (National Geographic Society).

Energy is often considered as the driving force for the economic development of any country (Badhotiya et al., 2021). Hence, the economy of a country depends on its energy basket (Rühl et al., 2012). The energy consumption of India is one-third per capita compared to a global level (IEA, 2021). In the India's energy Thermal Power Projects (TPP) significantly contribute the large share (61.7%) as a non-renewable energy resource. Currently, coal based energy contributes about 72 % of India's electricity generation and the country's coal supplies are predicted to be exhausted by 2050 (Badhotiya et al., 2021). The use of coal will increase the total carbon emissions of the country in nearby future. TPP and coal are exhaustible and liability on these for a longer duration is questionable. Government of India (GoI) is focusing on the hydropower potential, especially in the Indian Himalayan region (IEA, 2016), irrespective of its fragility. Hydropower being renewable has environmental consequences, which seems to be ignored for economic benefits. Thus, there is need of an alternate energy source which can promise to combat the growing population demands for electricity. Such eco-friendly energy resources will definitely gain much importance and sustainability of clean environment.

India's solar energy potential is rich and vast (> 300 sunny days and 2300–3200 sunshine hours per year) because of its geographical location in the equatorial sunbelt region. As a result, the country's average intensity of daily and annual solar radiation (GHI) is 1.1–5.9 kWh/m^2 (Fig. 1a) and 414.6–2159 kWh/m^2 (Fig. 1b), respectively. The daily and annual averages of India's photovoltaic electricity production (PVOUT) are 1.37–6.03 kWh/kWp (Fig. 2a) and 500.8–2205 kWh/kWp (Fig. 2b), respectively, which are comparable to the solar radiation received in tropical and subtropical countries (Global Solar GIS). Solar energy in India varies geographically and is broadly classified into eight categories (Fig. 1). Gujarat, western and southern Rajasthan, eastern MP,

[1] An ecosystem is a geographical area where plants, animals, and other organisms as well as atmosphere and landscapes work together to form life.

Maharashtra, Karnataka, Telangana, Tamil Nadu, Andhra Pradesh, and Ladakh have the highest annual global solar radiation (1942-2159 kWh/m^2) in the country. The other states/UT's like Haryana, Madhya Pradesh, Uttar Pradesh, Chhattisgarh, Chandigarh, Orissa, Andhra Pradesh, eastern West Bengal, Kerala, and some parts of Uttarakhand, Himachal Pradesh, Jammu and Kashmir, Maharashtra, Bihar, Andhra Pradesh, Tamil Nadu, Telangana, Mizoram, Assam, and Nagaland also receive a relatively large (1.724–1941 kWh/m^2) amount of solar radiation (Fig. 1).

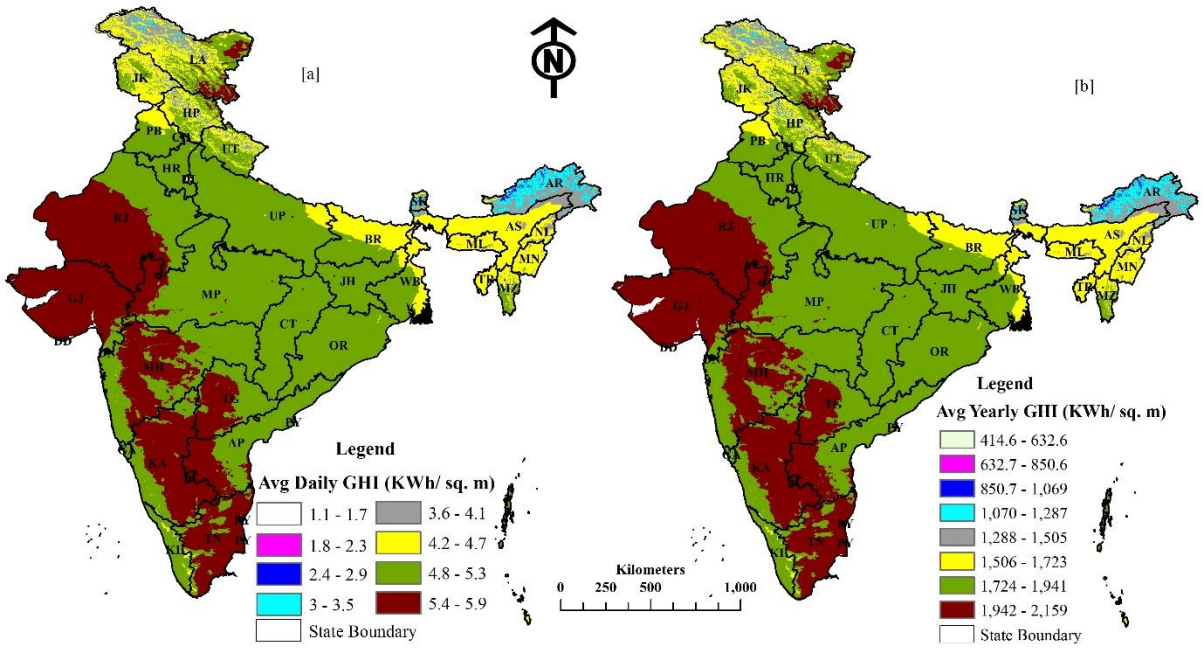

Fig. 1. [a] Showing average daily Global Horizontal Irradiation (GHI) in kWh/m^2 and [b] shows average annual Global Horizontal Irradiation (GHI) in in kWh/m^2.

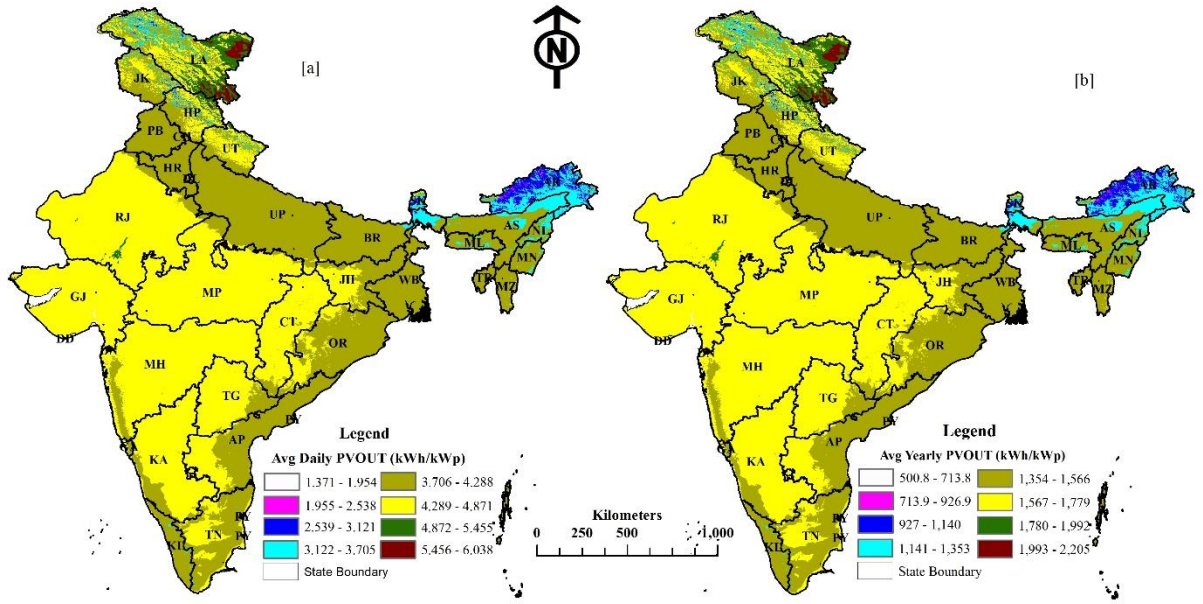

Fig. 2. [a] Showing average daily Potential Photovoltaic Electricity Production (PVOUT) in kWh/kWp and [b] shows average annual Potential Photovoltaic Electricity Production (PVOUT) in kWh/kWp.

The most remarkable story in India's electrical industry in recent years has been the tremendous expansion of solar energy, which has greatly increased its fraction in the entire energy mix. Ministry of New and Renewable Energy (MNRE, 2021) reported 60% rise in the installed solar power capacity of the country. The present study was carried out to make an overview of the country's solar energy potential, installed capacity and solar power generation. Categorization of the major states was done based on the installed capacity through atlas considered as solar atlas (Rafique et al., 2020). Various solar energy policies/schemes initiated by the GoI are reviewed.

1.2. Data sources and assessment procedure

The present study is based on different spatial and non-spatial ancillary data sources which was collected from different govt portals and other organizations (i.e., MNRE, IRENA, Electricity central authority, IEA reports, Govt of India power portal and Global solar atlas, etc.). The Bray Curtis clustering was done using the Wards method to visualize and classify the states/UT's based on installed capacity. This was done by using PAST (3.0 version) software. The month-wise (July 2020 to May 2021) solar generation data was obtained from the Central Electricity authority portal of the Government of India. The Photovoltaic power output (PVout), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiation (DIF), Global Tilted Irradiance (GTI), and Global Horizontal Irradiance (GHI) data were retrieved from the global solar atlas via simulation model tool (Fig.3) and mapping was done in ArcGIS software.

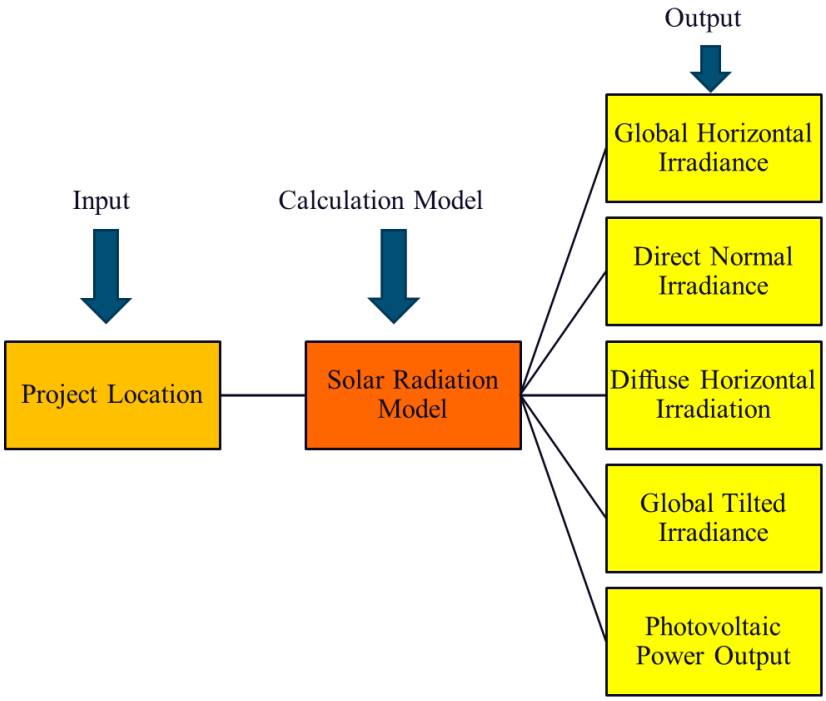

Fig. 3. Schematic chart showing the process of solar energy atlas using simulation model-based tool of Global solar atlas. (Source: Global solar atlas)

1.3. Current Scenario of Solar Power in India

1.3.1. Solar Installed Capacity & Potential

India has an overall solar power (SP) installed Capacity of 48556.65 MW and ranked fifth in the world, followed by China (254354.8 MW), the United States (75571.7 MW), Japan (66999.949 MW), and Germany (53783 MW) (MNRE, GoI 2021; IRENA 2021). The ground-mounted Solar Power Plants (SPP's), solar roof tops and off-grid contribute about 41001.49 MW, 6111.06 MW and 1,444.10 MW respectively (Table 1). Government of India documents the immense potential (748.99 Gwp) of solar energy (Table 1) and trying to boost the solar power capacity to achieve the target of 100 GW upto 2022 including 40 GW from solar rooftops (MNRE GoI 2020-21).

India has twenty-eight states and eight Union territories (UTs), encompassing an area of 3.287 million km². The four states viz. Rajasthan (9229.8 MW) followed by Karnataka (7483.4 MW), Gujarat (6116.85) and Tamil Nadu (4757.76 MW) has the maximum on-grid SP installed capacity share, the least being Lakshadweep (0.75MW) and Meghalaya (0.19 MW) (Fig. 4 & Table 1). On categorizing the states on the basis of installed Capacity Rajasthan and Karnataka solely forms 15-20%; Tamil Nadu and Gujrat (10-15%); Maharashtra, M.P, Telangana, Andhra Pradesh (5-10%); Uttarakhand, Haryana, Punjab, Uttar Pradesh (1-5%) while rest of the state's hardy has <1% share (Table.2).

Table. 1: - India's State-wise Solar Potential, SP Target, On-Grid and Off-Grid Solar Power installed Capacity.

S. No.	STATES / UTs	Solar Potential (GWp)	SP target by 2022	On-Grid SP Capacity 2020-21 (as on 30.11.2021)				Off-Grid Solar Power Cumulative Capacity (as on 31.03.2021)					
				Ground Mounted (MW)	Roof Top (MW)	Total (MW)	%	SLS (street)	HLS (No's)	SL (No's)	SPP (KWp)	Solar Pumps (No's)	Electrified Villages (No's)
1	Andaman & Nicobar	0	27	24.63	4.59	29.22	0.06	1135	468	6296	167	5	0
2	Andhra Pradesh	38.44	9834	4146.01	146.36	4292.37	9.11	15795	22972	77803	3815.6	34045	13
3	Arunachal Pradesh	8.65	39	1.27	4.34	5.61	0.01	13741	35065	125581	963.2	22	297
4	Assam	13.76	663	25.67	33.48	59.15	0.13	17384	46879	647761	1605	45	1953
5	Bihar	11.2	2493	138.93	30.55	169.48	0.36	47152	12303	1735227	6800	2813	0
6	Chandigarh	18.27	153	6.34	46.3	52.64	0.11	901	275	1675	730	12	0
7	Chhattisgarh	0	1783	277.14	31.69	308.83	0.66	3730	42232	3311	31372.9	61970	568
8	D & N Haveli	0	449	2.49	2.97	5.46	0.01	0	0	0	0	0	0
9	Daman & Diu	0	199	10.15	30.57	40.72	0.09	0	0	0	0	0	0
10	Delhi	2.05	2762	8.96	200.7	209.66	0.45	301	0	4807	1269	90	0
11	Goa	0.88	358	0.95	17.42	18.37	0.04	707	393	1093	32.72	15	19
12	Gujarat	35.77	8020	4544.37	1572.48	6116.85	12.98	5004	9253	31603	13576.6	11615	38
13	Haryana	4.56	4142	195.8	397.4	593.2	1.26	34625	56727	93853	2321.25	10103	286
14	Himachal Pradesh	33.84	776	25.75	19.29	45.04	0.10	92500	22592	33909	1905.5	46	21
15	J & K	111.05	1155	2.49	22	24.49	0.05	24904	144316	51224	8129.85	39	349
16	Jharkhand	18.18	1995	19.05	34.51	53.56	0.11	13916	9450	790515	3769.9	5051	700
17	Karnataka	24.7	5697	7145.05	338.35	7483.4	15.88	5069	52638	7781	7854.01	7496	30
18	Kerala	6.11	1870	150	156.3	306.3	0.65	1735	41912	54367	16078.39	818	607
19	Ladakh	0	0	6	1.8	7.8	0.02	0	0	0	0	0	0
20	Lakshadweep	0	4	0.75	0	0.75	0.00	4465	600	5289	2190	0	0
21	M.P	61.66	5675	2431.88	160.14	2592.02	5.50	14258	7920	529101	3654	25047	577
22	Maharashtra	64.32	11926	1646.24	860.57	2506.81	5.32	10420	3497	239297	3857.7	11315	340
23	Manipur	10.63	105	0	6.36	6.36	0.01	22367	24583	9058	1580.5	40	240
24	Meghalaya	5.86	161	0	0.19	0.19	0.00	5800	14874	40750	2004	19	149
25	Mizoram	9.09	72	0.1	1.43	1.53	0.00	10117	12060	107217	3864.6	37	20
26	Nagaland	7.29	61	0	1	1	0.00	15125	1045	6766	1506	3	11
27	Odisha	25.78	2377	383.56	21.66	405.22	0.86	17955	5274	99843	2191.51	9661	1614
28	Pondicherry	0	246	0.8	11.07	11.87	0.03	417	25	1637	121	21	0
29	Punjab	2.81	4772	828.58	222.51	1051.09	2.23	43448	8626	17495	2066	5689	0
30	Rajasthan	142.31	5762	8617.78	612.02	9229.8	19.59	7114	187968	225851	30449	56819	382
31	Sikkim	4.94	36	0	2.76	2.76	0.01	504	15059	23300	850	0	13
32	Tamil Nadu	17.67	8884	4424.15	333.61	4757.76	10.10	40324	298641	16818	13052.6	6447	131
33	Telangana	20.41	0	3822.32	209.74	4032.06	8.56	2208	0	12000	7450	424	0
34	Tripura	2.08	105	5	4.41	9.41	0.02	6887	32723	288941	867	214	842
35	Uttar Pradesh	22.83	10697	1731.5	258.78	1990.28	4.22	291392	235909	2351205	10638.31	31609	335
36	Uttarakhand	16.8	900	277.78	262.71	540.49	1.15	34218	91595	163386	4059.53	26	594
37	West Bengal	6.26	5336	100	51	151	0.32	15605	145332	17662	1730	653	1179
38	Others*	0.79	0	0	0	0	0.00	9150	140273	125797	23885	4621	0
	Total	**748.99**	**99534**	**41001.49**	**6111.06**	**47112.55**	**100**	**830373.00**	**1723479.00**	**7948219.00**	**216407.67**	**286830.00**	**11308.00**

Table.2: - State-wise contribution in overall installed capacity of Solar Power in India

On-grid installed capacity (%)	Names of states under different capacity class
< 1%	Meghalaya, Lakshadweep, Nagaland, Mizoram, Sikkim, D & N Haveli, Arunachal Pradesh, Manipur, Ladakh, Tripura, Pondicherry, Goa, J & K, Andaman & Nicobar, Daman & Diu, Himachal Pradesh, Chandigarh, Jharkhand, Assam, West Bengal, Bihar, Delhi, Kerala, Chhattisgarh, Odisha
1%-5%	Uttarakhand, Haryana, Punjab, Uttar Pradesh
5%-10%	Maharashtra, M.P, Telangana, Andhra Pradesh
10%-15%	Tamil Nadu, Gujarat
15%-20%	Rajasthan, Karnataka

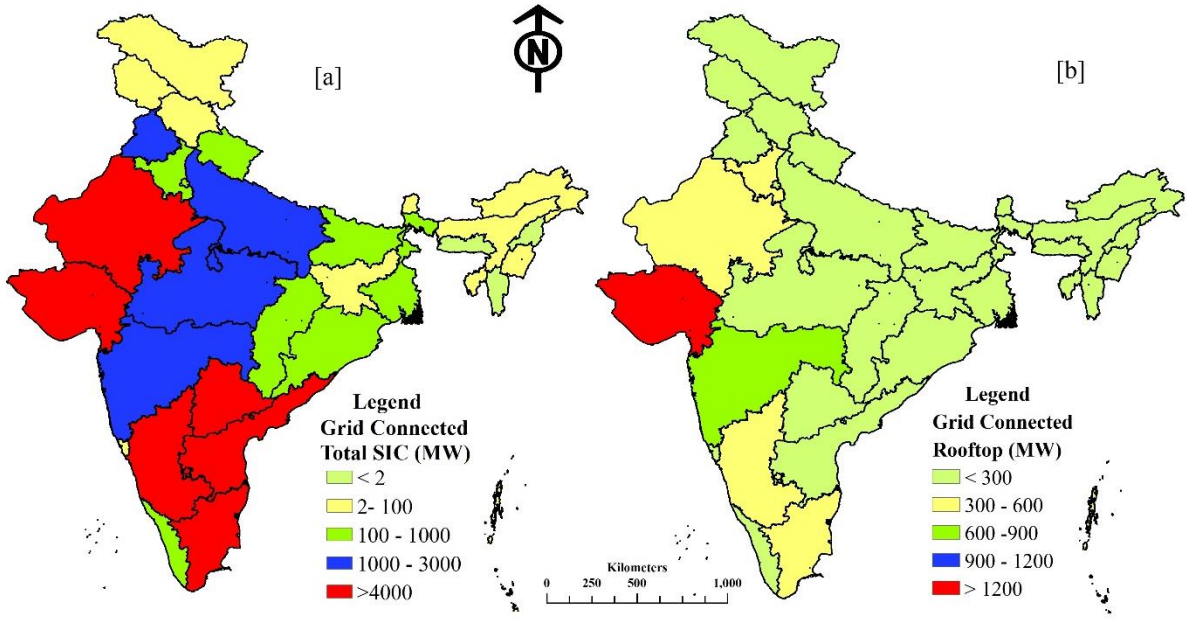

Fig. 4. [a] Showing state wise total solar installed capacity and [b] shows grid connected rooftop solar installed capacity upto 30th Nov 2021 according to available data of MNRE.

On the basis of cluster analysis, in order to classify the states in terms of installed capacity, it was found that, the six states/UTs were considered as high installed capacity (> 4000 MW), four as moderate to high capacity (1000 to 3000 MW), eight low to moderate (100 to 1000 MW) (Fig. 5). Most of the states (14) having low installed capacity (2 to 100 MW) forms individual group and the remaining states are considered as very low capacity (0.1 to 2 MW). Others form an out group with very low installed capacity (>0.1 MW) (Fig. 5).

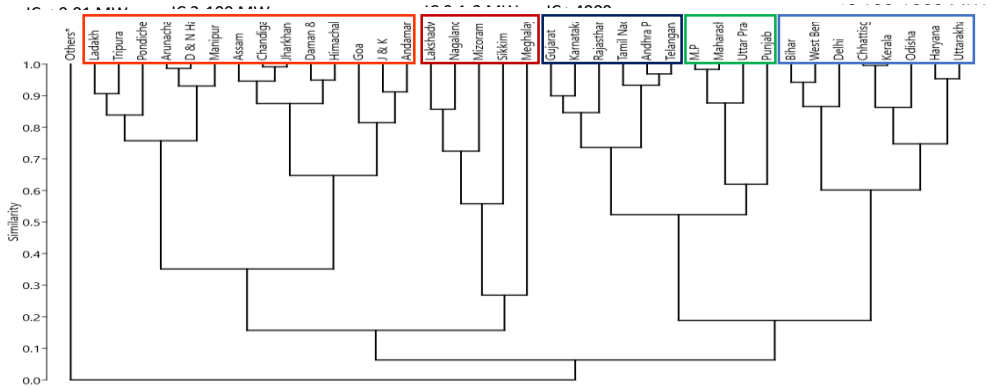

Fig. 5. Bray Curtis (Wards method) Classification of the states/UT's on the basis of installed capacity. Only six states/UT crosses the 4000 MW and considered as high-capacity states whereas most of the states has installed capacity below 100 MW considered as low-capacity states/UTs.

However, in terms of solar potential, Rajasthan (142.31 Gwp), Jammu and Kashmir (111.05 Gwp), Maharashtra (64.32 Gwp), Madhya Pradesh (61.66 Gwp) are acknowledged to have the maximum potential (Fig. 6a & Table 1). The majority of the state's, irrespective of high potential, still witness low capacity (Fig. 7), suggesting the Government pay more attention to developing the infrastructure and awareness, thereby formulating suitable policies. The state/UT wise target of solar power is illustrated in Fig. 6b and Table 1.

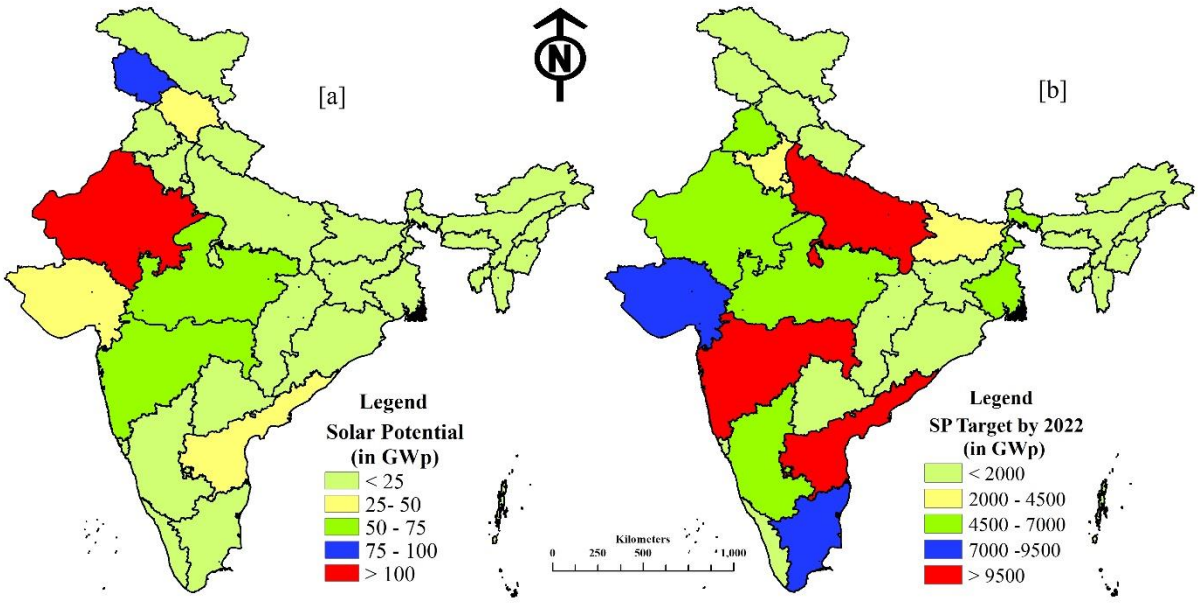

Fig. 6. [a] Showing state wise solar potential of India and [b] shows solar power target upto 31st march 2021 according to available data of MNRE.

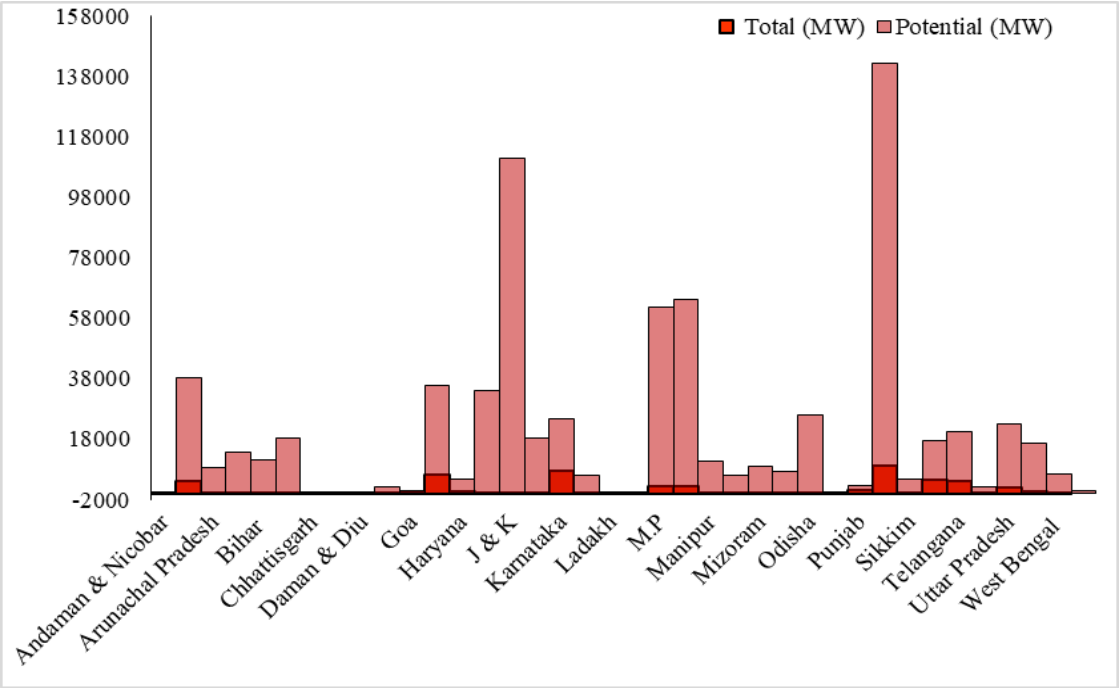

Fig. 7. Bare graph representing the gap between potential and installed capacity in the states of India. The potential of few states/UT (Chhattisgarh, is not available on the MNRE website, hence the bars (potential) dips. Irrespective of the rich potential the installed capacity is very low indicating the development of solar power at its nascent phase in India.

1.3.2. Off-Grid SP installed capacity

The Off-Grid and Decentralized Solar PV Applications Programme was initiated by the Government in 1992 (MNRE annual report 2021). This program offers assistance (Central Financial Assistance) for the deployment of solar street lights, solar study lamps, and solar power plants to rural regions of the country. Among these solar street lights figures the maximum number (1723479) least being solar pumps (286830) (Table.1). However, the capacity of small solar power plants is 216407.7 KWp, which is expected to increase in the near future gradually.

The off-grid solar capacity varies from state to state in the country, irrespective of the solar potential. Uttar Pradesh is the leading street light installer state with the highest number (291392) followed by Himachal Pradesh (92500), Bihar (47152), Punjab (43448), Tamil Nadu (40324), Haryana (34625), Uttarakhand (34218), and Jammu and Kashmir (24902) (Fig. 8a & Table 1).

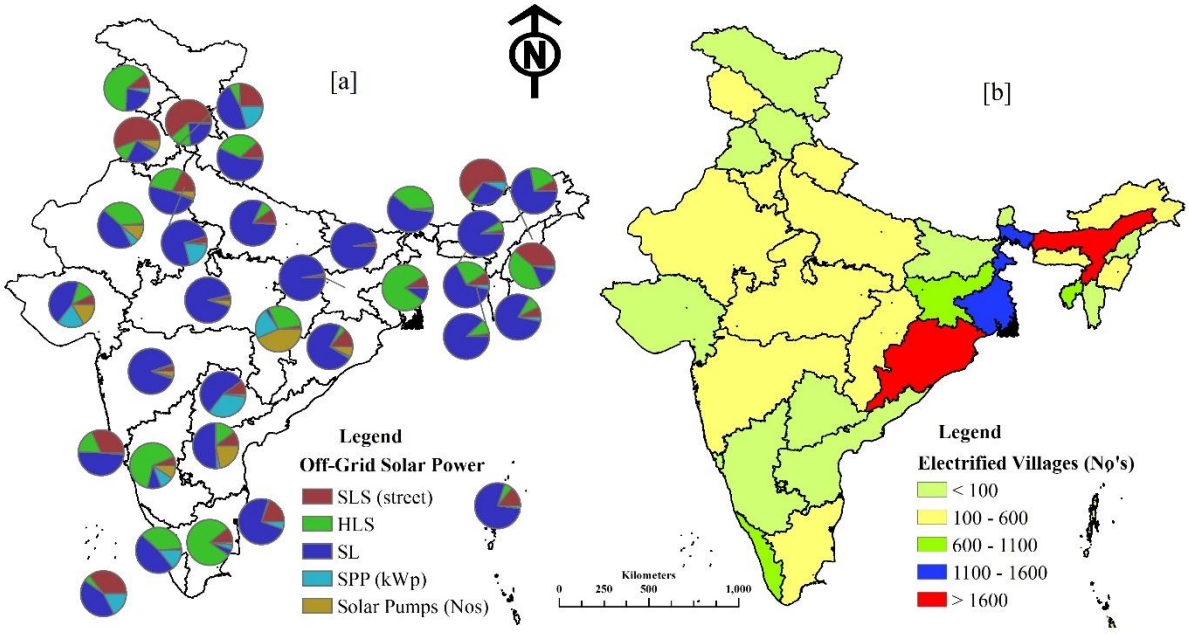

Fig. 8. [a] Showing state wise off-grid solar power capacity (SLS, HLS, SL, SPP's & Solar Pumps) and [b] shows state wise electrified villages through off-grid solar power upto 30th march 2021 according to available data of MNRE.

The pattern was quite different in case of home lights (Tamil Nadu >Uttar Pradesh > West Bengal > Jammu and Kashmir > and Uttarakhand), solar pumps (Chhattisgarh > Rajasthan > Andhra Pradesh > Uttar Pradesh > Madhya Pradesh > Gujarat and Maharashtra), study lamps (Uttar Pradesh > Bihar > Jharkhand > Assam > M.P > Tripura, > Maharashtra > Rajasthan > Uttarakhand) and off-grid solar power plants (Chhattisgarh > Rajasthan > Kerala > Gujarat > Tamilnadu > UP > J&K >Karnataka > Telangana > Bihar > Uttarakhand) (Fig. 8a & Table 1). The off-grid solar power has been recorded to electrify 11308 villages/hamlets. Assam has the highest number (1953) of electrified villages followed by Odisha (1614), West Bengal (1179), Tripura (842), and Jharkhand (568) till March 2021 (Fig. 8b & Table 1).

1.4. Growth pattern of installed capacity

The installed capacity of renewable energy is 104031.32 MW (as per MNRE physical progress, November 2021). Solar energy has the biggest share of the total, at 46.68% (Fig. 8), followed by wind energy (38.48%), Biomass (9.78%), and small hydropower (4.64 %) (MNRE, Nov 2021). A sharp rise in installation capacity of solar energy (565.5 MW to 48556.65 MW) is observed in the recent decade (Fig. 9), documenting a massive growth in the installed capacity. The cumulative installed capacity was 41236.02 MW (March 2021). A rapid rise (7320.63 MW) in very short period (i.e., April-November 2021) has been seen in the overall capacity (Fig. 9), which reflects the country's efforts for renewable energy and vision to reduce greenhouse gases.

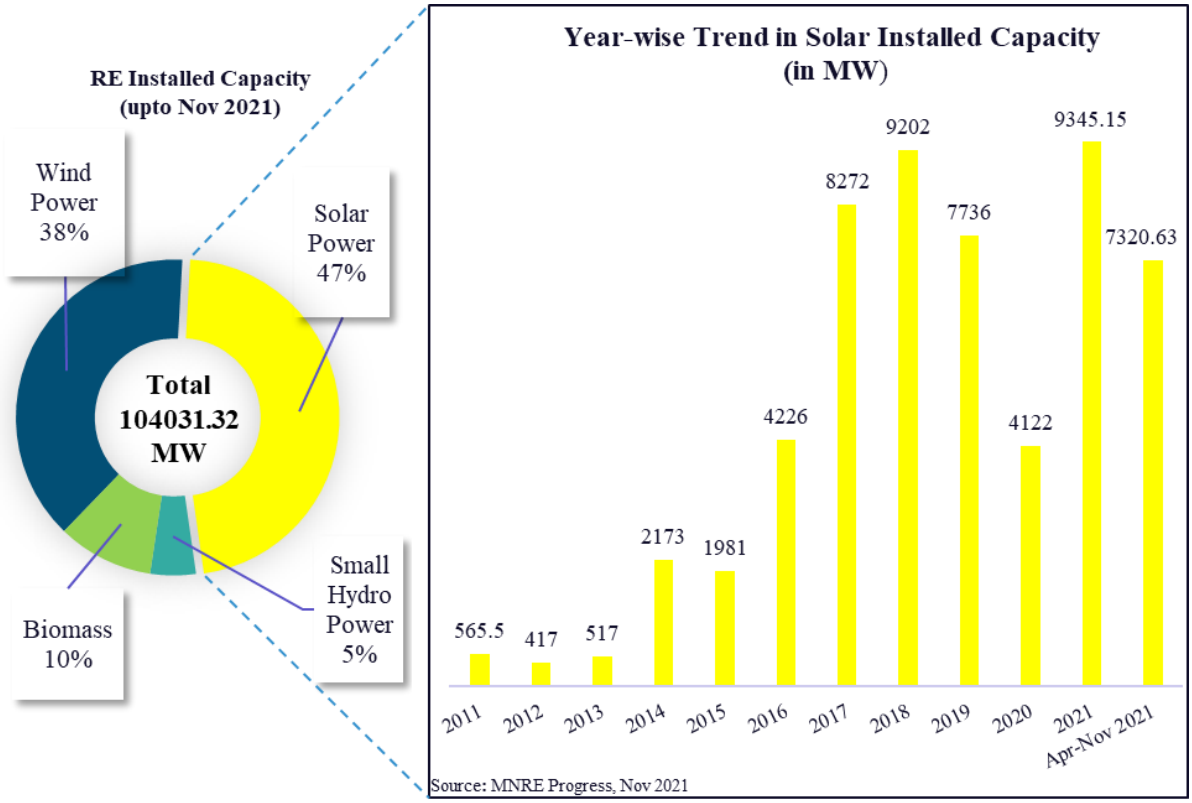

Fig. 9. Share of Renewable energy installed capacity and the annual pattern of solar installed capacity from 2011 to Nov 2021 and recent rise from April – November (eight months) of 2021.

1.5. Solar Parks (SPs)

Solar Parks are grid-connected large photovoltaic power stations (Bloss et al., 1991) where the developers generate electricity through solar panels. The development of Solar Parks and Ultra Mega Solar Power Projects, with a cumulative capacity of 20,000 MW, was unveiled in December 2014. The potential of the Solar Park Scheme was projected to 40,000 MW in March 2017 with an aim to establish 50 new solar parks by 2021-22. Currently, the total number of solar parks (commissioned/approved) in the country is 42 (March 2021) (Table 3 & Fig.10), with a total installed capacity of 25751 MW (Table 3). Regardless of the number of SPs, Gujarat (3 SPs) has the highest solar power capacity (6200 MW). Manipur, Meghalaya, and Mizoram have the lowest capacity (20 MW) due to the least number of SPs (One each). Rajasthan, on the other hand, has a capacity of 4331 MW and 6 SPs (Table 3), and has the largest SP (2245 MW) in the country.

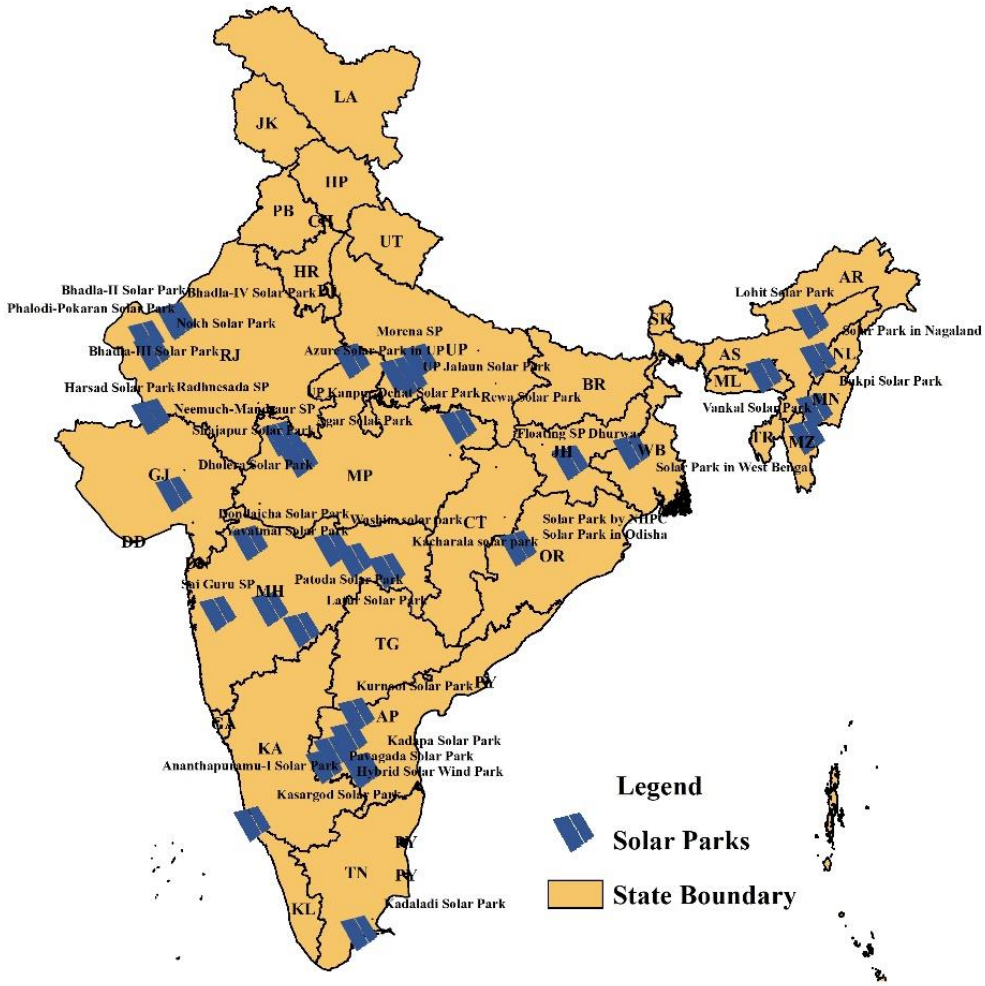

Fig. 10. Mapping of established solar parks in India (approved/commissioned as per 31 march 2020). Maharashtra (7) state has the maximum number of parks, followed by Rajasthan (6) and Madhya Pradesh and Andhra Pradesh (5 each).

Table. 3: - Solar Parks (approved/commissioned) in India as per 31st March 2021 (MNRE, annual report 2021)

Sl. No.	Solar Parks	Capacity (MW)	State & SPPD	Location
1	Ananthapuramu-I Solar Park	1500	(Andhra Pradesh)	NP Kunta of Anantpuramu & Galiveedu of Districts Kadapa
2	Kurnool Solar Park	1000	AP Solar Power Corporation Pvt. Ltd. (APSPCL), JVC of SECI, APGENCO and NREDCAP	Gani and Sakunala Village of District Kurnool
3	Kadapa Solar Park	1000		Vaddirala, Pannampalli, Thalamanchi,, Ramachandrayapalli, Dhidium and Konna Ananthapuram villages in MylavaramMadal, Kadapa district
4	Ananthapuramu-II Solar Park	500		Talaricheruvu & Aluru Villages, Anathapuramu
5	Hybrid Solar Wind Park	160		Kanagana palli Mandal, District Ananthapuramu
6	Lohit Solar Park	30	Arunachal Pradesh (APEDA)	Tezu town in Lohit district
7	Radhnesada SP	700	Gujarat	Radhnesada, Vav, Distt. Banaskantha
8	Harsad Solar Park	500		Harsad and Navapara, Villages District-Banaskatha

9	Dholera Solar Park	5000	(GPCL)	SIR (Dholera Special Investment Region), Ahmedabad District
10	Floating SP	150	Jharkhand (SECI)	Getalsud and Dhurwa Dam
11	Pavagada Solar Park	2000	(Karnataka) KSPDCL, JVC of KREDL & SECI	Valluru, Balasamudra, Rayacharlu, , Thirumani Kyathaganacharlu, of Tumkur district.
12	Kasargod Solar Park	105	(Kerala) RPCKL, JVC of SECI	Kinanoor Paivalike, Kraindalam, Meenja and Ambalathara villages of Kasargode district
13	Rewa Solar Park	750	Madhya Pradesh (RUMSL, JVC of MPNRED & SECI)	Gurh t, District Rewa
14	Neemuch-Mandsaur SP	700		Neemuch site: Badi, Kawai and Bardwada in Singoli tehsil, Mandsaur site: Runija and Gujjarkhedi in Suwasra Tehsil, Mandsaur district
15	Agar Solar Park	550		Susner & Agar tehsil of Agar District
16	Shajapur Solar Park	500		Moman, Badodiya & Shajapur tehsil of Shajapur District
17	Morena SP	250		Morena, (Chambal)
18	Sai Guru SP	500	Maharashtra M/s Sai Guru Mega Solar Park Pvt. Ltd.	Bhamer Village, Dhule District
19	Patoda Solar Park (Paramount)	500	Maharashtra M/s Paramount Solar Power Pvt. Ltd.	Villages Tambarajuri, and Wadzari, Dist. Beed.
20	Dondaicha Solar Park	500	Maharashtra Maharashtra State Electricity Generating Company Ltd. (MAHAGENCO)	Vikhran & Methi, villages of Dhule district
21	Latur Solar Park	60		Sindala Lohara of District-Latur
22	Washim solar park	170		PardiTakmor (30 MW), Babhulgaon (20 MW), Dudhkheda (60 MW), Saykheda (20 MW), and Kanzara (40 MW) in District Washim
23	Yavatmal Solar Park	75		PimpriIjara (25 MW), Mangladevi (25 MW), & Malkhed (25MW) in District Yavatmal
24	Kacharala solar park	145		Kacharala, village of district Chandrapur
25	Bukpi Solar Park	20	Manipur (MTDCL)	Bukpi Village in District Pherzawl
26	Solar Park in Meghalaya	20	Meghalaya (MePGCL)	Thamar, West & East Jaintia Hills districts
27	Vankal Solar Park	20	Mizoram (ZEDA)	Vankal & Khawzal RD Block in district Chmaphai
28	Solar Park in Nagaland	23	Nagaland (DNRE)	Jalukie (11 MW) of Peren district & Ganeshnagar (12 MW) of Dimapur district
29	Solar Park in Odisha	275	Odisha (GEDCOL)	Keonjhar, Balasore, Boudh, Deogarh, Kalahandi and Angul

30	Solar Park by NHPC	100	Odisha (NHPC Limited)	Landeihil Village of Tehsil Jagannath Prasad, Ganjam District
31	Bhadla-II Solar Park	680	Rajasthan (RSDCL)	Village Bhadla in Jodhpur District
32	Bhadla-III Solar Park	1000	Rajasthan (SUCRL) JVC of State Govt	Village Bhadla in Jodhpur District
33	Bhadla-IV Solar Park	500	Rajasthan (AREPRL) JVC of State Govt	Village Bhadla in Jodhpur District
34	Phalodi-Pokaran Solar Park	750	Rajasthan (ESUCRL) JVC of State Govt	Ugraas, Nagnechinagar & Dandhu villages in tehsil Phalodi, Jodhpur (450 MW) and Lavan & Purohitsar of tehsil Pokaran in district Jaisalmer (300 MW)
35	Fatehgarh Phase-1B Solar Park	421	Rajasthan (AREPRL) JVC of State Govt	Fatehgarh & Pokaran, Jaisalmer
36	Nokh Solar Park	980	Rajasthan (RSDCL)	Nokh & Pokaran villages in Jaisalmer
37	Kadaladi Solar Park	500	Tamil Nadu (TNEB)	Narippaiyur village of tehsil Kadaladi in Ramanathapuram District
38	Solar Park in UP	440	Uttar Pradesh (LSPDCL) JVC of UPNEDA & SECI	Kalpi & Orai Tehsils of Jalaun, , Chaanbe tehsil of Mirzapur, Akbarpur tehsil in Kanpur, Meja tehsil of Allahabad Dehat districts
39	UP Kanpur Dehat Solar Park	50		Village Leharapur of tehsil Akbarpur in District Kanpur Dehat
40	UP Jalaun Solar Park	50		Mirzapur Jagir village of tehsil Madhogarh in District Jalaun
41	UP Kanpur Nagar Solar Park	30		Village Katar of Tehsil Ghatampur in District Kanpur Nagar
42	Solar Park in West Bengal	200	West Bengal (WBSEDCL)	East & West Mednipur in Bankura District

1.6. Renewable energy generation in India

Renewable energy sources contribute 147678.3 MU (million units) of the total electricity generation from June 2020 to May 2021 (Central electricity authority, GoI). Solar power alone accounts for 41.68% (61256 MU) (Fig.11) led by wind energy (41.48%), biomass (2.18%), bagasse (7.24%), small hydel (6.26%) and others (1.17%). The solar power generation was highest in Karnataka 21.45 % (13200.72 MU), followed by Rajasthan (17.21 %), Andhra Pradesh (11.64 %), Telangana (10.33 %), Gujarat (7.93 %), M.P (6.83 %), Maharashtra (5.09 %), and Uttar Pradesh (3.35%) (Ministry of Power, Government of India).

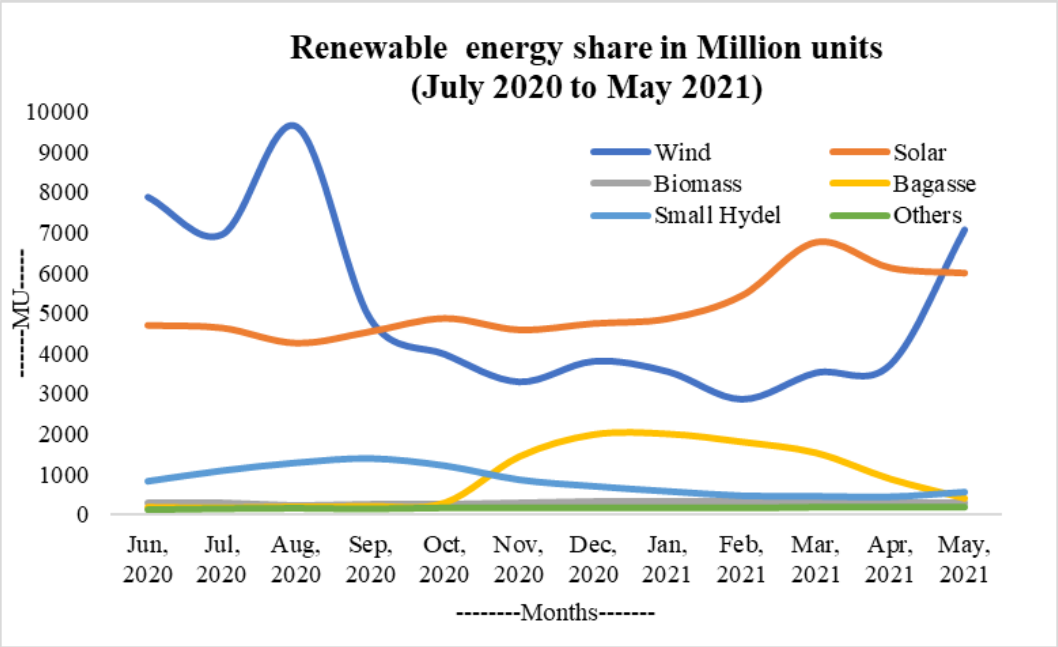

Fig. 11. A monthly contribution of renewable sources of energy to the total renewable electricity generation in India. Solar energy has the highest proportion over the majority of the year except for few months where wind energy dominates.

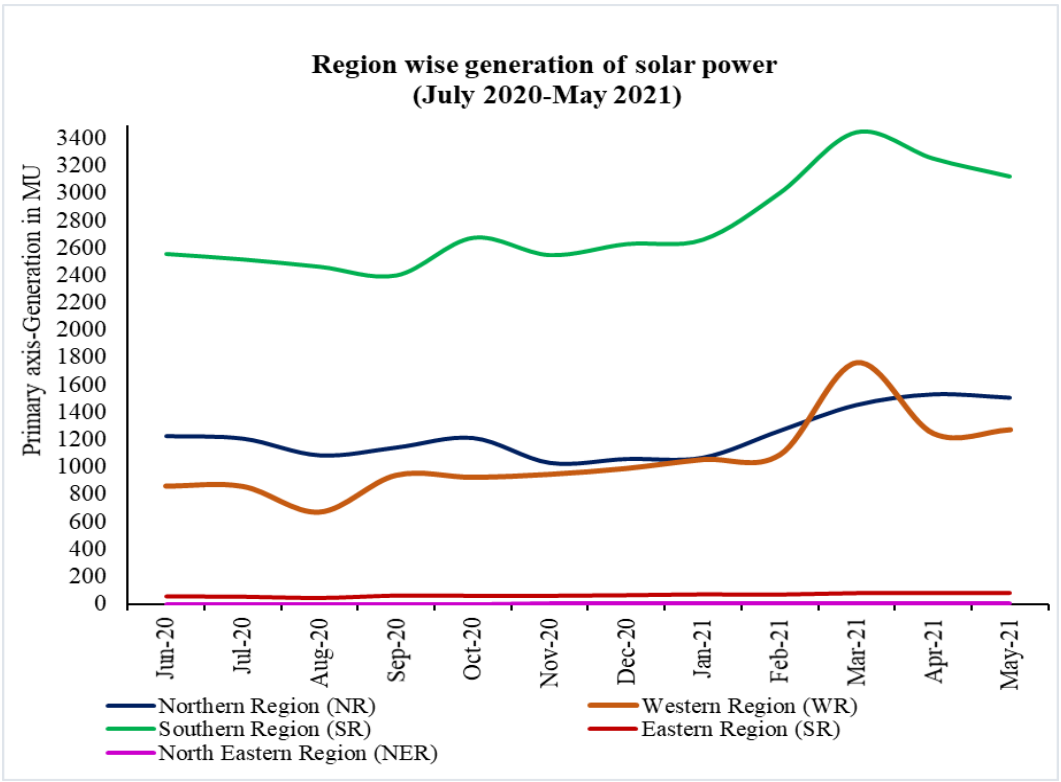

Fig. 12. Temporal pattern of solar power generation (in million units) in different regions of India. SR and WR has maximum generation while ER, NER and NR has least.

The southern region states collectively claim maximum generation, followed by Northern and Western (Fig.12). Irrespective of the short sunny days, maximum generation was observed in February. This can be possibly attributed to the seasonal tilt, which determines the concentration of solar radiation perceived by the Sun.

1.7. Solar atlas of top 10 cities in India in terms of solar power capacity

The Solar Atlas web-based tool is used to compute the long-term average of solar resources and their potential for power generation at a specific location (Rafique et al., 2020). Solar Atlas of any location depends on several parameters such as photovoltaic power

output[2] (PV out), Direct Normal Irradiance[3] (DNI), Diffuse Horizontal Irradiation[4] (DIF), Global Horizontal Irradiance[5] (GHI), and Global Tilted Irradiance[6] (GTI). Solar atlas for the top 10 states of India with maximum solar power capacity was designed using simulation model-based tool of Global solar atlas (Fig. 9). The daily average value of PV_{out} (4.40 kWh/KWp), DNI (4.03 KWh/m^2), DIF (2.48 KWh/m^2), GHI (5.28 KWh/m^2), and GTI (5.64 KWh/m^2) (Table 4) suggests the great potential of solar energy across these states.

Table.4: - Solar power capacity in urban centres of top 10 states

State	P_{Vout} (KWh/KWp per day	GHI KWh/m2 per day	DNI KWh/m2 per day	DIF KWh/m2 per day	GTI KWh/m2 per day
Rajasthan	4.766	5.487	4.820	2.329	6.129
Karnataka	4.436	5.403	4.142	2.458	5.668
Tamil Nadu	4.389	5.571	3.934	2.624	5.672
Andhra Pradesh	4.25	5.285	3.77	2.560	5.504
Telangana	4.434	5.354	4.023	2.496	5.668
Gujarat	4.658	5.542	4.867	2.273	6.033
Madhya Pradesh	4.449	5.228	4.149	2.416	5.696
Maharashtra	4.361	5.315	3.872	2.586	5.619
Uttar Pradesh	4.109	4.843	3.313	2.565	5.223
Punjab	4.153	4.795	3.446	2.511	5.27

Source: Global solar atlas generated using simulation model-based tool

1.8. Role of agencies in developing solar power in India

The National Solar Mission (NSM) from 2010 has taken the major initiative towards developing renewable energy have a target of 100 GW by 2022. NSM also launched several policies to strengthen India as a global leader in solar energy and ultimately meet the UN's sustainable goal of providing clean and affordable energy. In line to develop solar power development in India, *Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan (PM-KUSUM)* provides sustainable water and energy security for farmers by empowering them Annadata (food producer) as well as Urjadata (energy producer). In addition to this, Roof Top Solar (RTS) Programme (2015) provides subsidies to residential, institutions and social sectors for roof-top solar power generation. Solar Parks Scheme and Green Energy Corridor (2015) also make a huge impact in generating power at a large scale. Off-Grid Solar PV Applications Programme (Phase III) provides energy supply in remote rural areas, whereas the solar city concept aims to generate clean and sustainable energy.

Conclusion

A rapid growth in solar power installation showcases the efforts of the Government towards clean and green energy to achieve the sustainability goals. But, are these efforts enough to meet the projected target and harness the enormous potential is a matter of concern. Only nine states contribute the maximum share (75.65%) of solar potential. There is a need to establish more solar power plants in favourable geographical locations where the potential is high. This can be possibly done by identifying the more suitable sites in the region where very low or negligible solar power capacity is recorded. The use of modern emerging GIS-based techniques to perform this task is highly suggested. Identifying the potential rich locations will provide a future road map for establishing solar power plants. Further, the high potential regions must be effectively harnessed using the recent innovations in harnessing devices.

Although the GoI has initiated different awareness programs (web & apps), there is still a need for much more small-scale schemes at the local level. The schemes of the GoI to provide training and education to the youth in the field of solar power (renewable resources) indicates a clear vision of govt towards sustainable development. Such scholarship-based schemes must be enhanced, which may possibly result in innovations. GoI has yet to accomplish its aim of employing solar energy as an alternative energy source, but it is relying on hydropower plants despite its environmental implications. Thus, it is suggested to pay more attention to clean and green energy. The other major factor is the affordability of solar panels. The initial price, efficiency, and price per watt of the solar panel are the factors that affect affordability. The higher the efficiency, the more electricity will produce by each panel.

[2] PV_{out} represents the amount of power generated per unit of the installed PV capacity over the long-term, and it is measured in kWh/kWp

[3] Direct irradiance is the part of the solar irradiance that directly reaches a surface

[4] Diffuse irradiance is the part that is scattered by the atmosphere

[5] Global irradiance is the sum of both diffuse and direct components reaching the same surface

[6] Global Tilted Irradiance represents irradiation that falls on a tilted surface

With positive indicators that energy is becoming more sustainable and broadly available, the world is making progress in achieving UNs Sustainable Development Goal 7 till 2030. In poorer countries, access to electricity has begun to increase, energy efficiency is improving, and renewable energy is making significant progress in the power sector.

Conflict of interest

The authors declare that they have no known competing financial interests or personal ties that might have influenced the research presented in this study.

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