Harnessing Solar Energy from Wind Farms: Case Study of Four Wind Farms

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1 Introduction

Large-scale solar photovoltaic (PV) and wind energy systems are developed all over the world for fulfilling the demand of electricity. Solar and wind resources have great potential for power generation due to their social, economical, and environmental benefits and are also motivated by government policies and incentives. As per the Ministry of New and Renewable Energy (MNRE) of the Government of India, the achieved total solar and wind power installed capacities are 33.730 GW and 37.505 GW, respectively, in the country till the end of December 2019 [1]. But both, solar PV and wind energy systems operate at varying times depending on their availability, and thus continuous reliable power production is not possible in separate solar PV and wind power plants.

In wind farms, a large amount of land is vacant to avoid wake losses. The better utilization of this free land in between wind turbines can be possible by the installation of solar PV modules. Therefore, additional electricity can be generated from the same wind farm [2, 3]. A combined solar PV-wind power plant is more reliable and economical than a standalone power plant. Also, the combined systems provide other advantages-like saving the land, having the same grid for both systems and greater reliability of the power system for the supply of energy to the grid. The combined solar-wind power plant becomes cost-effective as the cost of solar PV module is continuously reducing [4].

The study [5] presented a grid-connected solar-wind hybrid system performance at a remote island in India and observed a low tariff rate of electricity. The levelized cost

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of electricity was observed as 2.74 Rs/kWh as compared to supply from the grid. The study [6] discussed the performance and detailed design of a grid-connected solar-wind hybrid system at a large scale with the incorporation of control approaches. The authors illustrated the annual energy yield was 1.509 TWh/year from hybridization of 50 MW solar power plant and 200 MW wind power plant. A feasibility study of hybridization of the solar power plant in exiting wind farm of 18 wind turbines (each of 2 MW) was presented in [7]. The authors observed the annual capacity improvement was 90% and the payback period is 7 years only. The repowering of the wind farm concept not only improves the system performance but also increases the lifespan of the system too. In this context, the study [8] presented an analytical study of wind farm repowering by the integration of new wind turbines and solar photovoltaics. Using PVsyst, the authors analyzed the shaded area between wind turbines for PV module installation with an understanding of sun geometry. The wind turbines installed in 5D × 7D configuration in 6 MW wind farm at Kayathar, Tuticorin District, Tamil Nadu. They observed huge power improvement with the integration of solar power plants in vacant land.

From the motivation, the following work presents a theoretical performance study of the wind farms integrated with solar photovoltaic power plants installing in vacant land between wind turbines. As per MNRE [1], the wind and solar installation potential wise, the top seven states in India are Karnataka, Rajasthan, Tamil Nadu, Andhra Pradesh, Gujrat, Maharashtra, and Madhya Pradesh. Therefore, four different wind farms located in four states Tamil Nadu, Rajasthan, Andhra Pradesh, and Karnataka of India are considered in the present study. The wind farm layout has been considered as 5D × 7D and a comparative study of the electricity generation from solar PV plant in different cases of vacant space coverage has been presented.

The paper embodied as Sect. 2 explains the concept of combined solar PV and wind power plants. In Sect. 3, the electric energy production and performance of solar photovoltaic power plants at four wind farm sites by taking six cases of the area covered by solar PV modules are estimated. The monthly electric energy production for 5% of area coverage and annual electric energy production for 5%, 10%, 15%, 20%, 25%, and 30% of area coverage by PV modules are estimated using PVsyst software. Section 4 presents the conclusions of this paper.

2 Combined Solar PV and Wind Power Plant

The arrangement of wind turbines (micro siting) has to be done properly in a wind farm for minimizing the wind farm array losses and enhancing the performance of the wind power plant [9]. The land between wind electric generators remains unutilized and can be used for producing electric energy. The performance of separate solar PV power plant is dependent on weather conditions and hence its reliability is also less. The combined solar PV-wind power plant will be more reliable and more efficient than a separate solar PV and a separate wind power plant. The advantage of the combined system is that the same land can be used for the dual purpose of producing electricity from two different types of power plants and efficient utilization of land is possible. The spacing between wind turbines can produce additional electricity by implementing the solar photovoltaic power plant in between wind turbines. Solar photovoltaic and wind energy systems are complementary to each other and their respective power generation timing is also different for most of the time. This will improve overall power fluctuations.

3 Case Study of Four Wind Farms Located in Four Different States for Feasibility of Combined Solar PV and Wind Power Plants

In India, most of the states have the availability of solar insolation that is sufficient for energy generation by using solar PV modules for about 300 days in a year. The states like Tamil Nadu, Gujarat, Rajasthan, Madhya Pradesh, and Andhra Pradesh have sites with high wind power density for wind electricity generation and also high solar insolation for solar PV based electricity generation. In this paper, four locations namely Pratapgarh in Rajasthan, Davangere in Karnataka, Tirunelveli in Tamil Nadu, and Anantpur in Andhra Pradesh are selected for estimation of solar PV power plant electricity generation at four previously installed wind farms in these four sites. The locations of four chosen sites are shown in Fig. 1.

Fig. 1 Four wind farm sites are located on the India map for which solar PV power plant feasibility analysis is done

3.1 Description of the Four Working Wind Farm Sites

Site 1: wind farm of 45 MW is located at village Dalot, taluka Arnod of district Pratapgarh in Rajasthan (RJ) state of India. The geographical coordinates of the project site are latitude 23º 39’ 28.7” N and longitude 74º 47’ 42.9” E, respectively. May and June are the hottest months. After summer, rainfall occurs due to the southwest monsoon. The month of December and January are the coldest. The wind farm consists of thirty 1.5 MW ReGen Powertech make wind turbines and are installed by Green Infra Wind Farms Assets Limited (GIWFAL). The annual electric energy production of the wind farm is 78,840 MWh at a plant load factor (PLF) of 20% [10].

Site 2: a 29.70 MW wind power project is situated at Davangere district in Karnataka (KA) state of India. This project is spread in two villages namely Anabaru and Arasinagundi in Jagalur taluka, with Anabaru having an installed capacity of 13.20 MW and Arasinagundi having an installed capacity of 16.50 MW. These villages are approximately 250 km from Bangalore city of Karnataka. The site is situated between latitudes 14°28’–14°34’ N and longitudes 76°20’–76º23’ E. The altitude is 700-810 m above mean sea level. This project has eighteen 1.65 MW Vestas V82 make wind turbines. The annual electric energy production of wind farms is 94,884.72 MWh at a plant load factor of 36.47%. The owner of the project is Accion Wind Energy Pvt. Ltd. (AWEPL) [11].

Site 3: this wind farm of 33 MW is covering the four villages namely Melamaruthapapuram, Balapathiramapuram, Keelakalangal, and Ichchanda of V.K. Puthur taluka, Tirunelveli district in Tamil Nadu (TN) state of India. The project is located between latitudes 9°01’19.2”–9°03’ N and longitudes 77°18’18”–77°22’24” E. The wind farm has twenty-two 1.5 MW Suzlon S82 wind turbines. The annual electric energy production of the wind farm is 86,377.104 MWh at a plant load factor of 29.88%. The project owner is Super Wind Project Private Ltd [12].

Site 4: a wind farm of 50.4 MW is situated at Anantpur district in Andhra Pradesh (AP) state of India. The site is located around the villages Gondipali, Duddebanda, Kogira, and Mustikovilla. The geographical coordinates of the site are latitude 14°10’32.3” N and longitude 77°34’15.7” E. The wind farm has sixty-three 0.80 MW Enercon E53 make wind turbines. The annual electric energy production of the wind farm is 1,12,186.166 MWh at a plant load factor of 25.41%. Tadas Wind Energy Private Limited (TWEPL) initiated this project [13].

The specifications of wind turbines installed at the above-mentioned four wind farms are given in Table 1. The estimation of electricity production by the solar photovoltaic power plant is done by using PVsyst 6.6.2 software. The global solar radiation data of chosen sites are taken from PVsyst through Meteonorm 7.1 database and is shown in Table 2 and its comparative analysis is shown in Fig. 2. The technical parameters of the PV module and inverter used in PVsyst software for designing solar PV power plants are shown in Table 3.

Table 1 Specifications of wind turbines installed at four wind farms of case study

Parameters	Site 1 (RJ)	Site 2 (KA)	Site 3 (TN)	Site 4 (AP)
Make	ReGen Powertech	Vestas	Suzlon	Enercon
Model	V82	V82	S82	E53
Rotor diameter (m)	82	82	82	53
Hub height (m)	85	78	82	75
Rated power (kW)	1500	1650	1500	800
Cut in speed (m/s)	3.5	3.5	4	3
Rated speed (m/s)	12	7.5	14	12.6
Cut out speed (m/s)	18	20	20	28

Table 2 Solar radiation data of four chosen sites

Months	Global horizontal solar irradiation (kWh/m^2/day)			
	Pratapgarh (RJ)	Davangere (KA)	Tirunelveli (TN)	Anantpur (AP)
Jan	4.78	5.43	5.45	5.54
Feb	5.67	5.97	5.98	5.87
Mar	6.81	6.64	6.37	6.5
Apr	7.04	6.64	5.92	6.4
May	7.3	6.3	5.42	6.05
Jun	6.12	5.38	4.51	5.04
Jul	4.41	4.91	4.74	4.77
Aug	4.1	4.76	5.18	4.53
Sep	5.47	5.32	5.43	5.08
Oct	5.74	5.38	5.11	4.97
Nov	4.87	5.18	4.60	4.97
Dec	4.54	5.09	4.98	5.04
Annual	5.57	5.58	5.30	5.39

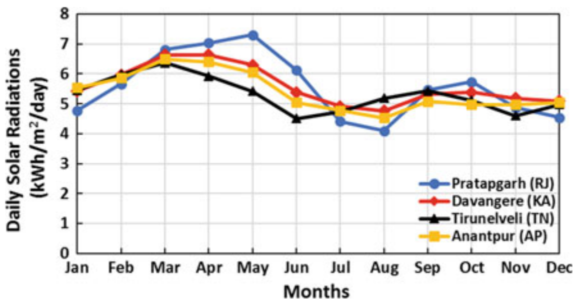

Fig. 2 Monthly average daily global horizontal solar radiation of four locations used in the case study

Table 3 Design parameters of solar PV power plant used in PV syst software for four locations

Components	Parameters	Specifications
PV module	Solar tracking mode	Fixed
	Type	Poly-Si
	Tilt angle	Latitude angle
	Surface azimuth angle	0° (South facing)
	Manufacturer	Canadian solar Inc.
	Model	CS6X—305P
	Module area	1.92 m^2
	Open circuit voltage	44.8 V
	Short-circuit current	8.97 A
	Max. power point voltage	36.3 V
	Max. power point current	8.41 A
	Maximum power	305.3 W
Inverter	Manufacturer	SMA
	Model	500CP XT
	Operating voltage	430–850 V
	Nominal AC power	500 kW_{ac}
	Maximum AC power	550 kW_{ac}

3.2 *Methodology of Calculation*

(1) *Free area available in wind farm for solar PV plant*

In this study, it is assumed that the wind farm layout is of a 5D × 7D configuration. The free space area for installing solar photovoltaic modules in the wind farm is calculated by using (1) [2]:

$$A = (5D \times 7D) - \left(\frac{\pi(D + H)^2}{4}\right) \quad (1)$$

where A is the free area for solar photovoltaic modules installation around a single wind turbine, D is the rotor diameter, and H is the hub height of the wind turbine. For neglecting the shadow of the wind turbine on the solar photovoltaic module, the area $\pi(D + H)^2/4$ is subtracted in (1). The number of wind turbines in a wind farm is multiplied by (1) for calculating the total available area in a wind farm for installation of the solar PV power plant.

(2) *Performance Ratio (PR)*

Various researchers have analyzed the performance of grid-connected solar PV power plants [14–16]. The performance ratio is a factor by which a solar PV system's efficiency is calculated. This factor also indicates that how much electric energy is available for supply to the grid. The performance ratio is useful for comparative analysis of different PV module technologies. PR is calculated by using (2):

$$PR = \left(\frac{E_{\text{Grid}}/P_o}{G_{\text{inc}}/G_o} \right) \tag{2}$$

where, E_{grid} is AC electric energy supplied to grid, P_o is nominal power, G_{inc} is global solar radiation on tilted surface, and G_o is global solar radiations (1000 W/m^2) at Standard Test Condition (STC).

(3) *Capacity Utilization Factor (CUF)*

It is the ratio of electric energy generated from PV system to nominal power of solar PV power plant at STC in a specific time interval. It is a method for calculating solar PV plant performance. The environmental factors-like solar radiation and module degradation factor are not considered for calculation of CUF. CUF is also an indicator to check the reliability of solar PV modules [17]. The monthly CUF is calculated by using (3):

$$\text{CUF} = \frac{E_{\text{Grid}}}{n \times 24 \times P_o} \tag{3}$$

where, E_{Grid} is the AC electric energy generated from PV module and n is the number of days in specific month for calculating monthly CUF.

3.3 Electric Energy Production by Solar PV Power Plant

This paper considers six cases of 5, 10, 15, 20, 25, and 30% of total available area in the wind farm for installation of PV modules for utilization of unused land for additional energy generation. Table 4 shows the solar PV power plant installed capacity for six cases of areas as mentioned above.

By considering that 5% of the total free available area is used for the installation of the solar PV power plant, the monthly DC electric energy produced by the plant and monthly AC energy supplied by inverter to the grid are estimated by using PVsyst software. Tables 5, 6, 7 and 8 show the monthly global solar radiation on a tilted surface, monthly DC energy generated by solar PV plant, and monthly AC energy supplied to the grid by inverter for 5% of the total free area for Pratapgarh (RJ), Davangere (KA), Tirunelveli (TN), and Anantpur (AP) sites, respectively.

Table 4 Area used in wind farm for solar PV power plant installation and capacity of PV power plant

% Area of total available area covered by solar PV plant (%)	Solar PV plant capacity (MW_p) and Area Used (km^2)			
	Pratapgarh (RJ)	Davangere (KA)	Tirunelveli (TN)	Anantpur (AP)
5	45.80 (0.29 km^2)	27.71 (0.17 km^2)	33.71 (0.21 km^2)	38.51 (0.24 km^2)
10	91.60 (0.58 km^2)	55.42 (0.35 km^2)	67.42 (0.42 km^2)	77.01 (0.48 km^2)
15	137.41 (0.86 km^2)	83.14 (0.52 km^2)	101.13 (0.64 km^2)	115.52 (0.73 km^2)
20	183.21 (1.15 km^2)	110.85 (0.70 km^2)	134.84 (0.85 km^2)	154.03 (0.97 km^2)
25	229.01 (1.44 km^2)	138.56 (0.87 km^2)	168.55 (1.06 km^2)	192.54 (1.21 km^2)
30	274.81 (1.73 km^2)	166.28 (1.05 km^2)	202.27 (1.27 km^2)	231.04 (1.45 km^2)

Table 5 Monthly electric energy generated and supplied by solar PV power plant at pratapgarh (RJ) by covering 5% Area

Months	Global solar radiation on tilted surface [G_{inc}] (kWh/m^2)	DC energy from solar PV modules [E_a] (MWh)	AC energy supplied to grid by inverter [E_{Grid}] (MWh)
Jan	200.3	7568	7379
Feb	197.4	7279	7102
Mar	236.6	8419	8223
Apr	212.2	7478	7295
May	209.9	7418	7239
Jun	165.7	6075	5921
Jul	126.1	4774	4636
Aug	122.2	4667	4532
Sep	172.7	6393	6232
Oct	211.3	7672	7491
Nov	192.6	7166	6991
Dec	195.3	7339	7152
Annual	2242.3	82,248	80,193

3.4 Results and Discussion

The annual electric energy productions of solar PV power plants for six cases of available area in four wind farms are shown in Table 9. Figure 3 shows the annual electric

Table 6 Monthly electric energy generated and supplied by solar PV power plant at davangere (KA) by covering 5% area

Months	Global solar radiation on tilted surface [G_{inc}] (kWh/m^2)	DC energy from solar PV modules [E_a] (MWh)	AC energy supplied to grid by inverter [E_{Grid}] (MWh)
Jan	197.6	4414	4323
Feb	185.8	4061	3981
Mar	215.3	4597	4509
Apr	196.7	4190	4104
May	183.6	3988	3903
Jun	149.4	3343	3263
Jul	142.8	3204	3124
Aug	143.2	3216	3140
Sep	161.8	3601	3519
Oct	178.9	3984	3893
Nov	176.1	3952	3865
Dec	186.6	4196	4104
Annual	2117.8	46,746	45,728

Table 7 Monthly electric energy generated and supplied by solar PV power plant at Tirunelveli (TN) by covering 5% Area

Months	Global solar radiation on tilted surface [G_{inc}] (kWh/m^2)	DC energy from Solar PV Modules [E_a] (MWh)	AC energy supplied to Grid by Inverter [E_{Grid}] (MWh)
Jan	183.4	4955	4852
Feb	176.8	4759	4663
Mar	201.4	5361	5253
Apr	175.1	4728	4625
May	161.8	4403	4303
Jun	129.9	3615	3527
Jul	141.2	3925	3830
Aug	157.3	4327	4227
Sep	163.6	4483	4380
Oct	164.1	4471	4368
Nov	146.4	4021	3929
Dec	167.6	4576	4477
Annual	1968.6	53,624	52,434

Table 8 Monthly electric energy generated and supplied by solar PV power plant at Anantpur (AP) by covering 5% Area

Months	Global solar radiation on tilted surface [G_{inc}] (kWh/m^2)	DC energy generated from solar PV modules [E_a] (MWh)	AC energy supplied to grid by inverter [E_{Grid}] (MWh)
Jan	200.1	6222	6067
Feb	181.7	5540	5404
Mar	209.4	6243	6092
Apr	189.8	5671	5524
May	177.2	5352	5209
Jun	141.0	4398	4268
Jul	139.5	4387	4255
Aug	136.0	4292	4164
Sep	153.9	4818	4683
Oct	163.3	5095	4953
Nov	166.7	5257	5116
Dec	181.7	5718	5568
Annual	2040.3	62,993	61,303

Table 9 Annual electric energy produced by solar PV power plants for six cases of areas at four locations

% Area of total available area covered by solar PV plant (%)	Pratapgarh (RJ) (MWh)	Davangere (KA) (MWh)	Tirunelveli (TN) (MWh)	Anantpur (AP) (MWh)
5	80,193	45,728	52,434	61,303
10	160,347	91,181	104,874	121,214
15	240,874	137,190	157,008	179,184
20	320,121	182,454	209,346	245,227
25	402,059	228,654	262,178	307,393
30	481,752	273,988	314,016	368,294

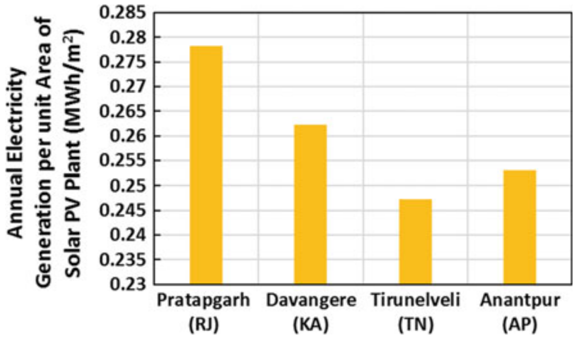

Fig. 3 Annual electric energy generation per unit area by solar PV power plant at four location

energy generation per unit area (MWh/m^2) by solar PV power plant at four locations. It is observed that solar PV electricity generation per unit area for Pratapgarh (RJ), Davangere (KA), Anantpur (AP), and Tirunelveli (TN) are 0.278 MWh/m^2, 0.262 MWh/m^2, 0.247 MWh/m^2, and 0.253 MWh/m^2 respectively. The month wise variation of performance ratio of solar PV power plants at four sites are shown in Fig. 4 and month wise variation of capacity utilization factor is shown in Fig. 5 for the case of 5% of available area of wind farm.

At Pratapgarh (RJ) the PR is maximum in the month of August (81%) and minimum in April (75.1%). At Tirunelveli (TN), the PR is maximum in month of June (80.5%) and minimum in March (77.3%). Monthly PR at Davangere (KA) and Anantpur (AP) are varying similarly and the annual PR at these two sites is calculated as 77.9% and 78.1%, respectively. The CUF of all four solar PV power plants is highest in the month of March. The annual CUF are calculated as 20%, 18.9%, 17.8%, and 18.2% for Pratapgarh (RJ), Davangere (KA), Tirunelveli (TN), and Anantpur (AP), respectively.

Table 10 gives the details of annual solar PV electricity generation, wind power plant electricity generation, and combined power plant electricity generation for per unit installed capacity (MWh/MW), respectively. Figure 6 shows a comparison of

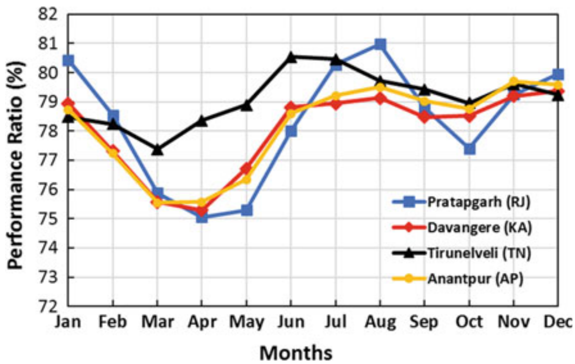

Fig. 4 Monthly variation of performance ratio of solar PV power plants at four locations for the case of 5% of available area of wind farm

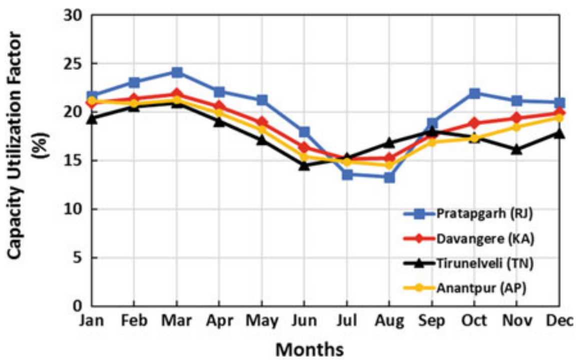

Fig. 5 Monthly variation of capacity utilization factor of solar PV power plants at four locations for the case of 5% of available area of wind farm

Table 10 Annual electricity production per unit installed capacity by covering 5% of the available area

Locations	Annual solar PV electricity (MWh/MW_p)	Annual wind electricity (MWh/MW)	Annual combined electricity (MWh/MW)
Pratapgarh (RJ)	1750.98	1752.00	1751
Davangere (KA)	1650.18	3194.77	2449.23
Tirunelveli (TN)	1555.49	2617.49	2080.85
Anantpur (AP)	1591.99	2225.92	1951.36

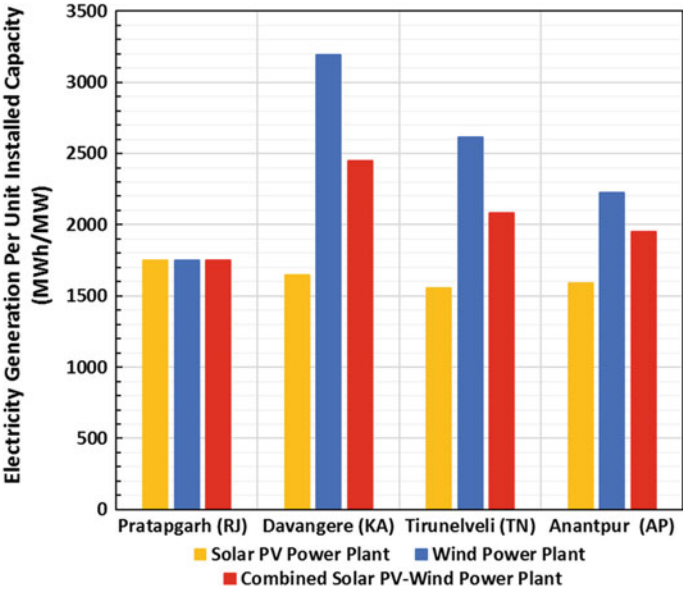

Fig. 6 Electricity generation (MWh/MW) by solar PV power plant, wind power plant, and combined solar and wind power plant

electric energy production per unit capacity (MWh/MW) of solar PV plant, wind power plant, and combined power plant at the four locations.It is noted that solar energy generation per square meter or per MW installed capacity in Pratapgarh (RJ) is maximum and wind energy generation at Davangere (KA) is maximum. So, the combined maximum electricity generation is obtained at Davangere (KA), followed by Tirunelveli (TN), Anantpur (AP), and Pratapgarh (RJ), respectively.

4 Conclusions

In this paper, power generation from the solar plant installation at vacant land of existing wind farms has been investigated. It is seen that solar PV electricity generation potential by covering 5% area of vacant land in wind farm by solar PV modules is maximum at Pratapgarh (1750.98 MWh/MW), followed by Davangere (1650.18 MWh/MW), Anantpur (1591.99 MWh/MW), and Tirunelveli (1555.49 MWh/MW). It is also noted that in Davangere, solar PV production per unit area is more than Anantpur, irrespective of the fact that available land area and plant installed capacity both are more at Anantpur than in Davengere. It may be due to slightly more daily solar insolation at Davengere than at Anantpur. The annual average performance ratio and annual average capacity utilization factor of solar power plants are varying from 77%–79% to 18%–20%, respectively, for the four locations. The annual wind electricity generation per unit installed capacity of the wind farm is highest at Davangere (3,194.77 MWh/MW) and is, followed by Tirunelveli (2,617.49 MWh/MW), Anantpur (2,225.92 MWh/MW), and Pratapgarh (1,752 MWh/MW). The combined electricity generation of solar PV and wind power plants are found to be the highest at Davangere in Karnataka and lowest at Pratapgarh in Rajasthan.

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