Wind and solar energy for reducing electricity deficits in Karnataka

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Karnataka suffers from chronic electricity shortages and daily load-shedding, which are expected to persist despite planned additions of conventional power. Using four illustrative scenarios based on different assumptions, we estimate the additional contributions wind and solar power sources could make to reduce these deficits by FY2022. The method developed estimates expected hourly deficits in FY2022 from projected unrestricted demands and expected availability from conventional sources. We estimate that additional 8000–8700 MW (11 BU) of wind and 3300–3500 MW (5 BU) of solar power would reduce the annual deficit by approximately three-fourths. A recommended pumped hydro storage facility will reduce the deficits further by 10% and help in meeting the daily peaks in demand.

Keywords: Conventional energy sources, electricity shortage, pumped hydro storage, wind and solar power.

THE total installed capacity (MW) of Karnataka in FY2014 constituted 46% thermal, 35% hydro and 18% wind installations. Solar power is just beginning to be installed. Thirty-three per cent of Karnataka's electrical energy (MWh) in FY2014 came from independent power producers (IPPs – mainly generated from thermal sources). The remaining came from thermal (25%), nuclear (10%), large hydro (22%) and wind (7%) generation. Three per cent came from net imports (Figure 1). All the energy contributions from conventional sources, along with those from wind plants, and some imports, add up to meet a large fraction of the demand, but do not meet all of it. The resulting deficits are managed by load-shedding. The extent of deficit in Karnataka is substantial, leading not only to inconveniences, but also to economic losses[1]. These deficits have to be substantially reduced to allow the economy of the state to grow faster. Compared to the average deficit of 2% in 2006–07 (ref. 2), in FY2014 Karnataka's average energy deficit had increased to around 10% with maximum energy deficit of 20% occurring in the month of April[3].

Expected additions to conventional power generation are likely to be insufficient to meet future demands at all hours. This point is addressed later in the article. We estimate the required installations of wind and solar power to reduce future deficits. If the installations, however, are carried out in an unplanned manner and without taking into account the hours of overlap between wind and solar power generation, they may lead to excesses and need curtailment when the demand is low, storage facilities are absent and export is infeasible. Alternatively, insufficient installation and imports would cause deficits to persist.

Demand for power from consumers changes from instant to instant. So does the power produced from the solar and wind sources. It is their matching that poses a challenge. In this article we estimate: (a) the hourly unrestricted demands for a target year; (b) the probability of meeting a large part of the unrestricted demands from conventional sources with (c) the remainder from wind and solar systems, assuming the availability (and non-availability) of a pumped hydro storage (PHS) system.

Each of the above steps involves future projections and corresponding uncertainties. We rely on seasonal patterns in daily power consumption, inevitable non-achievement of targets in conventional power production, and a

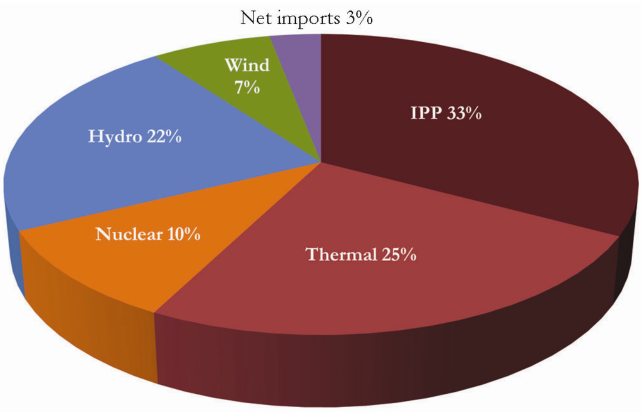

Figure 1. Karnataka's energy sources with percentage contribution for FY2014 (Source: SRLDC).

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seasonal pattern in the variable solar and wind generation for computing likely deficits in the future to plan the combination of solar and wind power installation. Contributions from existing small hydroelectric power plants are included in the hydro category and contributions from biomass generation are included in IPPs. We have not considered future growths in these sources because of their relatively smaller magnitudes.

Literature review

Lew *et al.*[4] studied the operational impact of up to 35% energy penetration of wind, photovoltaics (PVs), and concentrating solar power (CSP) on the power system in southwestern United States. They showed that it is operationally feasible to accommodate 30% wind and 5% solar energy penetration. System flexibility was enough to accommodate a lower 30% penetration of wind and solar power, and make the installation of a new PHS system economically infeasible.

Heide *et al.*[5] studied the design of a future European power supply with a very high share of renewables. A 100% wind plus solar scenario will require energy storage of 1.5–1.8 times the monthly load. As long as a fraction of fossil and/or nuclear power remains in the generation mix, the need for stored energy will be smaller.

Brower *et al.*[6] attempted to quantify the impacts of large-scale intermittent renewable energy sources on a power system. One of the limitations that the paper acknowledges is that the modelling is conducted on present-day power systems which have a high percentage of thermal generators. Future power systems are expected to be more low-carbon and therefore the modelling of those power systems would be different and would lead to different impacts.

According to Tongia[7], the Indian system with 6% penetration of renewables (on energy basis) behaves much like the German system with 25% penetration, because the German grid has access to four times its power requirement from neighbouring countries.

However, several of these preceding results are system-specific and not readily transferable to other systems. Our power systems, running on deficits, are inherently inflexible and the penetration criterion (30%) for power systems where demands are almost always met by supply is inapplicable to our systems. Tongia[7] also argues for storage devices to participate in both sets of markets, i.e. ancillary services and demand response. The distinctiveness of our approach is the matching of hourly deficits with the generation of wind and solar power as both of them are time-variant.

Methodology

Our objective is to estimate the contributions that wind and solar power could make in reducing expected power deficits in a future year, given the conventional generation that has been planned. In order to ascertain the hourly deficits in power supply, we need to estimate the unrestricted demands in a future year and subtract from them the amount of power that could be generated. Load curves usually depict the demand met (in MW) over 24 h. The following sequential steps describe the methodology we have adopted:

1. Estimate hourly unrestricted demand, expected generation from various sources (assuming 75% and 80% of projected thermal and hydro plants coming on-line) and resulting deficits for target FY2022 (being the last year of the 13th Five-Year Plan).
2. Compute the capacity utilization factor (CUF; ratio of energy generated by a plant in a certain period to the hypothetically maximum amount of energy the plant could produce in that period) for wind power and collect the CUF data for solar power.
3. Estimate combinations of wind and solar capacities taking into account the hours of their overlap in order to reduce the deficits in FY2022 and choose suitable ones from them.
4. Estimate the size of a PHS plant capable of operating for a maximum of 6 h at a time in generating mode to further reduce deficits in FY2022 and large enough to meet most of the daily peaks[8].

Estimating unrestricted demand

The Southern Regional Load Despatch Centre (SRLDC) provided minute-wise data for the demand met, load-shedding and frequency variation caused by demand/supply imbalance from FY2009 to FY2014. We only considered 70% of all days that were free from data-logging problems. We estimated unrestricted demand from these data. In Figure 2 *a*, we have plotted hourly data on load-shedding from FY2013 to FY2015 in Karnataka. While load-shedding is generally higher in summer compared to the other seasons, there is no day in a year without some load-shedding somewhere in the state. Unrestricted demand is estimated from the following equation:

Unrestricted demand =
Hourly peak demand met + planned load shed + unplanned load shed ± correction to be done for achieving nominal frequency.

The allowed supply frequency variation band in India in FY 2014 was 49.7–50.2 Hz. Whenever the frequency drops from the nominal value, the utilities are forced to shed load. Planned load-shedding is decided by each State Load Despatch Centre (SLDC) in advance based on the estimated demand and generation data. Unplanned load-shedding is in response to further demands and

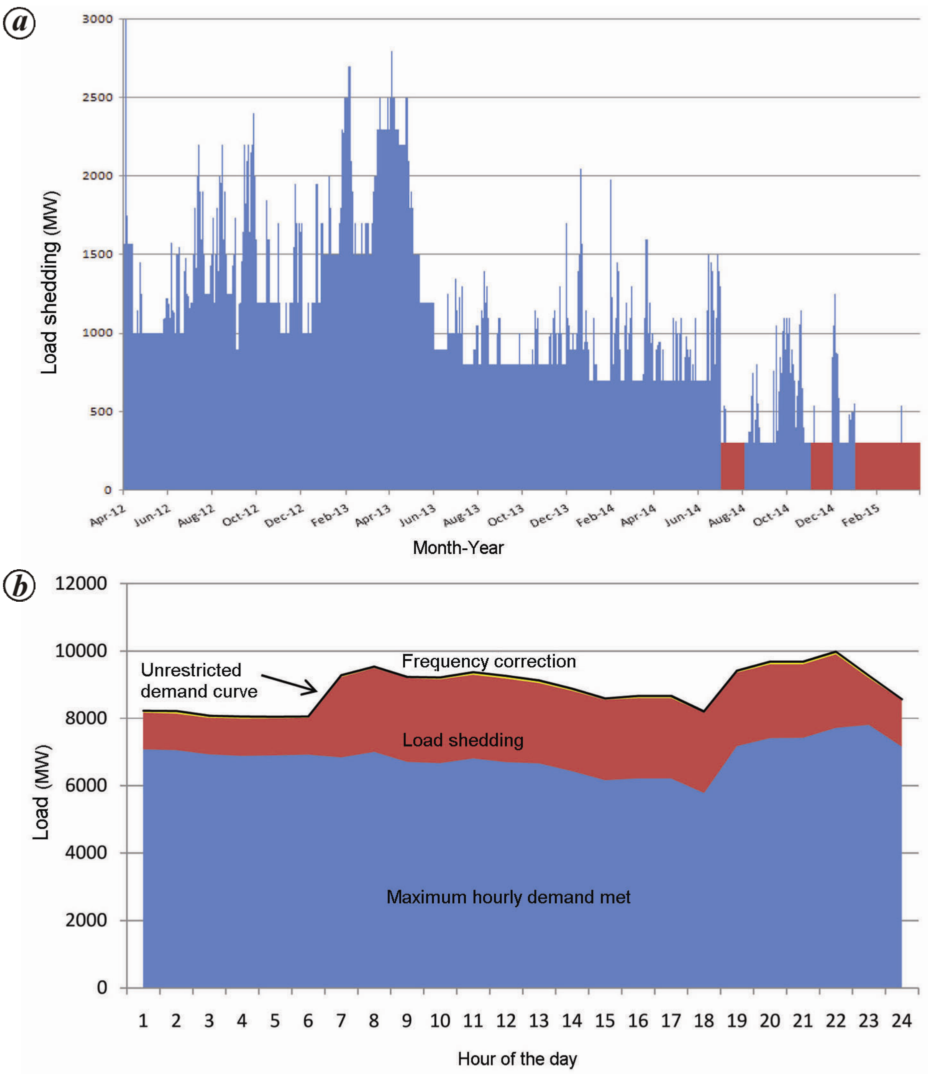

Figure 2. ***a***, Load-shedding from FY2013 to FY2015 on an hourly basis used for estimating unrestricted demand. Missing data are interpolated and indicated in red (source: SRLDC). ***b***, Estimation of unrestricted demand for 7 April 2013.

carried out for each hour on a real-time basis to maintain load-generation balance. The feeders for planned and unplanned load-shedding are identified based on average load relief expected and not on the maximum or connected load of the feeder.

The correction to be done for achieving nominal frequency is the amount of load-shedding that would have been required (or generation curtailed) to achieve the nominal frequency of 50 Hz. To calculate this, the difference between nominal frequency and the hourly frequency prevailing at that hour boundary is tabulated and multiplied with the power number or stiffness coefficient (MW required to change the frequency by 1 Hz) of the control area (Karnataka). In a large interconnected system with machines of hugely different inertias and controls, the variation of frequency for a certain change in load can only be obtained after complex analysis. This is beyond the scope of the present study. Empirically determined values of power number are used instead.

Frequency correction =

(nominal frequency – prevailing frequency) ×

power number of the control area.

For example, if 50 Hz is nominal frequency, and prevailing frequency is 49.7 Hz, when power number of Karnataka is 294 MW/Hz (source: SRLDC), then frequency correction = (50 – 49.7) × 294 MW = 88 MW.

Figure 2 *b* shows an example of how the load shed is added to the demand met and then corrected for frequency to obtain the unrestricted demand for one summer day (7 April 2013) when the load-shedding was very high. The correction for frequency ranges from –60 to 90 MW. This is small compared to the load-shedding in the state. Unrestricted demand does not include peak shaving due to shortages. But it will continue to include policy-based supply service norms for agricultural loads. The agricultural load which is the largest sector (35%), is supplied power irregularly only for 4–6 h.

Table 1. Values of ratios $R1$ and $R2$, as defined in the text below

Year	Unrestricted peak load (MW)	Unrestricted energy requirement (MU)	$R1$	$R2$
FY 2010	6897	44,557	0.71	0.66
FY 2011	8430	50,474	0.80	0.80
FY 2012	9062	54,345	0.86	0.87
FY 2013	9742	58,513	0.93	0.93
FY 2014	10,473	63,001	1	1
FY 2015	11,258	67,833	1.08	1.07
FY 2016	12,102	73,036	1.16	1.16
FY 2017	13,010	78,637	1.25	1.24
FY 2018	13,964	83,917	1.33	1.33
FY 2019	14,945	89,285	1.42	1.43
FY 2020	16,005	95,059	1.51	1.53
FY 2021	17,159	101,309	1.61	1.64
FY 2022	18,403	108,012	1.71	1.76

Source: Ref. 9.

Projections for estimating future demand

We base our projections of future demand from forecasts made by EPS18 (ref. 9), trusted to be the most reliable source for such information. EPS18 projects annual energy consumption (MU) and the maximum annual peak load (MW). We used these two pieces of information in our projections. Having chosen FY2014 as the base year and FY2022 as the target year, we obtain two factors: (1) Ratio ($R1$) of annual energy of target year to annual energy of base year FY2014 from EPS18; (2) Ratio ($R2$) of peak load of target year to peak load of FY2014 from EPS18 (ref. 9).

We multiply the hourly unrestricted demand of the base year (FY2014) independently by these factors ($R1$ and $R2$; Table 1) to project the likely demands for the target year (FY2022).

Multiplying loads for all hours of the base year by the factor $R1$ or $R2$, implies that we assume that the shape of the load curve in the projected year remains similar to (but not the same as) the shape in the base year on that day. Multiplying any graph other than a straight line parallel to the x-axis by a constant (>1) alters the shape of the graph, amplifying sections with larger magnitudes compared to those that are relatively smaller. The daily load curve is a combination of one or two peaks and a base load section. Therefore, multiplying a load curve with a constant will result in a larger absolute increase in the peak regions compared to the base load section.

The seasonal patterns of power demand for summer, winter and monsoon seasons are distinct but follow almost similar hourly patterns within a season. Morning peaks during winter months are caused by large-scale water heating (Figure 3 *a*). The evening peaks in winter are usually of shorter duration compared to those in summer. The average summer demand is higher due to needs for cooling throughout the day and night (Figure 3 *b*). Monsoon demands are generally low, particularly due to reduced agricultural power consumption. Figure 3 shows that seasonal daily load curves are similar in shape four years later between FY2010 and FY2014. We expect and assume that the shapes would remain similar in FY2022.

Estimation of expected generation for FY2022

We used the following formula to calculate the total generation in FY2014:

FY2014 total generation =
(FY2014 thermal generation +
FY2014 hydro generation +
FY2014 wind generation) ± FY2014 net imports
= ∑FY2014 Generation from each source
± FY2014 net imports.

The following formula was used to estimate the expected generation for FY2022:

FY2022 expected generation =
∑FY2014 generation from each source ×
ratio of expected total installed capacities of each source in FY2022 and FY2014
(neglecting net imports).

For FY2014, the data of generation from different sources (thermal, hydro and wind) are collected from SRLDC's supervisory control and data acquisition (SCADA) system on a minute-to-minute basis. We have calculated the hourly average power for all the sources. Assuming that the CUFs remain unaltered, we can multiply various generation values by the ratio of the respective installed capacities in FY2022 and FY2014, and finally sum them to arrive at the expected generation for FY2022.

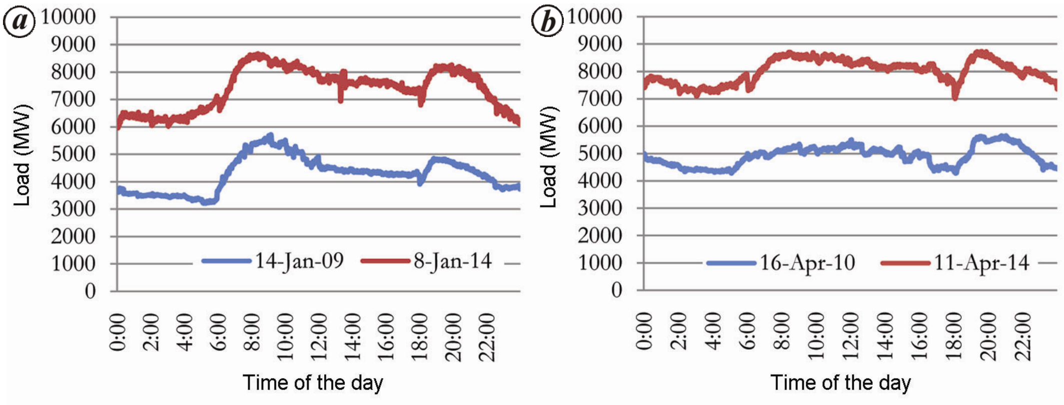

Figure 3. Seasonal sample load curves for (***a***) a typical Wednesday in winter and (***b***) a typical Friday in summer.

To find out the ratio of installed capacities in FY2022 and FY2014, we first found the magnitude of installed capacity in FY2014 (SRLDC website) and the future plans for addition of capacity in conventional sources (all thermal and hydro) as on 31 March 2014 (obtained from Power Corporation of Karnataka Ltd (PCKL)). While calculating the ratio of installed capacities in FY2022 and FY2014, we need to make educated assumptions related to practical realization of the planned capacity additions. Going by the record[10] and conversations with practitioners, 75% and 80% realization are thought to be reasonable assumptions. Most of the increase in installed capacity of conventional power in the state in the next ten years is expected to come from thermal energy sources. In the next section we provide an illustration of how additional solar and wind capacities are estimated that could have reduced Karnataka's electricity shortages in FY2014.

Additional wind and solar capacities that could have potentially reduced deficits in FY2014

We first propose a method of allocation of wind and solar power for FY2014 for which we have substantive recorded data. This is done as a test case where deficits are known, and also to sketch the proposed method for allocations of wind and solar power. For FY2014, one of the major constraints we imposed was to avoid curtailment due to excess energy production in the absence of energy storage.

We calculated the hourly deficits for all days in FY2014 (except for the days when the SCADA data had gaps). The deficits are related to the hour of the day. The minimum deficits generally occur in the early hours from 1 to 4 am which, of the two options of wind and solar energy, can be filled only by wind energy. If we were to have more wind installations than necessary, and there were no storage facilities available, or no opportunities for export at those hours (if there is excess generation), thermal generation may be reduced if schedules so permit. Otherwise, wind energy produced would have to be curtailed to reduce excess generation.

Noting when minimum deficits occur, we obtained the wind CUF at those hours on these days. We have taken into account hourly CUFs for both solar and wind power (Figure 4). We calculated hourly CUF for wind generation using the following formula:

Hourly wind CUF = hourly wind energy (MWh)/ rated hourly wind energy production (MWh).

Next we calculated the required additional wind installation capacity to meet the minimum deficits on a daily basis. The general formula for calculating installation capacity requirement based on deficit is given below.

Capacity required to meet the deficit = deficit/CUF at the hour when the deficit occurs.

Since the minimum deficits vary from one day to another, the required additional wind-installed capacity will also vary from day to day. If we were to adhere strictly to the constraints of no curtailment and no exports, we would choose the minimum deficit. If, however, we were to allow the possibility of exports (since the state is now integrated with the national grid), there would be differing estimates of the additional wind capacities required every day.

Figure 5 shows the minimum deficits on each day, and wind CUFs and minimum wind installation capacity required to meet the unrestricted demands at those hours. If we select the lowest of the additional wind installation capacity or the minimum point, we get the additional installed capacity (about 450 MW, Figure 5 *c*) which will help meet the minimum deficits on one particular day, but deficits at those hours on other days are likely to continue. If we intend to cover, say, 25% of the minimum deficits rather than on just one day, we would need to install

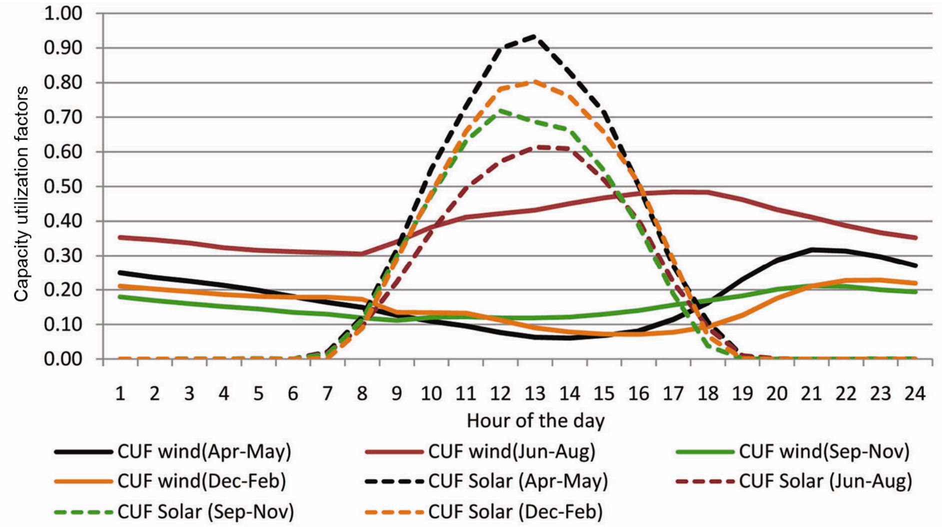

Figure 4. Seasonal wind (2012) and solar capacity utilization factors (CUFs) (2011). It may be seen that the CUFs for solar and wind power are complementary to some extent.

Table 2. Reduction in deficits for various additional solar and wind installations (FY2014)

Case no.	Additional wind installation (MW)	Additional solar installation (MW)	Reduction in deficit (%)	Increase in energy available for export (%)
W0S0	450	500	23	0
W0S25	450	800	30	0
W0S50	450	900	33	0
W0S75	450	1100	36	2
W25S0	1100	0	26	0
W25S25	1100	700	42	1
W25S50	1100	800	44	2
W25S75	1100	1000	48	3
W50S0	1700	0	37	3
W50S25	1700	500	48	4
W50S50	1700	800	54	6
W50S75	1700	1000	57	8
W75S0	3050	0	53	18
W75S25	3050	200	57	19
W75S50	3050	700	66	23
W75S75	3050	900	69	25

more wind power. We considered four cases in all for the additional wind power installation: one case for minimum or 0th percentile; other cases for 25th, 50th and 75th percentile (i.e. installations which could ensure that minimum deficits were met on 25%, 50% and 75% of the days respectively).

For each of these cases, we need to decide on the additional installed capacity of solar power, in view of the overlap of solar power and wind power during the day (Figure 4). The deficits during the day can be met with solar power which is available only during the day. So far as hourly variability of solar power is concerned, irradiance data for the year 2011 have been obtained from a pyranometer installed at the Divecha Centre, IISc, Bengaluru. The CUF for solar power is assumed to be proportional to irradiance. Even though solar irradiance varies across the state, we have used the hourly irradiance of Bengaluru for the year 2011 to calculate CUF for the entire state. The irradiance for Karnataka in summer, monsoon, and winter is 5.1–6.4, 3.5–5.3 and 3.8–5.9 kWh/sq m respectively[11]. If we calculate the average seasonal irradiance from the hourly irradiance used for calculation, the values for Bengaluru lie almost at the middle of the range given for Karnataka. As shown in Figure 4, the CUFs for solar and wind power are complementary to a certain extent. In the monsoon months, when solar insolation during the day is lower, wind energy picks up. In the non-monsoon months, when the solar energy is high during the day, wind speeds are low. During nights in all seasons when there is no sunshine at all, there is some amount of wind energy available.

As the base case for calculation of additional solar power requirement we decided to take the reduction in

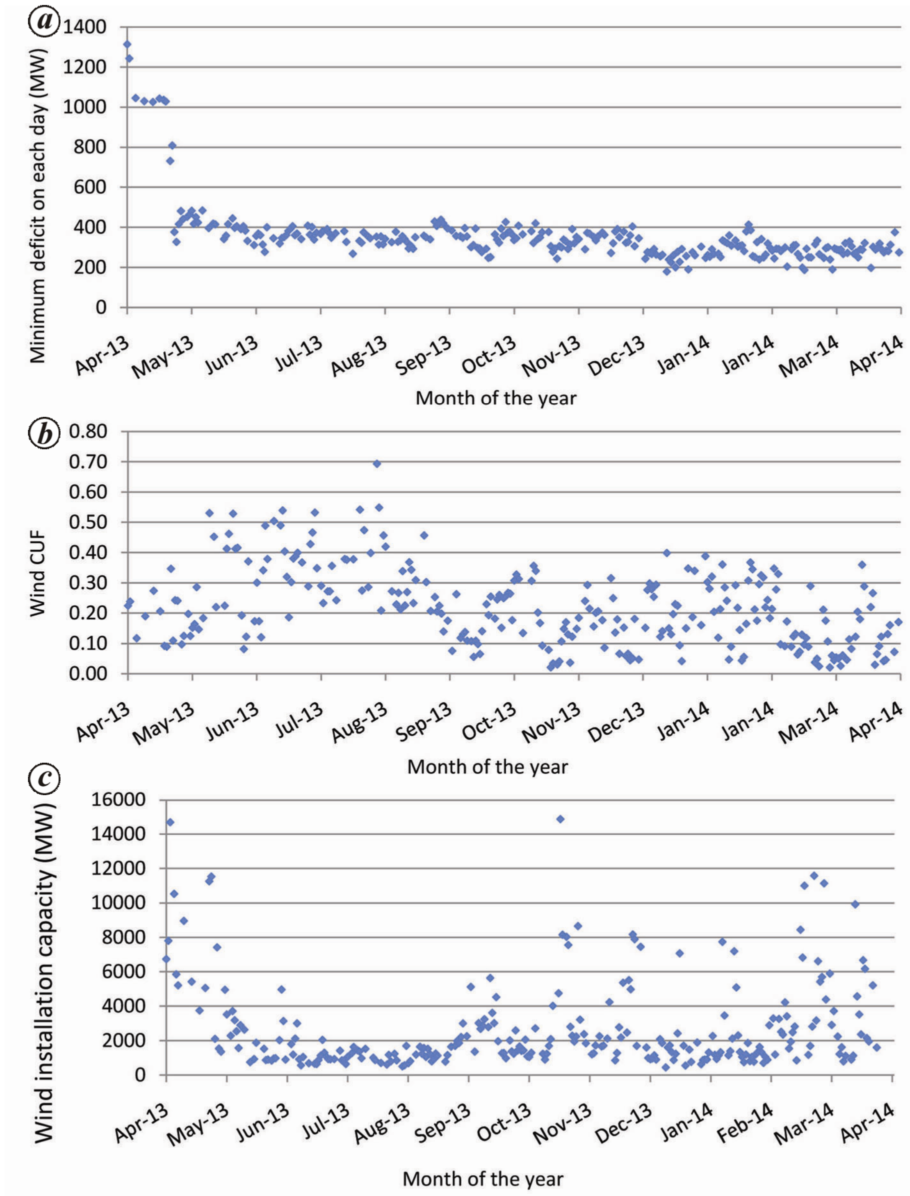

Figure 5 *a–c*. Allocation of wind installation capacity for FY2014. ***a***, Minimum deficits on each day (FY2014). ***b***, Wind CUF for the hour when minimum deficit occurred (FY2014). ***c***, Additional wind capacity to meet the minimum deficits on a daily basis (FY2014).

the deficit of power at 1 pm, when the solar intensity reaches its maximum in all seasons. We did this to ensure that we do not end up generating excess solar power during the peak solar luminance (at 1 pm), which may get curtailed. We first subtract the additional wind power obtained for each day of the year at 1 pm, having considered the appropriate CUF for wind at that time. This way we obtain the resultant deficit on a particular day which needs to be met by solar power. The additional solar installation capacity is calculated by dividing the resultant deficit at 1 pm by the solar CUF for 1 pm on that day. Since for any additional wind capacity, the required additional solar capacity to meet the demand at 1 pm will vary each day, we also get a distribution of solar capacities. We have chosen the 0th, 25th, 50th and 75th percentile to characterize this distribution.

Considering 0th percentile of wind installation (450 MW), the 0th percentile of additional solar capacity corresponds to 500 MW. That is, 500 MW of solar along with 450 MW of wind installation would have ensured that at least on two days in a year (FY2014), there would have been no deficit in the early hours on one day and at 1 pm on the other day. At all other times, deficits would still continue to persist.

If, however, we were to allow for exports, we could select larger capacities of wind and solar installations. It is for this reason that we consider installations that could meet deficits on 25%, 50% and 75% of the days in the

Table 3. Reduction in deficits for various additional solar and wind installations (FY2022)

Scenarios	Unrestricted demand projected based on energy ratio (*R*1)								Unrestricted demand projected based on peak ratio (*R*2)							
	Assuming 80% realization				Assuming 75% realization				Assuming 80% realization				Assuming 75% realization			
Case no.	Wind (MW)	Solar (MW)	Deficit reduction (%)	Excess (%)	Wind (MW)	Solar (MW)	Deficit reduction (%)	Excess (%)	Wind (MW)	Solar (MW)	Deficit reduction (%)	Excess (%)	Wind (MW)	Solar (MW)	Deficit reduction (%)	Excess (%)
W0S0	0	0	0	0	0	100	1	0	0	100	1	0	0	400	3	0
W0S25	0	2100	24	1	0	2500	25	1	0	2700	25	1	0	3000	25	1
W0S50	0	2800	30	3	0	3200	30	3	0	3400	30	3	0	3900	30	3
W0S75	0	3900	37	9	0	4400	36	8	0	4600	36	8	0	5000	35	7
W25S0	200	0	2	0	1200	0	11	1	1400	0	12	1	2200	0	17	1
W25S25	200	2100	26	1	1200	2300	33	2	1400	2400	34	2	2200	2700	38	2
W25S50	200	2800	32	3	1200	3000	38	4	1400	3100	39	4	2200	3500	43	4
W25S75	200	3800	38	9	1200	4100	44	9	1400	4300	45	9	2200	4700	48	9
W50S0	2000	0	20	3	3400	0	29	4	3700	0	30	4	5000	0	35	6
W50S25	2000	1800	39	5	3400	1900	46	7	3700	2000	46	7	5000	2100	50	8
W50S50	2000	2500	45	7	3400	2700	52	9	3700	2900	52	9	5000	3100	56	11
W50S75	2000	3600	51	13	3400	3900	58	15	3700	4100	58	15	5000	4200	61	15
W75S0	5800	0	45	20	8000	0	51	26	8700	0	53	27	10700	0	56	31
W75S25	5800	1000	54	22	8000	900	59	28	8700	900	59	29	10700	600	60	32
W75S50	5800	2000	63	26	8000	2200	68	32	8700	2300	68	33	10700	2500	71	37
W75S75	5800	3100	69	33	8000	3300	73	38	8700	3500	74	39	10700	3800	76	43

early hours and 1 pm respectively. Thus for each of the four cases of additional wind power we have four options of additional solar installation, a total of 16 cases (Table 2). The nomenclature of the cases is based on the wind and solar percentile used for a specific case. As an example, in the first case (additional wind 450 MW and additional solar 500 MW) it is 0th percentile for both wind and solar, and labelled as W0S0.

Each of these 16 cases, involving different amounts of additional wind and solar installations, would have reduced deficits to different extents and also provide some excess for export. Thus, for example, if we had 1700 MW of additional wind and 800 MW of solar (W50S50), we could have reduced annual deficits by 54%, with 6% excess available for export (Table 2).

Estimating wind and solar power in FY2022 without storage

The first step is to estimate the likely deficits for every hour in FY2022, based on the difference between the projected unrestricted demand and the expected generation from conventional power sources expected in FY2022. In view of the assumption we have made for projecting unrestricted demand (based on peak power or annual energy from EPS18) and two cases projecting available supply (75% and 80% realization), we will get four sets of results, one for each scenario. The annual deficits in FY2022 for both cases (for 80% realization with the ratio $R2$ and 75% realization with the ratio $R1$) are expected to be close to 17%.

In the second step of the task, an attempt is made to fill the gaps in hourly deficits with a combination of additional wind and solar energy, assuming that no grid-scale storage facilities are available in the state. In the first step, for all four cases the minimum additional wind requirement is zero, as there is no deficit on some days. However, load-shedding still continues during other hours.

Following similar methodology as explained in the case of FY2014, various options of wind and solar installation are found for FY2022 and shown in Table 3 for all four scenarios. Also shown with each scenario and case are the percentage reduction in annual deficits and increase in excess available for export (expressed as a percentage of the annual deficit).

In order to emphasize reduction in deficits and downplay availability for export or excesses, we recommend the case W50S50. Then by eliminating both the extreme scenarios in Table 3 (80% realization with $R1$ and 75% realization with $R2$), we arrive at a recommendation of 3400–3700 MW of wind and 2700–2900 MW of solar installations. With these values, the reduction in annual deficits will be 52%, with 9% excess generation available for export. These are the values obtained for two central cases of 75% realization with ratio $R1$ and 80% realization with ratio $R2$.

Estimating wind and solar power installations in FY2022 with storage

Most electrical grids are able to incorporate variable renewables when the penetration of renewables is small without the need for storage mechanisms[4]. When the penetration of renewables becomes large, some sort of storage mechanism becomes necessary. In the preceding section we estimated that additional 3400–3700 MW of wind would be able to meet the demand at one of the early morning hours on about half of the days in a year. Similarly, 2700–2900 MW of solar installation would be able to meet the demand at 1 pm on about half of the days in the concerned year. These sets of days need not coincide. If, however, we were to choose larger installations of wind and solar power sufficient to meet these deficits on 75% of the days, we would require an additional 8000–8700 MW of wind and 3300–3500 MW of solar instllation. Our intention is particularly to use a PHS facility to reduce deficits during morning and evening peaks. We assume here that a PHS facility becomes operational by FY2022. The first step is to try and size the facility. We assume it will be capable of a maximum of 6 h of generation mode and 8 h of pumping mode[8]. Figure 6 is a plot of the surplus energy available assuming the 75th percentile installation of wind and solar for FY2022. We assume that this surplus will be available for pumping. Since PHS facilities could be environmentally intrusive, it is important to size them correctly. In order to size the pump-turbine of PHS, if we assume that for 50% of the hours in a year when surplus is available the machine can accept the surplus, then the size of the PHS ranges from 1200 to 1500 MW (Figure 5 shows 25th percentile line at 700 MW and 75th percentile line at 2800 MW for the case of 80% realization with the ratio $R2$).

We assume that the PHS has a variable speed machine with a round trip efficiency of 75% (ref. 12). Since every PHS has minimum and maximum draw-down levels, we have to keep track of the energy potential in the reservoir from one day to the next. Since we had discarded data for several days in FY2014 because of data-logging problems, we would not have projections for the corresponding days in FY2022. Therefore, we can 'simulate' the operation of the plant more reliably only when we have data for several days in a row in FY2014. This is shown in Figure 7 *a* and *b* for projections of two periods spanning 12 days from September 2021 and 22 days from January 2022 respectively. The blue line indicates the energy stored in the PHS in MWh.

If the upper reservoir is at its full rated capacity and there is excess wind or solar generation, then that excess energy will need to be exported or curtailed (exports are shown as green lines in Figure 7). If the upper reservoir is at the minimum level and the demand exceeds generation, the state will experience a deficit (shown as brown lines in Figure 7). During these illustrative periods

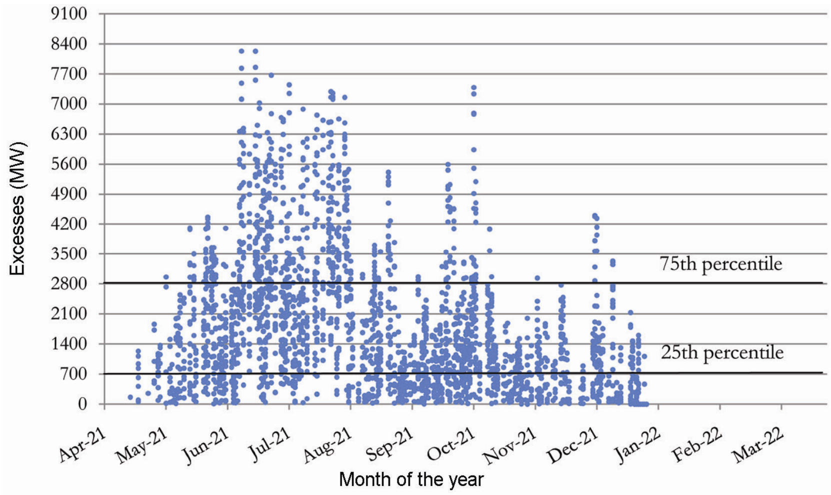

Figure 6. Estimation of pumped hydro storage (PHS) capacity for FY2022.

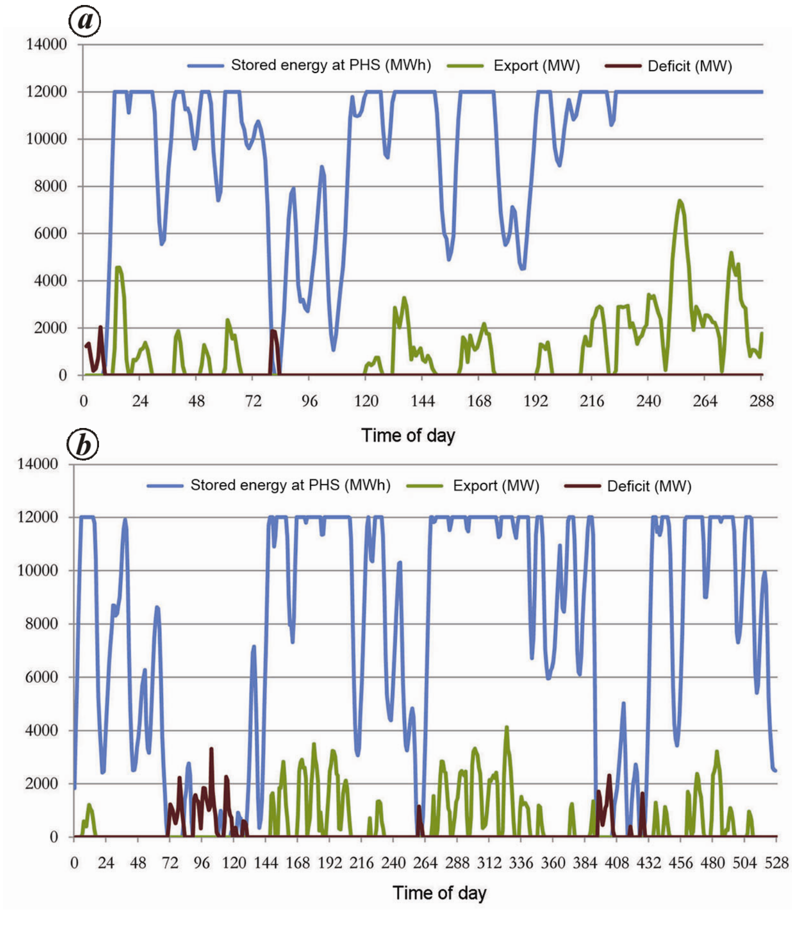

Figure 7. Operation of a proposed PHS for two illustrative periods of (***a***) 12 days from September 2021; (***b***) 22 days from January 2022.

the deficits would be reduced by another 9% and 11% respectively, after installation of PHS.

Stacked graph for a typical winter day is presented in Figure 8 *a*, considering additional wind and solar installation in FY2022 without any storage. Stacked graphs are visual depictions of demand and supply of energy from different sources, and the consequent deficits and excesses for a representative day. It is evident from the figure that mainly in peak load hours, i.e. in the morning (marked A) and in the evening (marked B), the generation

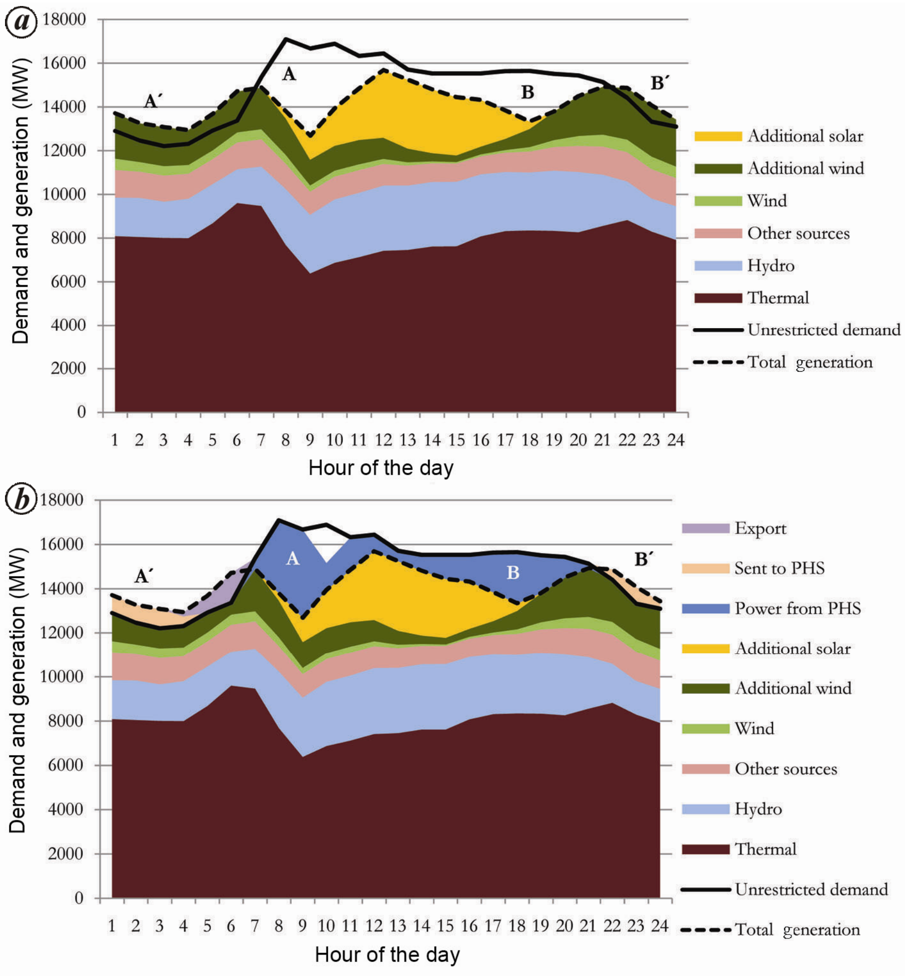

Figure 8. ***a***, Stacked graph of a typical winter day with additional wind and solar installation (without storage/PHS). ***b***, Stacked graph of the same day with additional wind and solar installation (using PHS).

Table 4. Recommendations for wind and solar capacity

		FY2022	
Year	FY2014	Without storage	With storage
Wind capacity (MW)	2163	5600–5900	10,200–10,900
Solar capacity (MW)	9	2700–2900	3300–3500
Wind + solar as a percentage of total installed capacity (%)	18	32–34	43–44
Wind + solar as a percentage of total energy (%)	7	15	22–23
Storage facility (MWh)	–	–	7200–9000
Expected reduction in annual deficits (%)	–	52	84
Expected increase in surplus energy available for export (%)	–	9	27

falls short of unrestricted demand. However, there is excess generation during early morning and late night hours (A′ and B′ from wind). In this scenario, in spite of having excess generation in some hours of a day, load-shedding becomes inevitable during peak load hours unless we decide to import. However, along with solar and wind installation if a storage facility is introduced, then the deficit situation improves markedly (Figure 8*b*). Storage facilities help absorb excess energy at certain hours (marked A′ and B′) to fill large portions of (but not all) deficits during some other hours (marked A and B). The situations change from one day to another, but the patterns represented in Figure 8 generally prevail.

Conclusions

We have confirmed that to remove all the deficits all the time will require very large additions of wind and solar installation. We recommend that by FY2022 (without any type of storage), 3400–3700 MW be added to the wind capacity in the state and 2700–2900 MW added to the solar capacity by FY2022. This would increase the renewable installed capacity from 18% of total installed capacity to 32–34% in that year; 15% of the contribution they will make to the state's energy will reduce the projected deficits by 52% (Table 4).

When a storage facility is available, wind and solar installations can be increased. We estimate that additional 8000–8700 MW (11 BU) of wind and 3300–3500 MW (5 BU) of solar installation would reduce the annual deficit by approximately three-fourths (Table 3, case no. W75S75). The results are summarized in Table 4. If a storage capacity of 1200–1500 MW, capable of generating for 6 h, is made available, it will reduce the annual deficits by another 10% and offer greater flexibility to the system operator, enabling power supply during hours of deficit and storing energy during hours of surplus generation.

The state should plan for and implement a large PHS system by 2022. Its exact size and the number of hours it is capable of operating will depend on site characteristics. Proposals to install or increase solar and wind power in any state in the country should be preceded by an analysis that will help determine the capability of the system to absorb that power without curtailment. Since constructing a PHS is time-consuming, the initial wind and solar installations may be based assuming that storage is unavailable while further increases should be coupled with programmes to set up storage schemes in parallel. The storage facility will enable the state to reduce electricity deficits significantly without resorting to excessive solar/wind installations, using the storage system to absorb energy when it is in excess and deliver it when required. It may not be necessary to build a new PHS from scratch. It may be possible to retrofit existing hydro reservoirs as PHS stations, especially where balancing reservoirs already exist and where distances are not too long. The quantity of water required for generating 600 MW for 6 h in a day works out to 3.89 Mcum (ref. 8). Calculating on a prorata basis, an upper reservoir and a lower reservoir each with 10 Mcum (assuming net head available for power generation is 400 m) minimum storage capacity will suffice for storing 1500 MW for 6 h of generation during morning and evening peak (3 h each), and would require 8 h of pumping (considering 75% cycle efficiency). The methodology demonstrated for Karnataka could be applicable to other states as well.

Although the estimates that have been presented, both for solar and wind power installations for different scenarios and that of the size of PHS are inexact, they are not arbitrary. The method suggested provides guidelines based on available data on load supplied, limited information on peak loads and energy demands for future years and expected installation of conventional sources of power in the future. It has been our attempt to minimize curtailment from projected renewable power sources, to decrease daily power deficits, and meet daily peaks in the mornings and evenings to the extent possible, especially with PHS.

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