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Brookings India Electricity and Carbon Tracker: A few insights

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Designed by Mukesh Rawat

1. Why an electricity and carbon tracker?

With the integration of large amounts of Renewable Energy (RE) into India's electricity grid, high future RE targets and the need to meet the IPCC (Intergovernmental Panel on Climate Change) commitments regarding emissions, time is right for a tool where we can visualise the electricity generation of India as well as the carbon emissions associated with this sector. The Brookings India Energy and Carbon Tracker (BECT) provides live information to the public and visualise how much electricity is generated from various generation sources and at what time. It also calculates the carbon emissions associated with electricity generation on a daily basis. The use of such granular data will be useful for planners, regulators and researchers, thus going beyond measuring electricity generation on a daily basis.

2. Key insights

1. Daily maximum vs daily minimum generation

The daily peak electricity demand is an important number for generation utilities, as it determines the generation capacity they need to bring online. If there is a large gap between the daily highs and lows, the generation needs to be greatly ramped up and down in the span of a day, which is difficult to do with coal-fired power plants, as their generation cannot be ramped up quickly. Thus, the daily low can also be an important metric. Here we use total generation as a proxy for demand.

Figure 1- Total Generation daily maximum and minimum

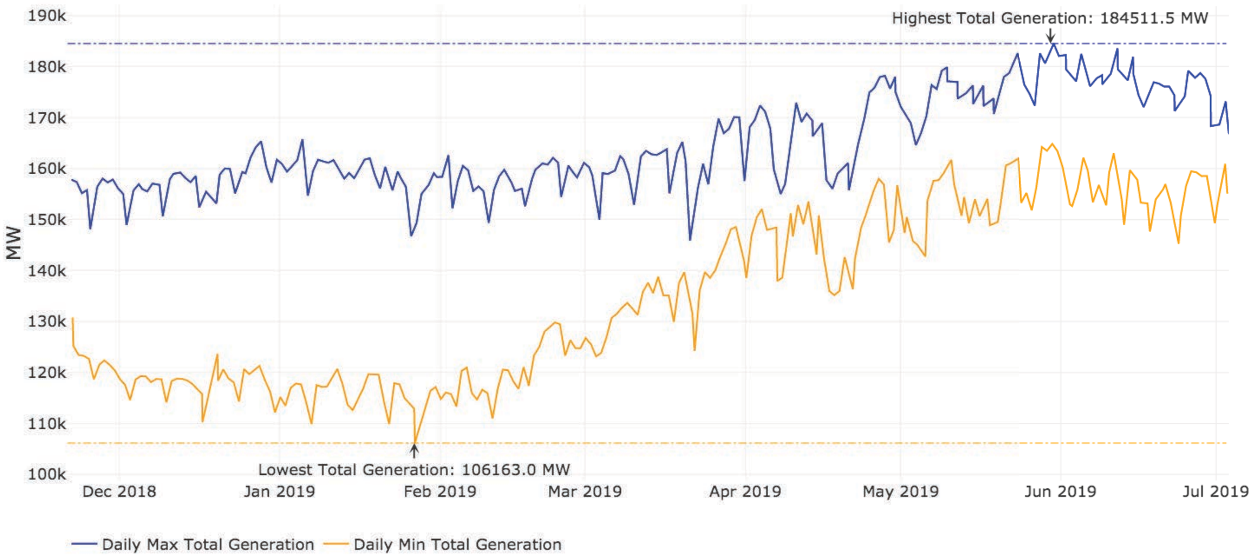
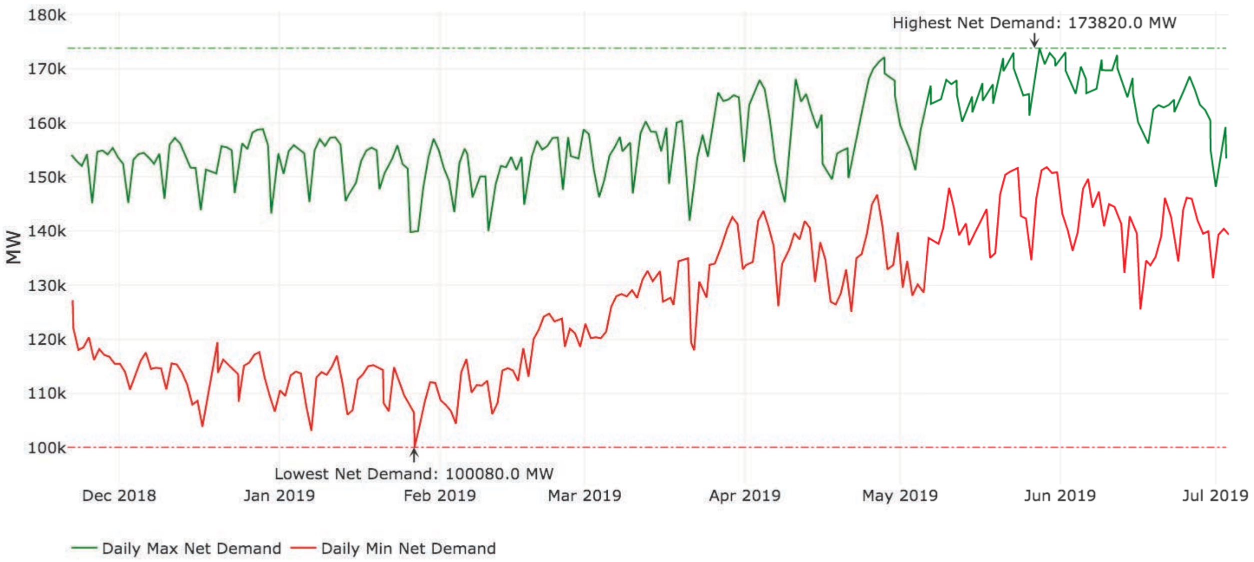


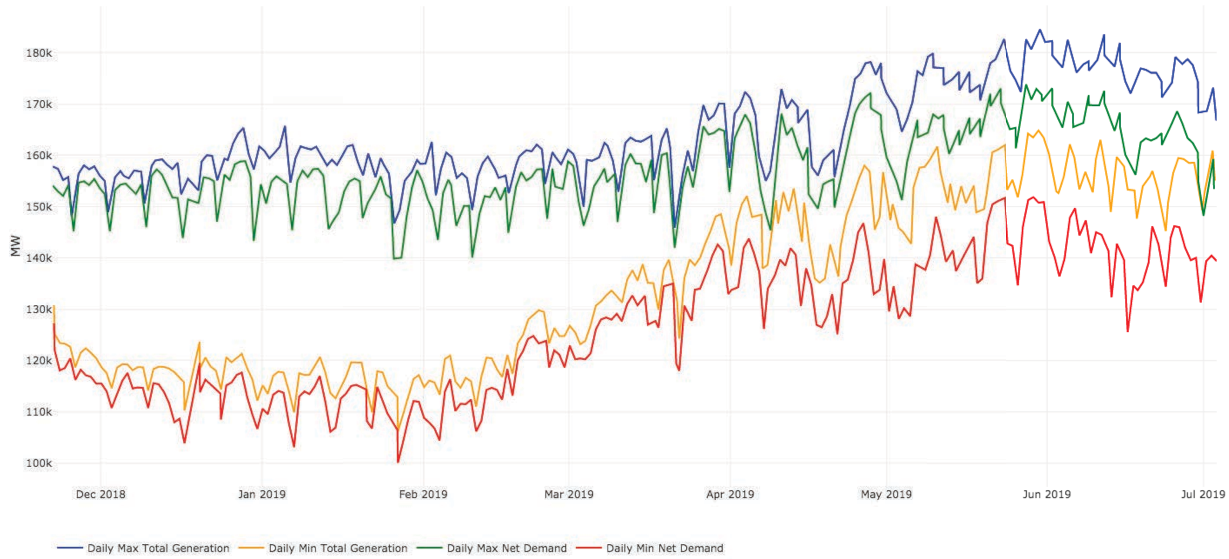
Figure 1 above shows the variation of daily highs and lows between December 2018 and June 2019. In March, we see that the daily low starts to rise, reducing the gap between the daily high and daily low generation. Thus, during winter, utilities require higher availability of flexible generation capacity (hydro and gas). So far, we also see that the highest demand for the year happens sometime at the end of May (peak summer), and the lowest at the end of January (winter).

Figure 2- Net Demand daily maximum and minimum



We see similar trends in daily highs and lows of Net Demand[1] as shown in Figure 2.
Overlaying both the figures onto Figure 3 shows that in mid-April, the gap between total generation and Net Demand starts to increase - which could imply that during the summer months, there is more renewable generation, or the timing of renewable generation aligns more closely with peaks, or both.

Figure 3- Maximum & minimum Total Generation and Net Demand



The fact that the gap between the high and low Net Demand is not smaller than that of total generation implies that renewables contribute a similar amount to the daily maximum and daily minimum generations. At first glance, this could suggest that daily demand peaks are not well-matched with times of peak renewable generation i.e. there is scope for demand shifting.

Figure 4- Load duration curve for Demand Met over time &corresponding RE Generation

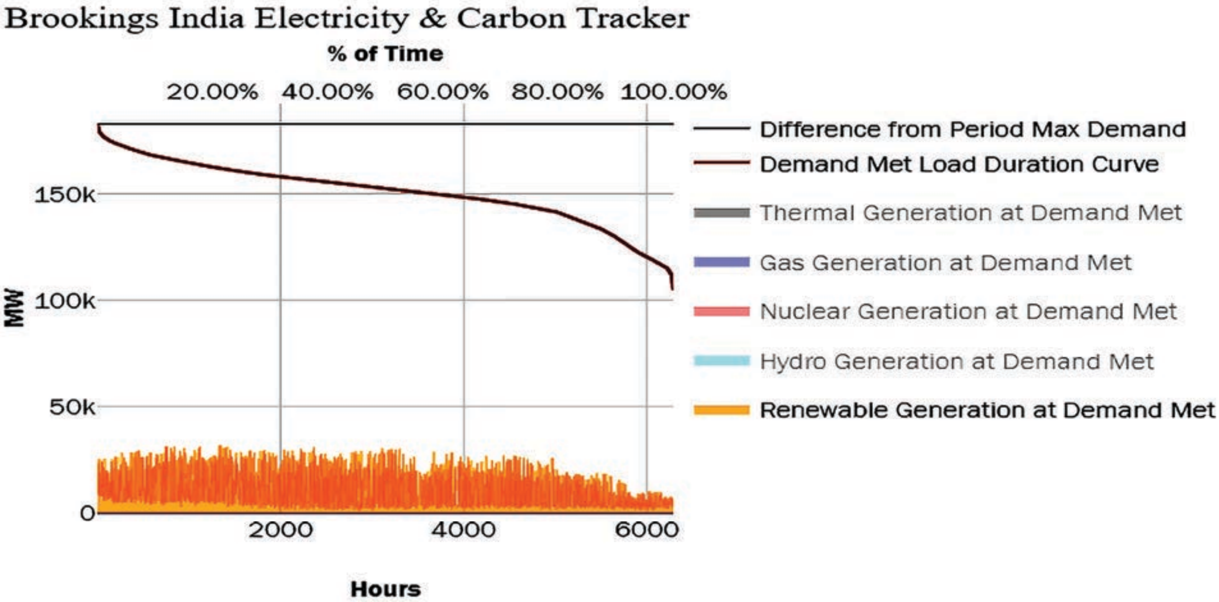
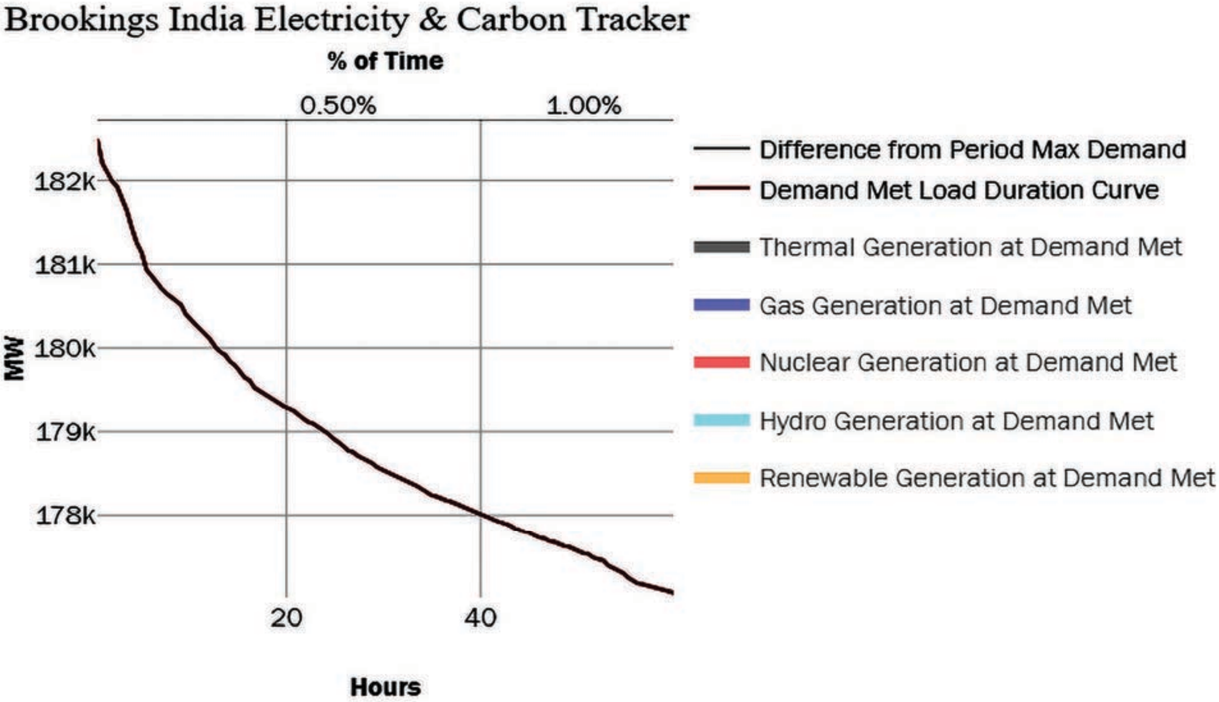


Figure 5- Top 1% of Demand Met between 01 Dec 2018 – 20 Aug 2019



From the above figures (Figure 4 and Figure 5) we see that the top 1% of Demand Met in between 1-Dec-2018 and 20-Aug-2019 has been above 177 GW, for an interval of around 60 hours. Thus around 5.5 GW of capacity is needed for less than a cumulative of 3 days over an approximate period of nine months. That translates to a Plant Load Factor (PLF) of less than 1% for the plants coming online at 177 GW and above.

2. Correlations between various generation sources

Looking at the correlation plots in Figure 6 below, we see some obvious relationships – thermal generation, total generation and Net Demand are all closely correlated with each other – but also some non-obvious ones. Hydro generation is closely correlated with total generation, and more so with Net Demand, implying that hydro is acting as a peaker in tandem with renewable generation. We also see this in the distribution of hydro generation, which is far more evenly spread out than both renewable and thermal generation. Interestingly, hydro generation is more closely correlated to Net Demand than thermal generation is to total generation.

Figure 6- Correlation plots for various generation sources (Dec 2018 – June 2019)

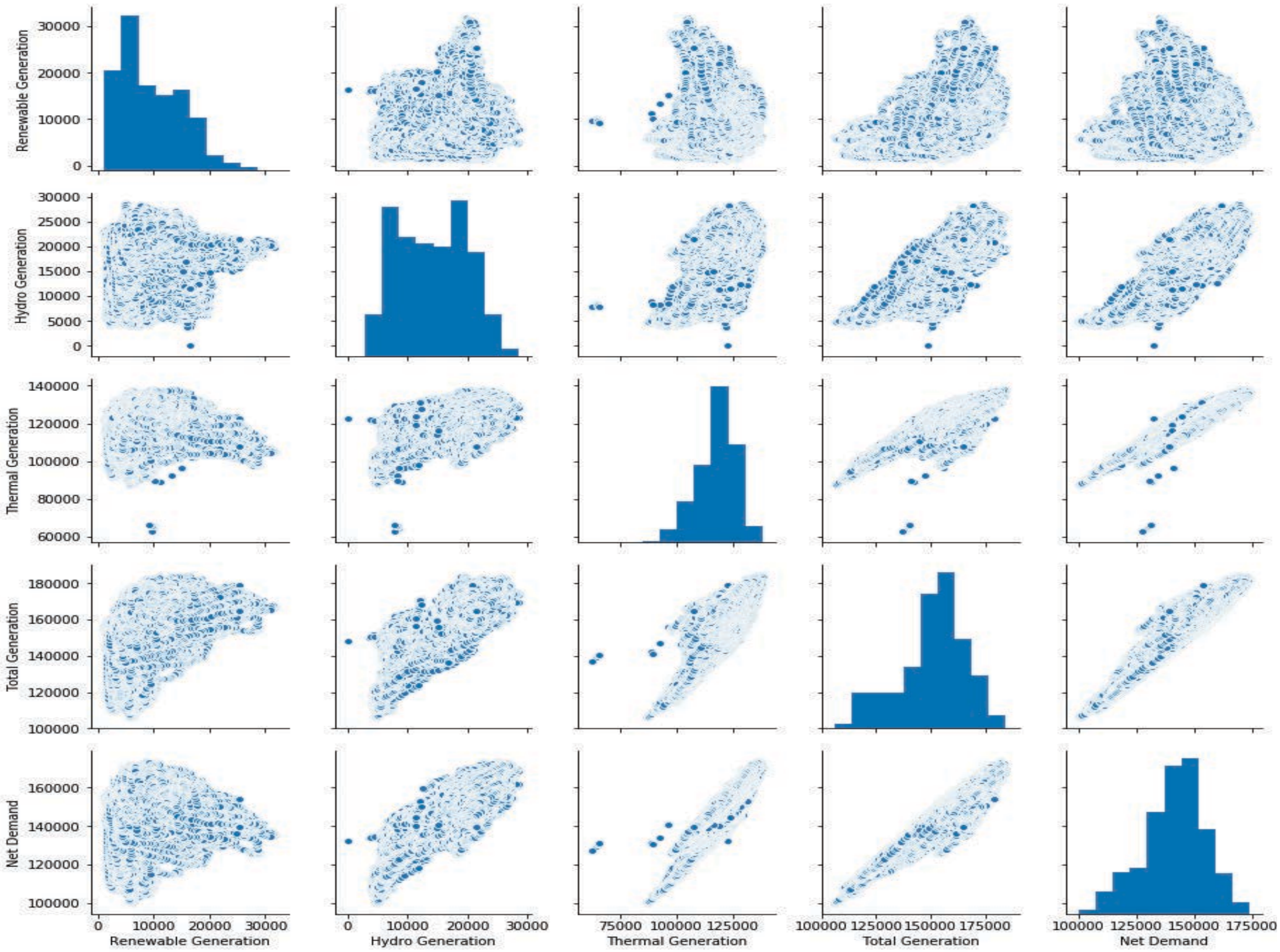


Table 1 below shows the calculated correlation factors for the various generation sources as well as Net Demand.

Table 1- Correlation factors for different generation sources and Net Demand

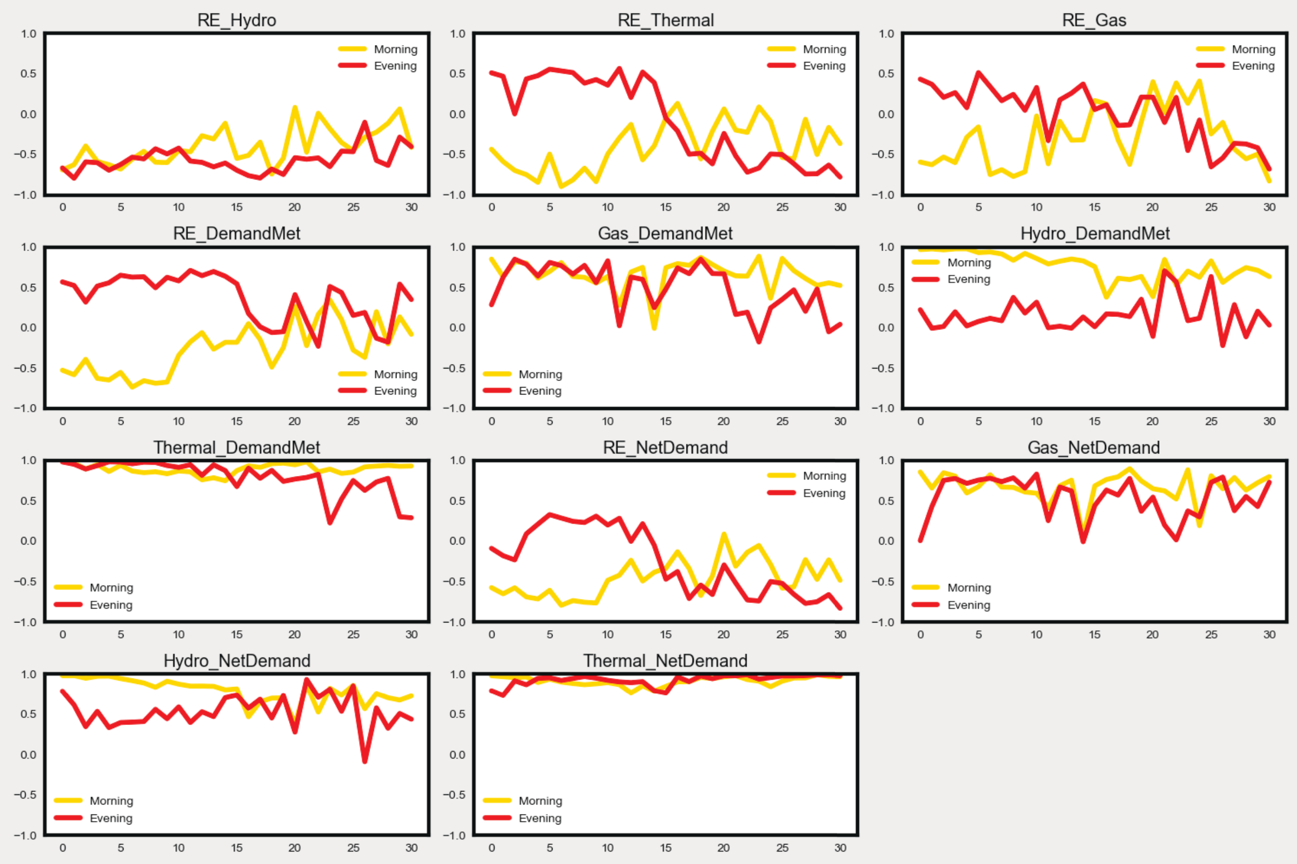
	Total Generation	Renewable Generation	Hydro Generation	Thermal Generation	Net Demand
Total Generation	1.00	0.51	0.81	0.84	0.93
Renewable Generation	0.51	1.00	0.18	0.09	0.16
Hydro Generation	0.81	0.18	1.00	0.58	0.85
Thermal Generation	0.84	0.09	0.58	1.00	0.92
Net Demand	0.93	0.16	0.85	0.92	1.00

3. Correlations by Time of Day (ToD)

Mornings (6.00 – 10.00) and evenings (18.00 – 22.00) are the times when we see the highest daily demands. These are also the times that witness an increase in the ramping requirements. In addition, RE starts to increase in the mornings (increase in solar) and decrease in evenings (decrease in solar). Thus, it is interesting to see how the various generation sources behave with respect to each other during these times. Based on the three-minute resolution generation data (from Merit India website) (Power, 2019), we calculated the weekly correlation factors for the morning and evening periods separately to see how the various generation sources vary with respect to each other between the months of December 2018 and June 2019. This time period equates to a total of 31 weeks.

Figure 7 below presents the correlations between the various generation sources, calculated on a weekly basis. We observe that the correlations keep varying. This is primarily due to change in temperature over time, which not only leads to change in Net Demand, but also PLF factors for the various generation sources like solar, wind and hydro.

Figure 7- Weekly correlation factors for various generation technologies and demand



Note- The figure shows the variation of correlation factors between different generation sources as well as demand over 31 weeks, from Dec 2018- June 2019.The x-axis represents the weeks starting from Dec 2018 and y-axis the correlation factors.

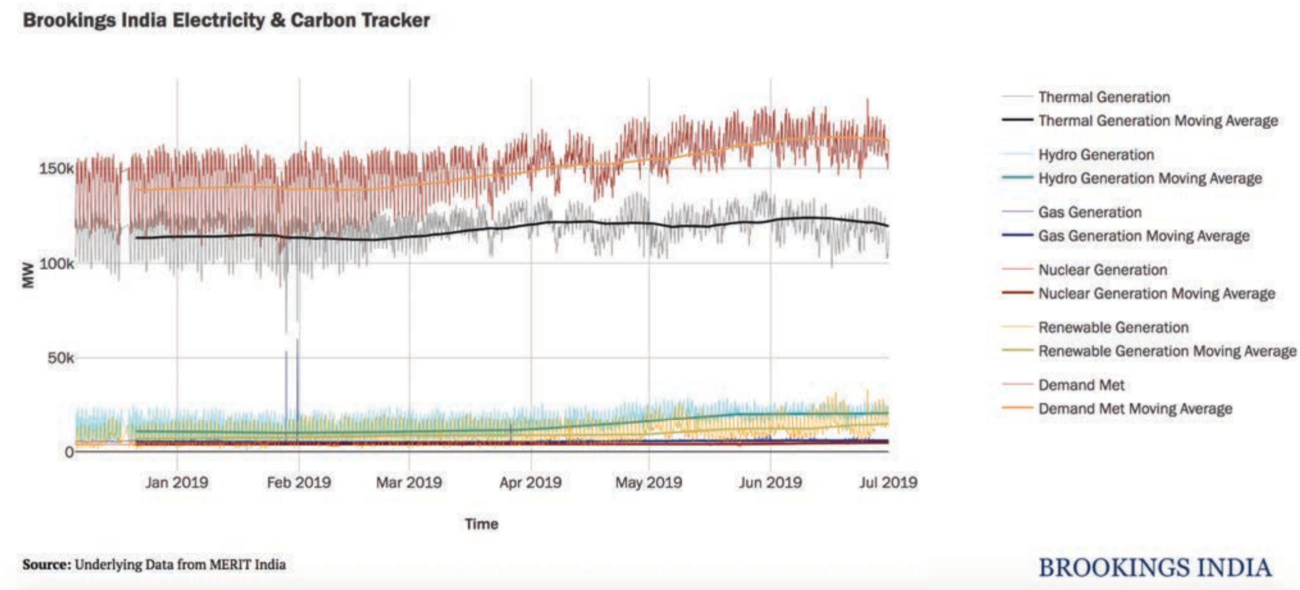
RE vs hydro presents an important correlation. We see that during the mornings and evenings i.e. the period of high ramp rates and high demand, the variations in RE are managed to a large extent by hydro (signified by strong negative correlations). Here we observe that the correlations are stronger in the evenings than in the mornings after February (week 10 in the above figure). RE vs Thermal and RE vs Gas also show similar trends, with the strong negative morning correlations becoming weaker as March (week 15) approaches. The strong evening correlations also decrease with the onset of summer. Thus, hydro, thermal and gas play a more important role in balancing the RE fluctuation in winters than in summers.

Hydro vs Net Demand is a very strong positive correlation. This reiterates the previous observation that a significant amount of increase in demand is catered by hydropower. Also from December to February hydro plays a stronger role in the morning to balance Net Demand.

With the decrease in solar generation in the evenings, we generally see a negative correlation in between RE and Net Demand. However, after March as the windy season picks up, with wind mostly concentrated in the night (approximation based on data broken down into wind and solar from Karnataka) we see that this correlation decreases. We also observe that RE usually does not provide energy when it is needed by the grid (in peak hours) but in fact does the opposite.

Figure 8 shows 30-day moving averages by generation source and we observe that the demand met starts to increase rapidly March onwards. There is a slight increase in thermal generation corresponding to this. However, hydro generation and renewable generation are the ones that show a significant increase in generation, and hence are major contributors in meeting this demand.

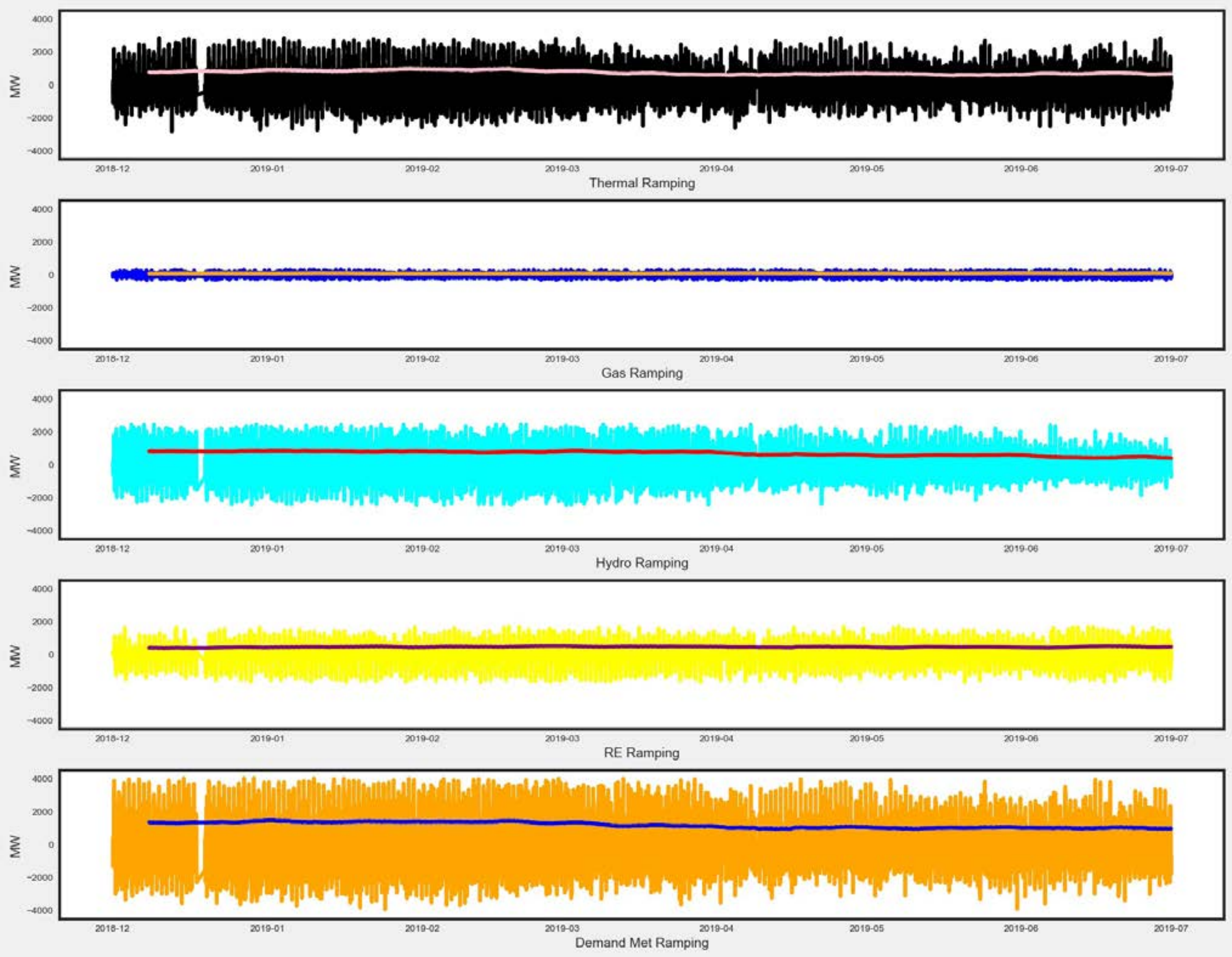
Figure 8- Monthly moving averages of different generation sources



4. Ramping

Figure 9 below shows the 15 minutes ramp rates[2] for the various generation sources between December 2018 and June 2019. We see that thermal generation has the highest ramp rates followed closely by hydro generation. Gas ramps are the smallest. RE cannot be controlled and its ramps require balancing measures. Currently, most of this balancing is being provided by hydro. However, as the share of RE increases (in line with the Government of India's plans), the ramping requirement for balancing it will be larger than can be balanced by hydro (as new hydro capacity is not being at the same rate). Thus, more capacity capable of high ramp rates will be required to be installed.

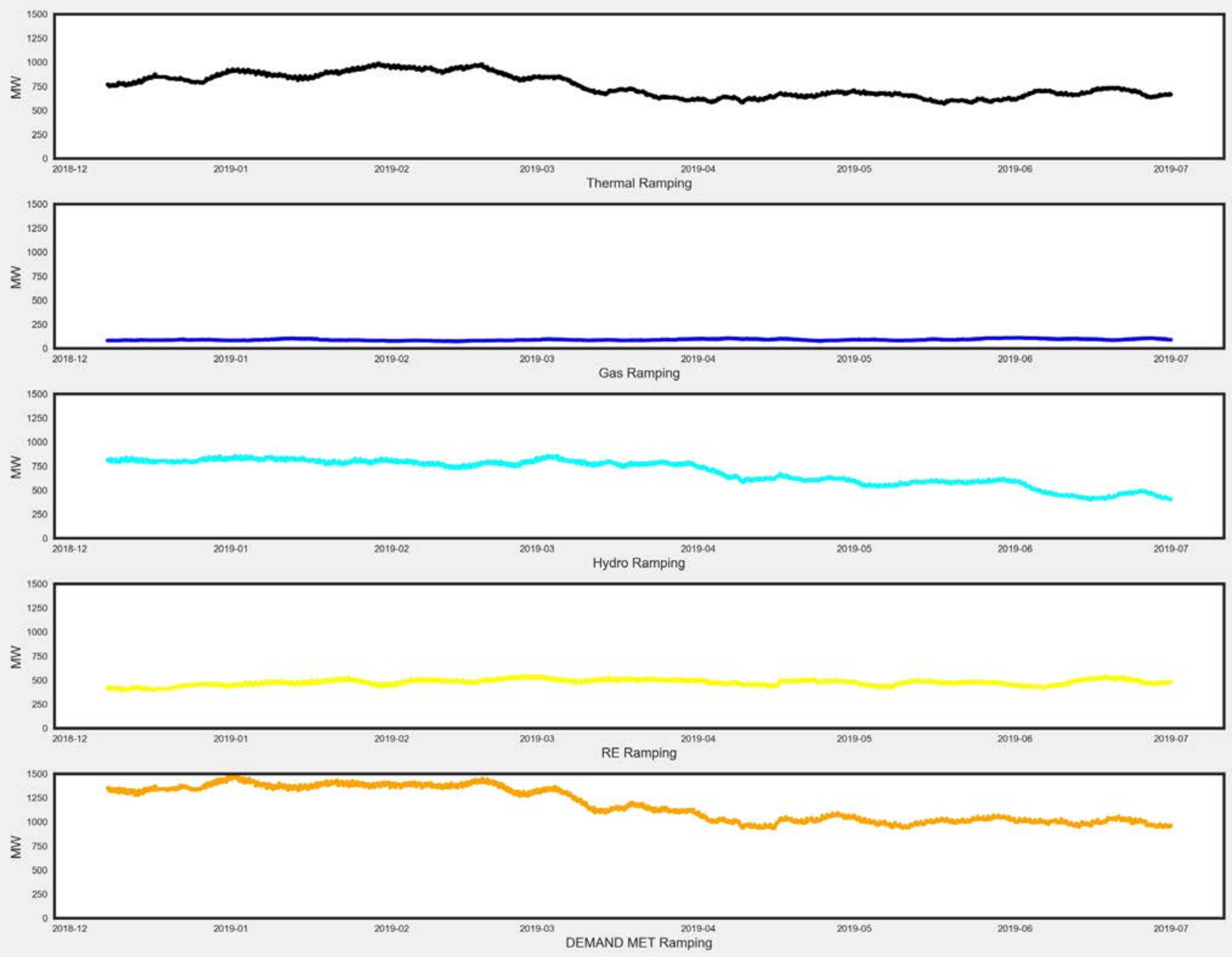
Figure 9- 15 minute ramp rates for various generation sources with weekly rolling standard deviation



Note: The gaps in the data are due to unavailability of data during those time periods. The horizontal lines represent the rolling standard deviations.

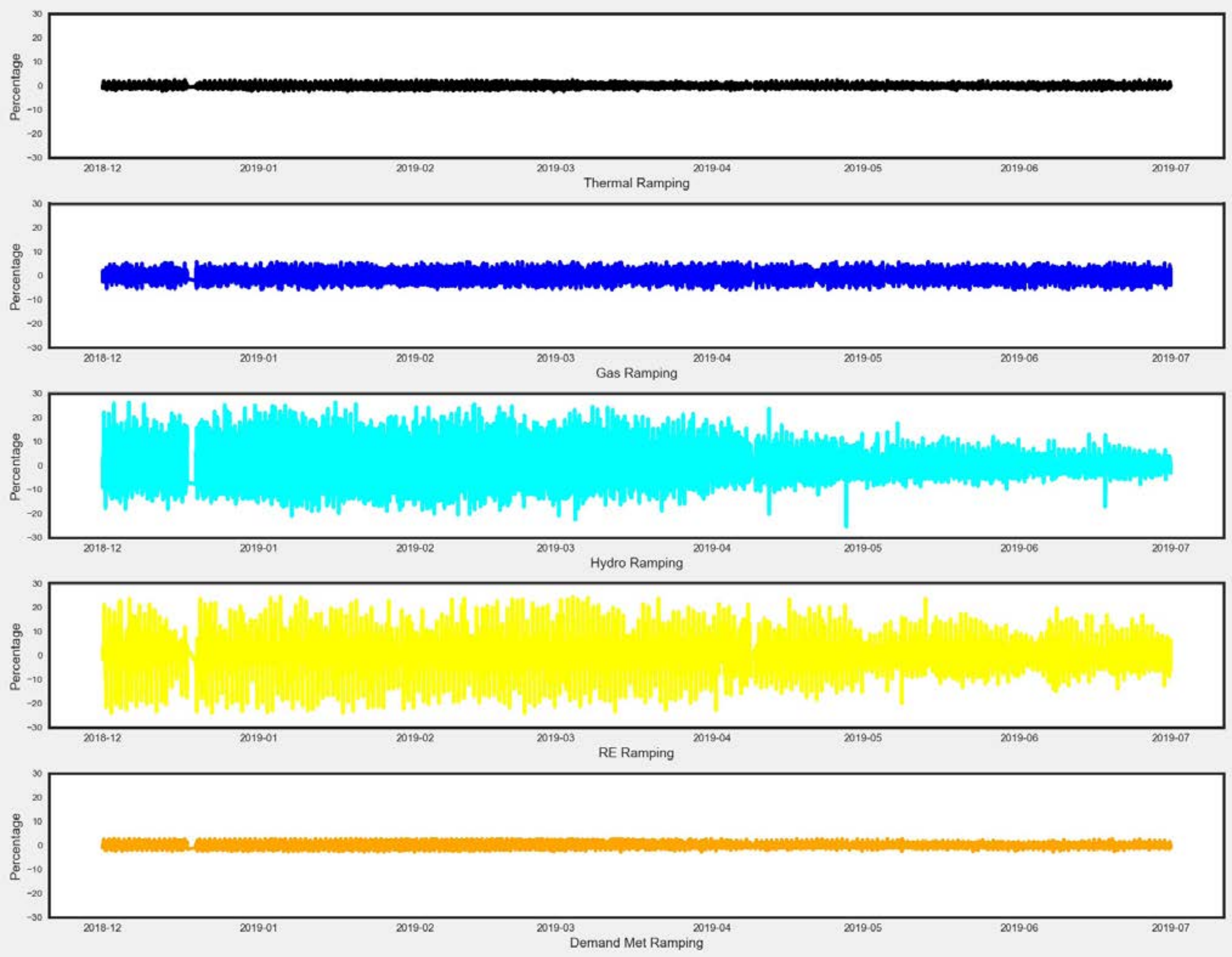
A closer look at the standard deviations for the 15 min ramp rates in Figure 10 below, shows that the standard deviation decreases for thermal and hydro, remains almost constant for gas and increases mildly for RE.

Figure 10- Weekly rolling standard deviations for 15 min ramp rates



However, based on capacity online, we have a different story as shown below. Figure 11 below shows the percentage increase/decrease in the ramps over 15 min, with respect to the capacity online in the previous 15 min block. On this basis, we find that thermal generation is providing the lowest percentage ramps, whereas hydro provides the highest ramps. We also observe that the ramping requirements as well as percentages tend to decrease from April. This can be explained with reference to Figure 3, where we see that the gap between the highest and lowest generation starts to decrease after March.

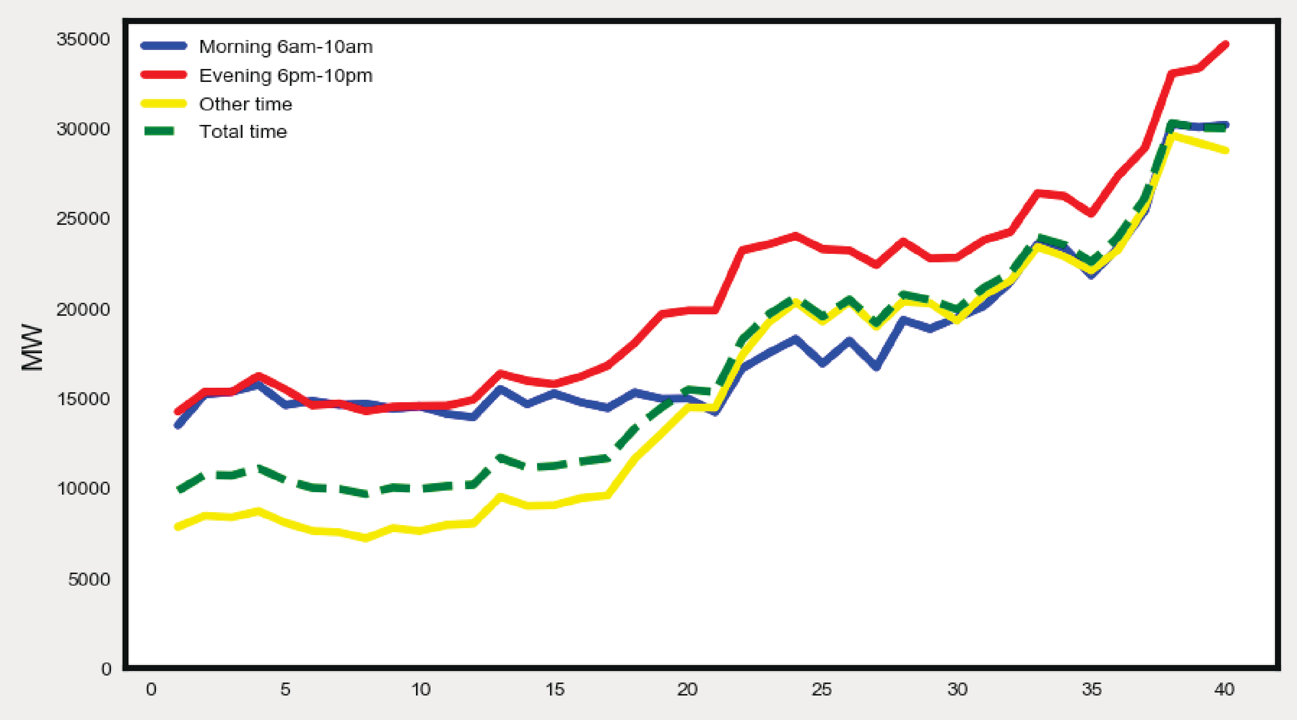
Figure 11- Percentage ramping (15 min) based on online generation capacity



5. Hydro generation

Hydro generation varies over months. In Figure 12 below we see how the hydro capacity online has varied from Dec 2018 - June 2019. Morning and evening timings have been separated, as during these times hydro plays an important role in balancing and is usually being run at a higher than average capacity. We observe that in the mornings and evenings, hydro generation has mostly been higher than at other times of the day. Also, after March the generation capacity online has consistently increased, thus pointing towards the "must-run" nature of hydro in these months.

Figure 12- Average weekly hydro capacity online (01 Dec 2018- 27 Aug 2019)



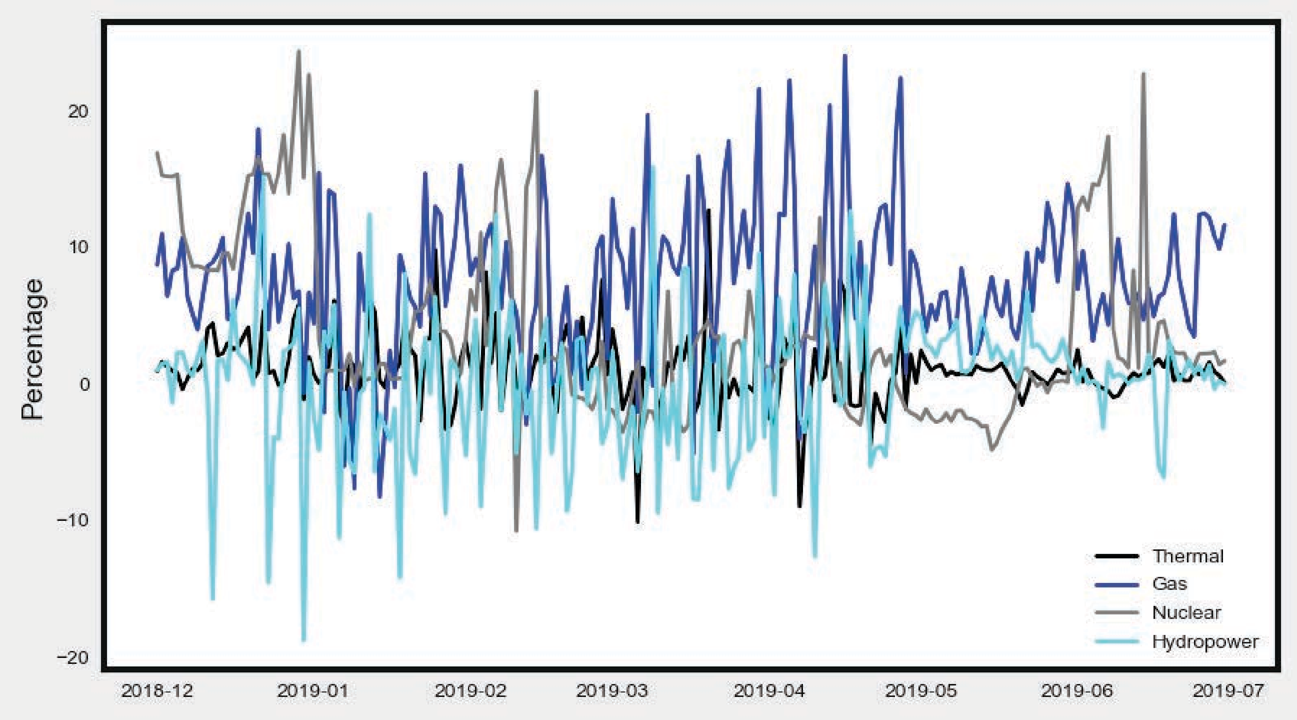
Note- The x-axis represents weeks starting from 01-Dec-2018 and ending at 30-June-2019

3. Errors and error corrections

1. Conventional generation

The Brookings Electricity and Carbon tracker works on real time data as provided by the Central Electricity Authority (CEA). However, not all the electricity generated by the generating plants is captured by the current live Supervisory Control and Data Acquisition (SCADA) system. While cross-checking with the Power System Operation Corporation Limited (POSOCO) monthly reports, we have found that there are discrepancies between what is reported in the live SCADA system and what is reported by POSOCO after consolidation of data from sources. In Figure 13 below, we present the discrepancies for the various reported figures in the tracker as compared to the daily figures in the monthly POSOCO reports.

Figure 13- Percentage error (excluding RE) of tracker readings vs daily figures in the monthly POSOCO reports



We have calculated the daily MU's (Million Units) generated based on the tracker readings and compared them with the monthly MU's reported by the National Load Despatch Centre (NDLC). The data is available to us at a resolution of three minutes.[3]

We observe that there is a positive error for most generation sources, indicating that the tracker is over reporting with respect to the generation reported in the monthly reports for thermal, gas and nuclear. Hydropower is the only conventional generation source where generation reported by the tracker has consistently lower values than that of the monthly reports (for months from January to April). The average error with respect to the monthly generation reports between the months of December 2018 to June 2019 is shown in Table 2 below.

Table 2- Average daily error percentage for daily MU generation

Generation Type	Error Percentage
Thermal	1.04%
Gas	7.79%
Nuclear	3.57%
Hydro	0.19%

On a percentage-wise basis, thermal has a small average error of 1.04%. However, given that the total thermal generation capacity online is large, in absolute terms the average error translates to a capacity of 1 GW to 1.4 GW. For gas generation on the other hand, the error is large and on an average is around 7.79%. Given that the total gas generation varies between 4 GW to 7 GW, this translates to a capacity between 0.3 GW to 0.8 GW. However, we also observe that the error variation in gas generation is large and varying from 0% to 20% in some cases.

Nuclear generation also has a high variation of error, with error margins as high as 25%. The average error during this period is just 3.57% though. As the number of nuclear power stations in the country is just seven with around 4000 MW online, the average error is of the order of a 150 MW. Hydro error presents a different challenge though. Here we have a negative average error till mid-April, i.e. the tracker is reporting lower generation than what is reported in the monthly reports. After that the error is in the positive direction. The average error though is quite low, at a value of 0.19%.

We believe that the sudden spikes in generation on some days may also be due to instrumentation errors or missing data. Currently we are working on reconciling this difference in numbers and will welcome any suggestions put forward in this regard.

2. Renewable generation

RE generation on the other hand is highly underreported in the tracker. On average, the tracker is only able to capture between 60% to 70% of the RE generated, as reported in the monthly reports. We have further divided the RE into two categories of Solar and Other RE (which includes wind, biomass etc.). Based on our calculations[4] we have also been able to divide the percentage of Solar RE captured and percentage of Other RE, as is shown in the figures below, for three different ratios of Other RE generation in day vs night.

Figure 14- Weekly moving average of RE captured (Other RE generation ratio- Day: Night- 30:70)

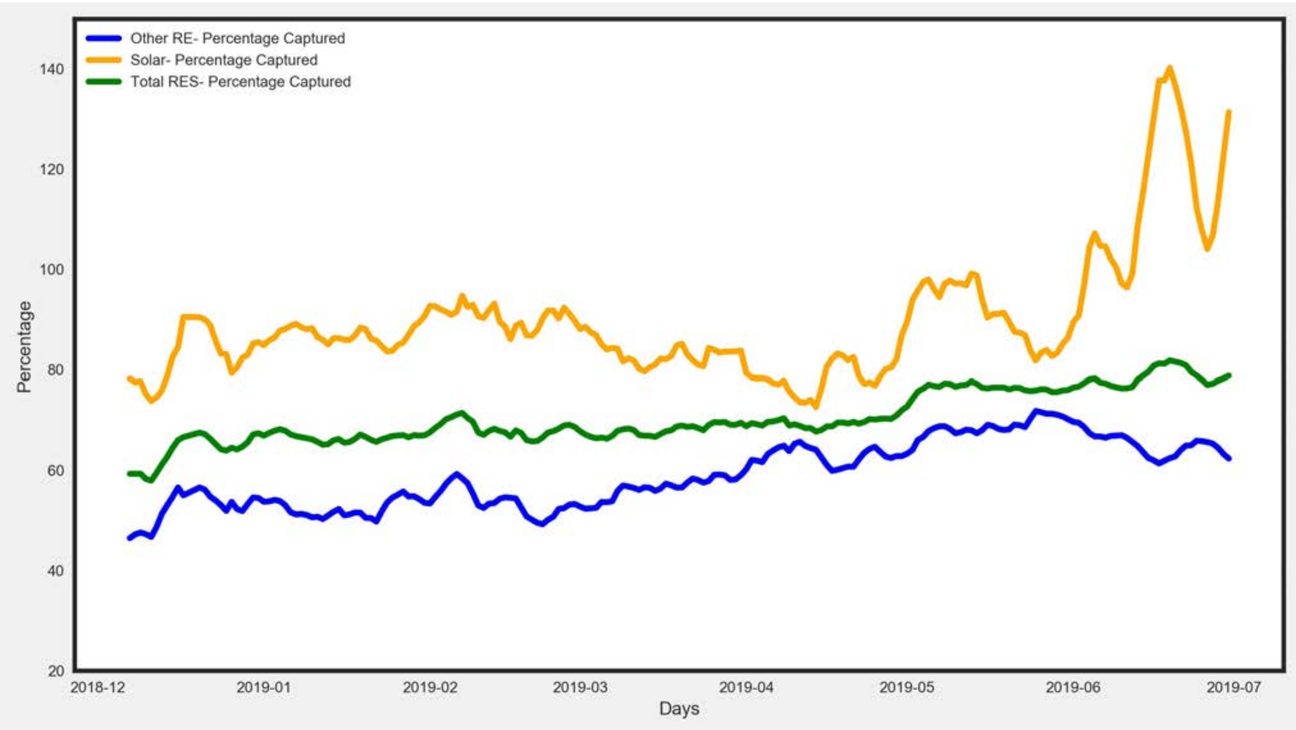


Figure 15- Weekly moving average of RE captured (Other RE generation ratio- Day: Night- 40:60)

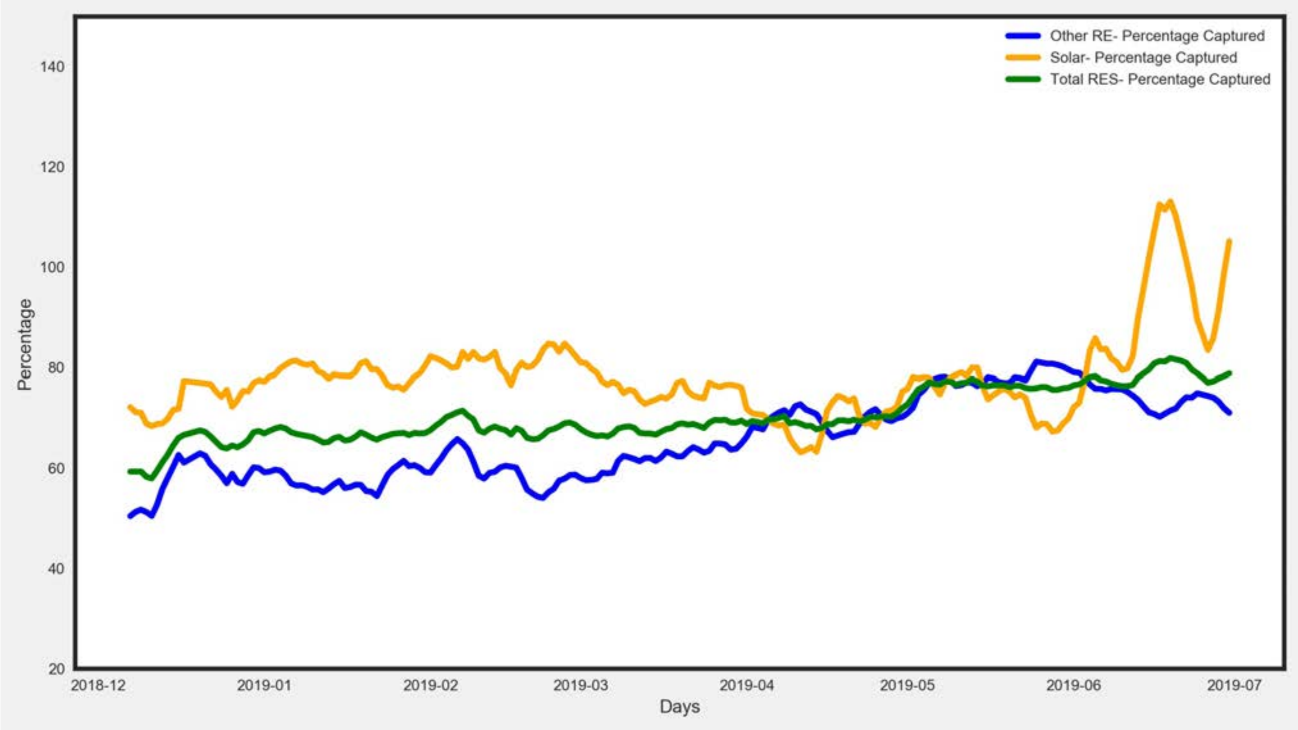
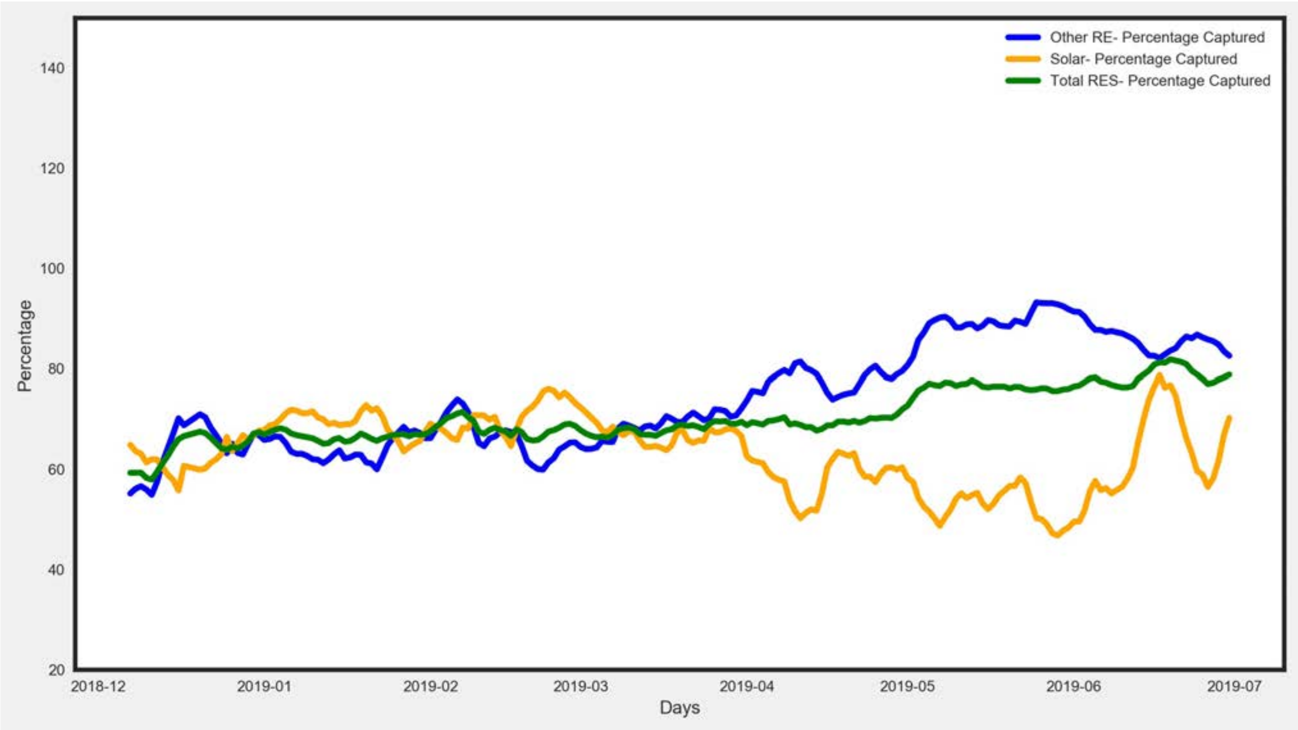


Figure 16- Weekly moving average of RE captured (Other RE generation ratio- Day: Night- 50:50)



From the above figures we find that solar generation is captured to a higher extent than Other RE between the months of December and April. After April, we find that percentage of Other RE captured increases, whereas for solar generation it shows different behaviors for different Other RE assumptions. This means that Other RE variation is not only based on day and night, but this variation is also changing over the months, something that is being incorporated in the model currently.

Using similar assumptions, we also quantified the percentage of *RE generated in the day* vs *RE generated in the night*, as shown in the figures below.

Figure 17- Weekly moving average of RE captured (Other RE generation ratio- Day: Night- 30:70)

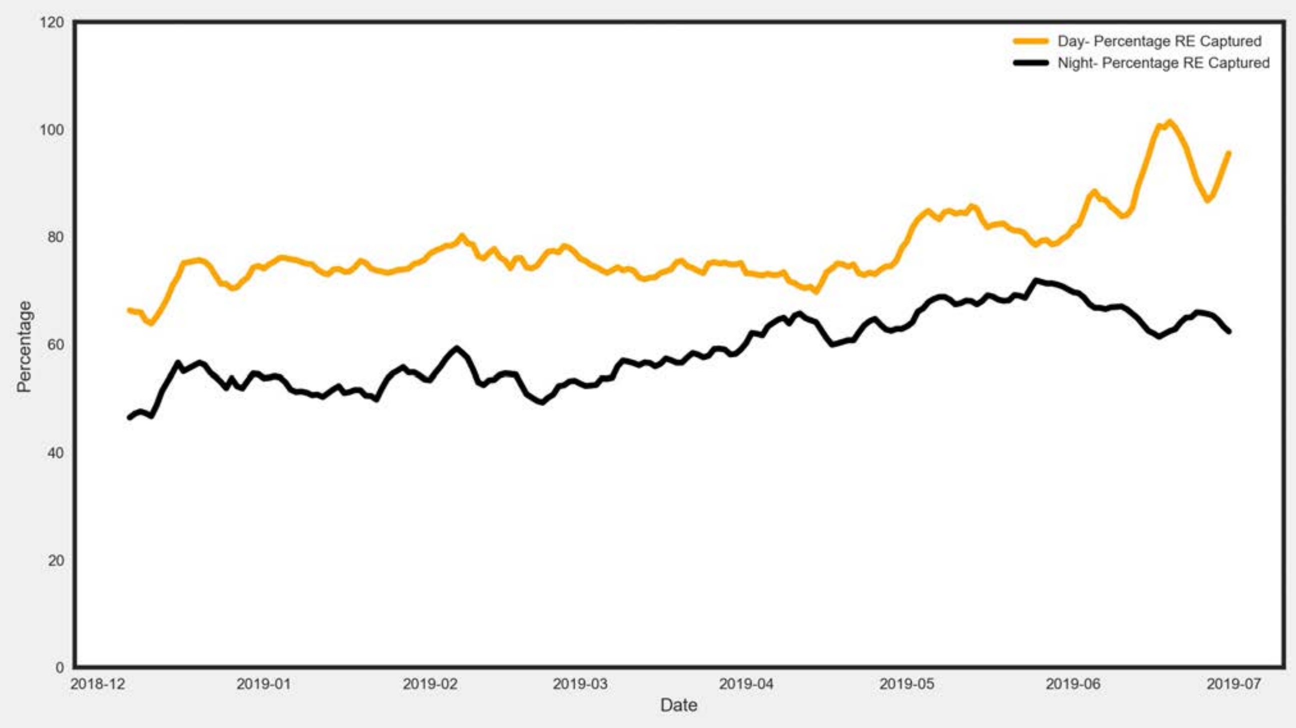


Figure 18- Weekly moving average of RE captured (Other RE generation ratio- Day: Night- 40:60)

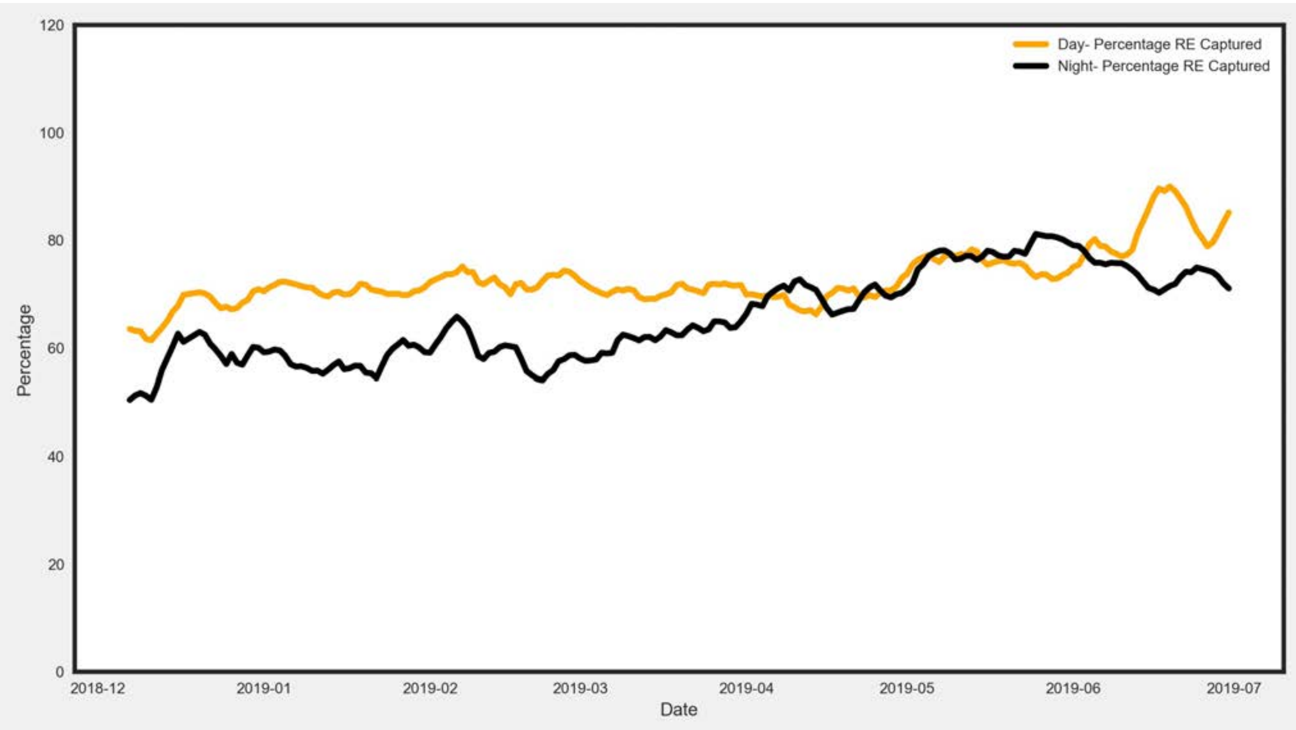
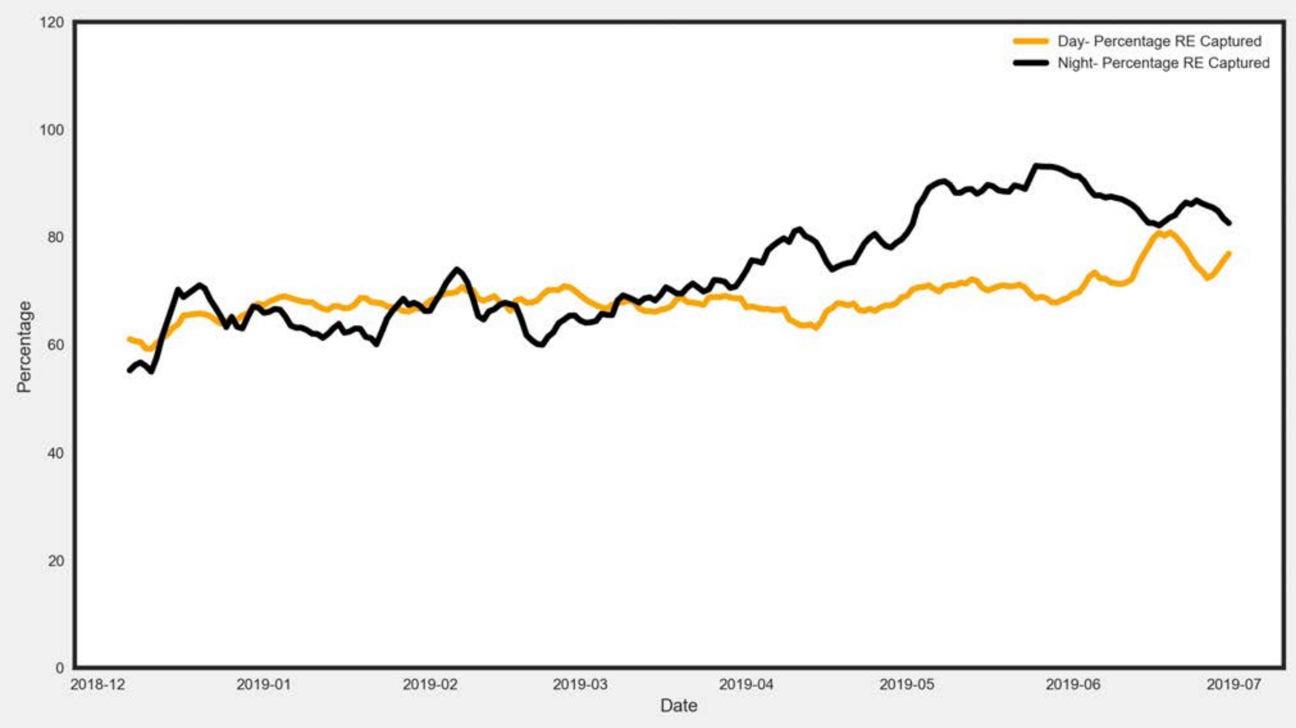


Figure 19- Weekly moving average of RE captured (Other RE generation ratio- Day: Night- 50:50)



3. Trends and analysis

In Table 3 we see the shift in the characteristics of daily peaks over time. From December to February, peaks are predominantly in the day, but March onwards, peaks are increasingly at night. Note that here we consider peaks between 00.00 and 6.00 to be night peaks, and these are mostly at or a little after midnight.

Table 3- Number of daily peaks by time of day per month

Month	00.00 - 6.00 Peaks	6.00 - 10.00 Peaks	10.00 - 14.00 Peaks	14.00 - 18.00 Peaks	18.00 -24.00 Peaks	Avg Renew-able % at Peak	Renewable % of Total Gen
Dec	0	11	7	1	12	5.43	4.94
Jan	0	22	5	0	4	6.89	5.32
Feb	0	16	2	1	9	6.51	6.13
Mar	0	8	2	0	21	4.02	5.74
Apr	3	0	1	2	24	4.41	6.01
May	6	0	0	4	21	6.35	7.58
Jun	8	0	0	4	18	7.24	9.00

Additionally, in Table 4 below, we see that in winter the median peak time is during the day, more closely matched to the median peak renewable generation time. March onwards daily peaks occur later, whereas median peak RE generation time is steady at around 12:30 pm.

Here we use daily average Net Demand as a benchmark for peak shifting, i.e. if renewable generation perfectly aligns with demand, the Net Demand will be flat throughout the day and will be equal to its daily average. In the ideal scenario, we can at most hope to lower peak Net Demand to the average of the Net Demand for the whole day by shifting the time of peak demand to the time of peak renewable generation. This is captured in Table 4 as well.

Table 4- Median peak times by month

Month	Median Peak Time	Median Daytime (6.00 –18.00) Peak Time	Median Peak Renewable Time	Avg Net Demand (MW)	Max % Reduction in Net Demand (Peak Net Demand – Avg Net Demand)
Dec	10:25	10:05	12:10	133710.23	10.24
Jan	09:45	09:40	12:40	132604.35	10.21
Feb	09:45	09:40	12:45	133137.63	9.81
Mar	19:05	09:55	12:30	140979.00	8.80
Apr	19:45	15:00	12:35	146879.39	8.27
May	22:45	15:25	12:20	152259.88	7.60
Jun	22:25	15:00	12:35	150885.33	8.24

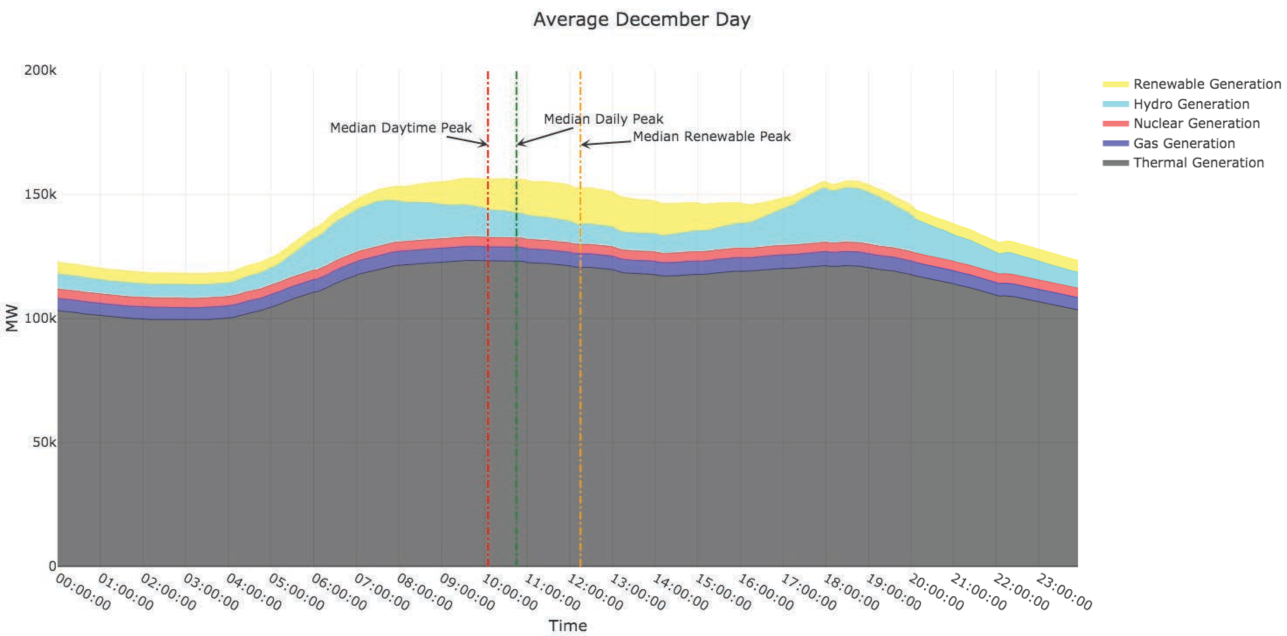
Table 5 below shows the average peak demand during day and night, as well as the average of minimum and maximum generations

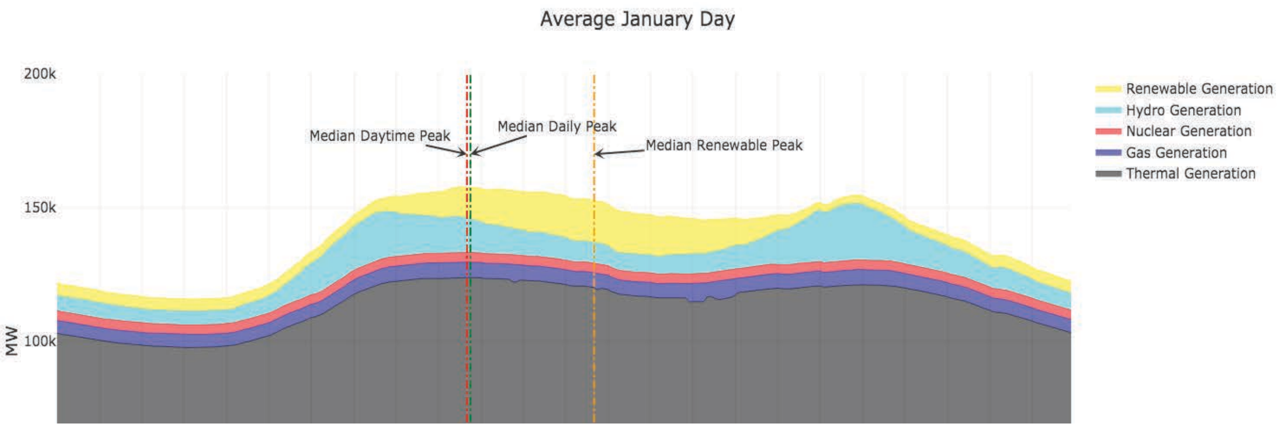
Table 5- Demand peaks and generation peaks

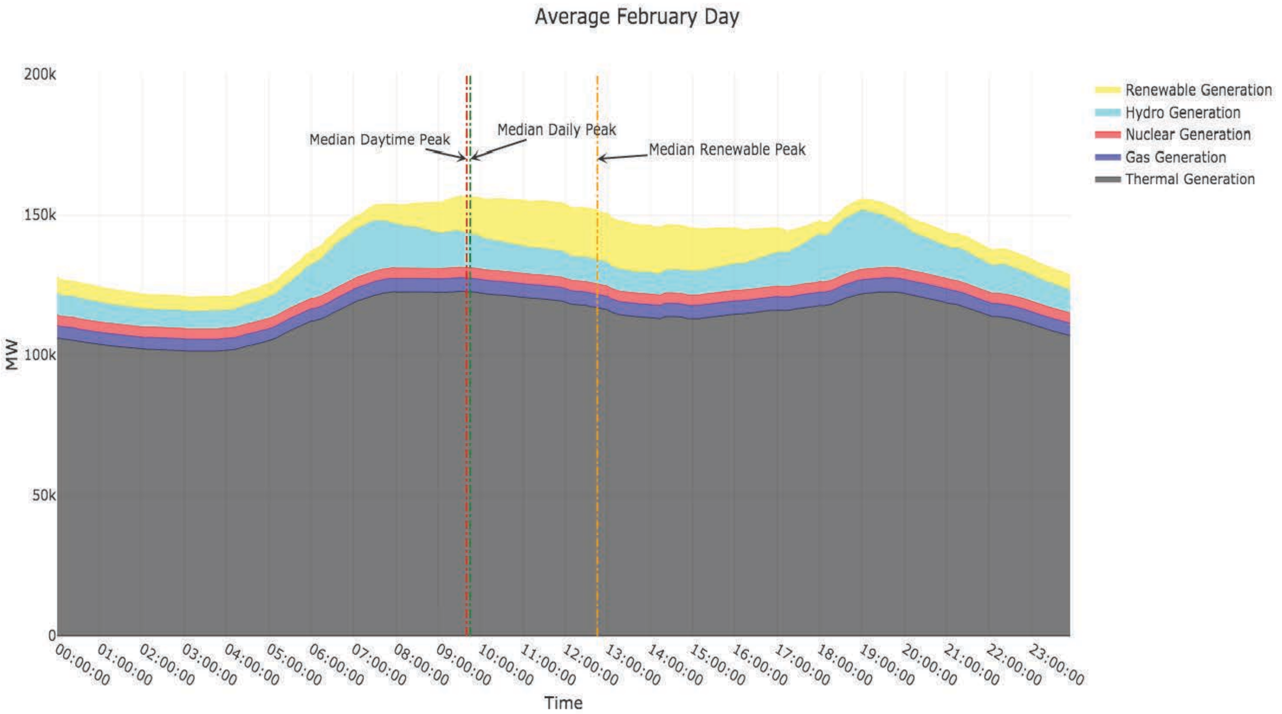
Month	Avg Daytime (6.00 –18.00) Peak (MW)	Avg Evening (18.00– 24.00) Peak (MW)	Avg Daytime Peak/Avg Evening Peak	Avg Max Generation (MW)	Avg Min Generation (MW)	Avg Max Generation - Avg Min Generation (MW)
Dec	157385.30	155808.53	1.01	157565	117960	39604
Jan	158354.26	154944.15	1.02	158622	115537	43085
Feb	157203.11	155914.25	1.01	157866	120380	37486
Mar	158728.60	160248.66	0.99	161034	134850	26183
Apr	159789.25	167226.93	0.96	167443	146614	20829
May	171078.76	174582.61	0.98	175973	154792	21180
Jun	172682.88	177108.02	0.98	177239	155359	21880

We also see this better in the plots of what an average day for each of our months looks like in the figures below.

Figure 20-Average daily generation profile averaged over a month




Average January Day
200k
150k
100k
MW
Median Daytime Peak
Median Daily Peak
Median Renewable Peak
Renewable Generation
Hydro Generation
Nuclear Generation
Gas Generation
Thermal Generation


Average February Day
200k
150k
100k
50k
0
MW
Median Daytime Peak
Median Daily Peak
Median Renewable Peak
Renewable Generation
Hydro Generation
Nuclear Generation
Gas Generation
Thermal Generation
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00
06:00:00
07:00:00
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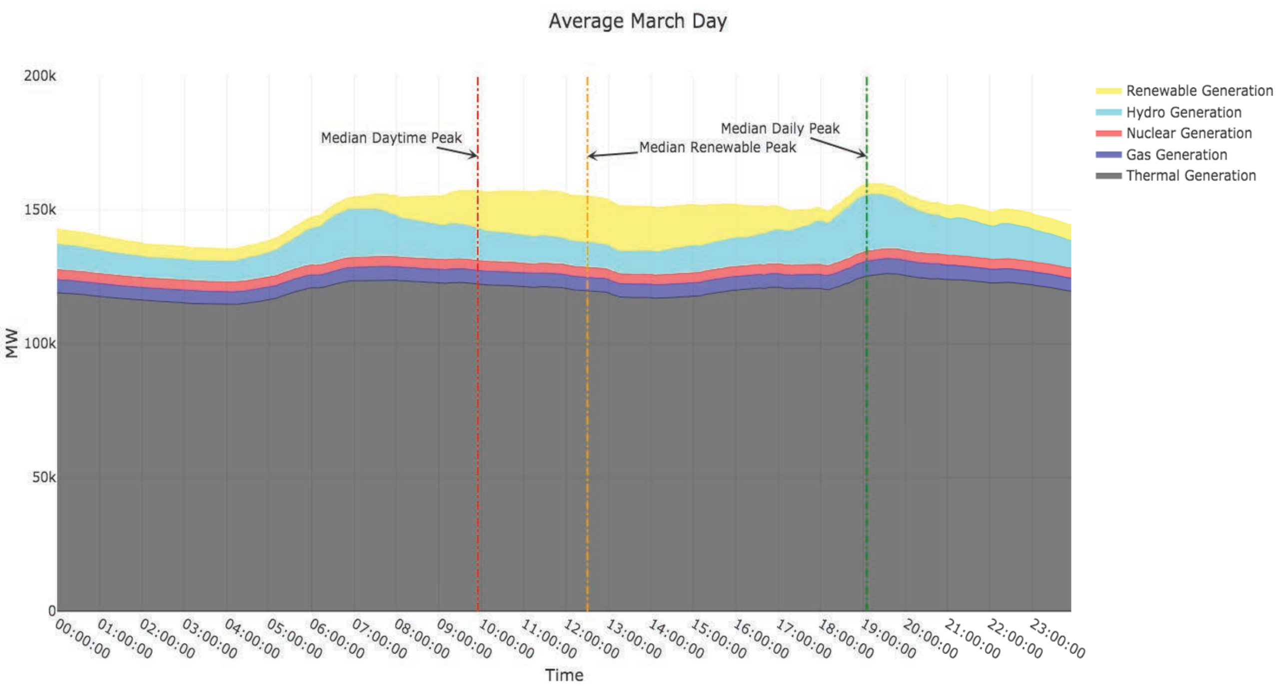
22:00:00
23:00:00
Time


Average March Day
200k
150k
100k
50k
0
MW
Median Daytime Peak
Median Daily Peak
Median Renewable Peak
Renewable Generation
Hydro Generation
Nuclear Generation
Gas Generation
Thermal Generation
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00
06:00:00
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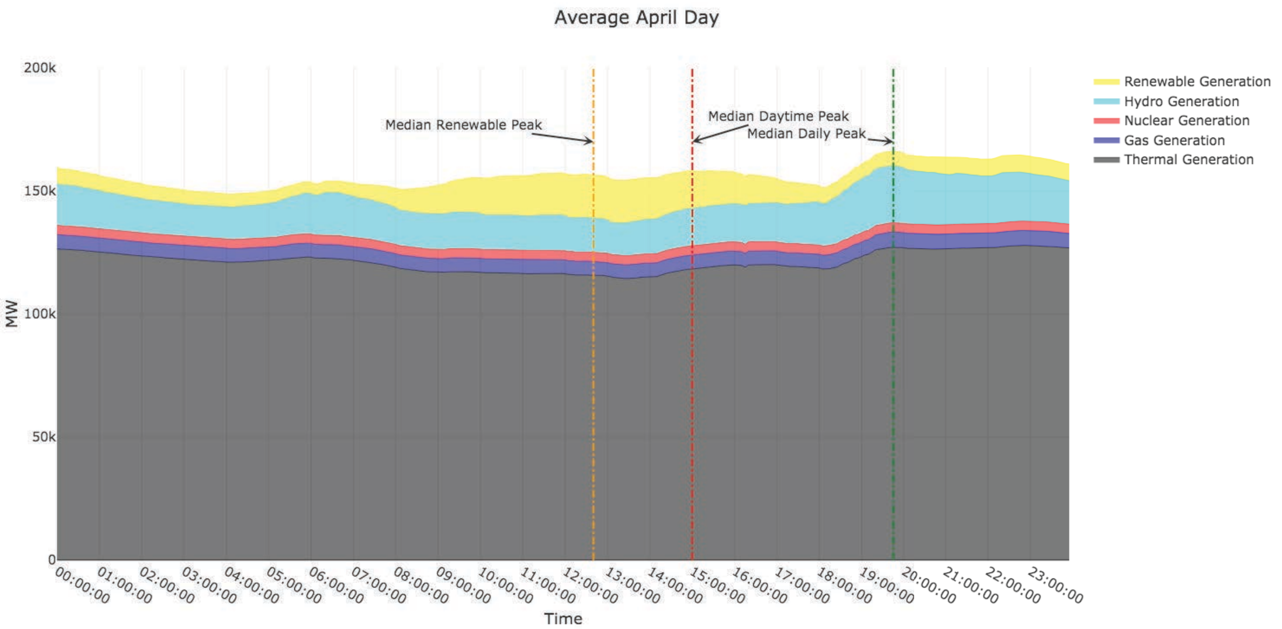
Time


Average April Day
Renewable Generation
Hydro Generation
Nuclear Generation
Gas Generation
Thermal Generation
Median Renewable Peak
Median Daytime Peak
Median Daily Peak
MW
200k
150k
100k
50k
0
Time
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00
06:00:00
07:00:00
08:00:00
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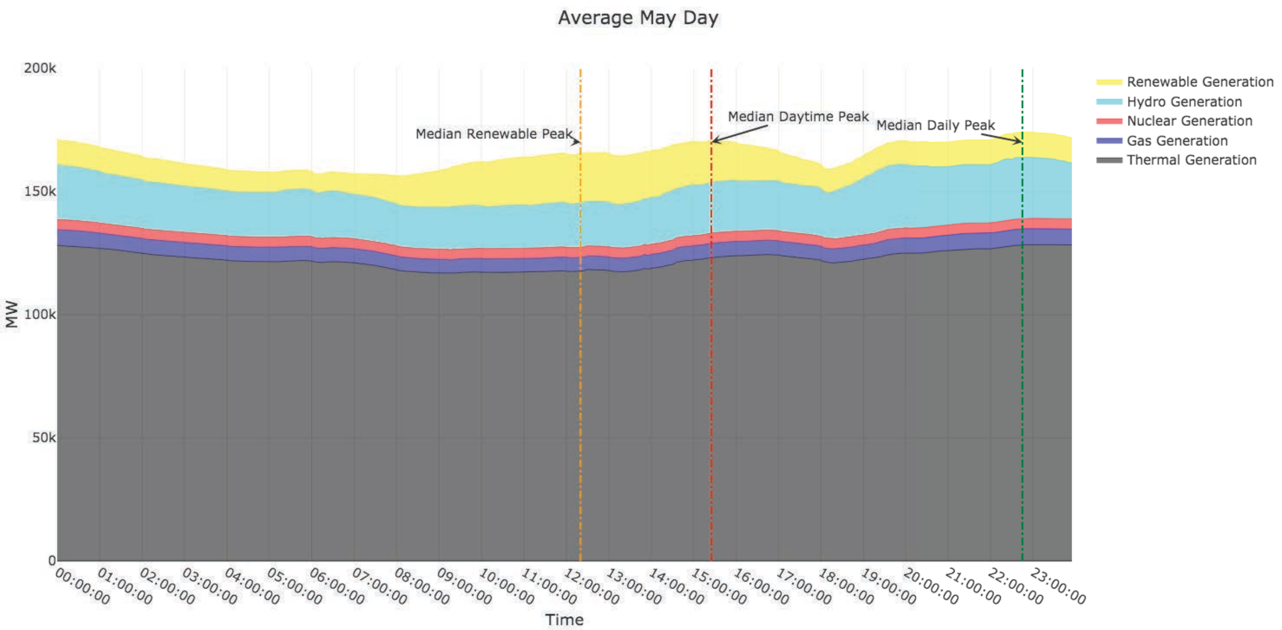
Average May Day
Renewable Generation
Hydro Generation
Nuclear Generation
Gas Generation
Thermal Generation
Median Renewable Peak
Median Daytime Peak
Median Daily Peak
MW
200k
150k
100k
50k
0
Time
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00
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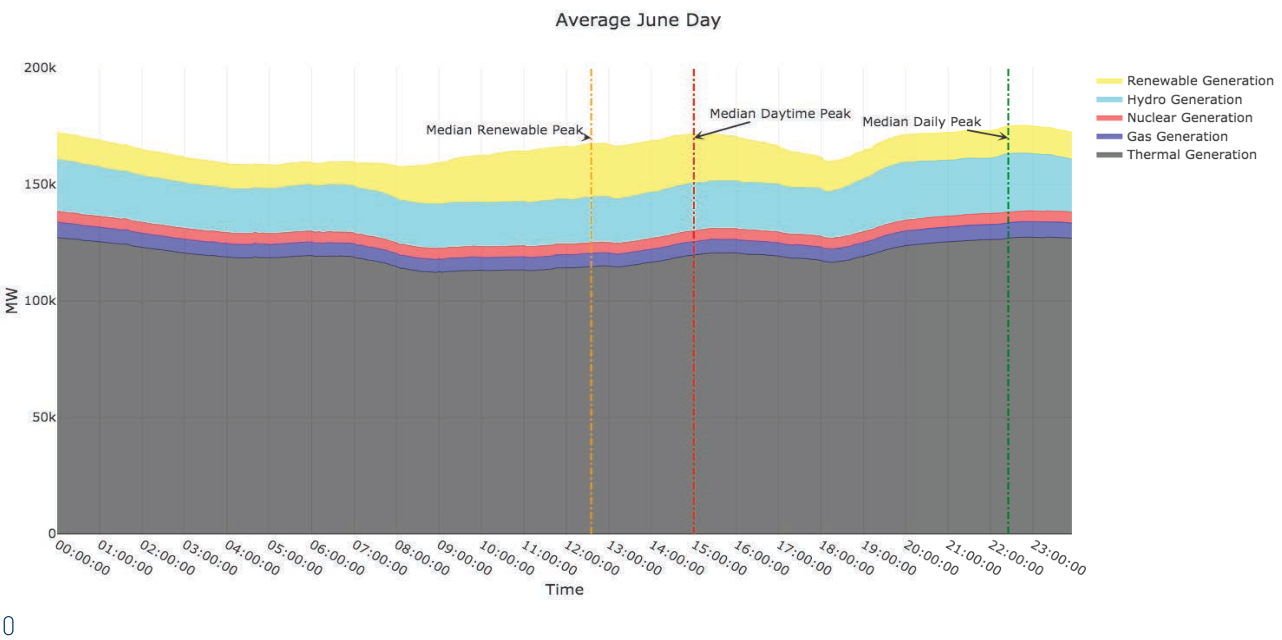
Average June Day
Renewable Generation
Hydro Generation
Nuclear Generation
Gas Generation
Thermal Generation
Median Renewable Peak
Median Daytime Peak
Median Daily Peak
MW
200k
150k
100k
50k
0
Time
00:00:00
01:00:00
02:00:00
03:00:00
04:00:00
05:00:00
06:00:00
07:00:00
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Figure 21 and Figure 22 show generation breakup by source for average daily peak of each month, both in terms of total generation and percentage of total generation. After March, percentage share of thermal generation at the peaks decreases, while hydro's and RE's increases.

Figure 21- Average Daily Peaks averaged per month by source of generation

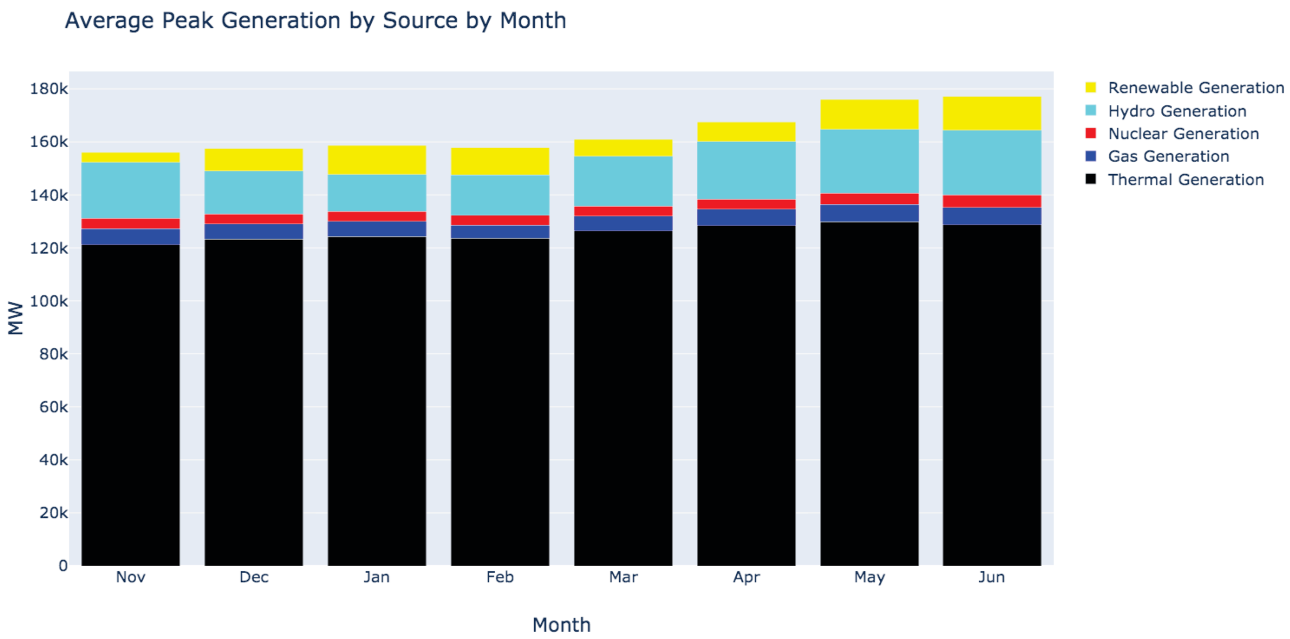
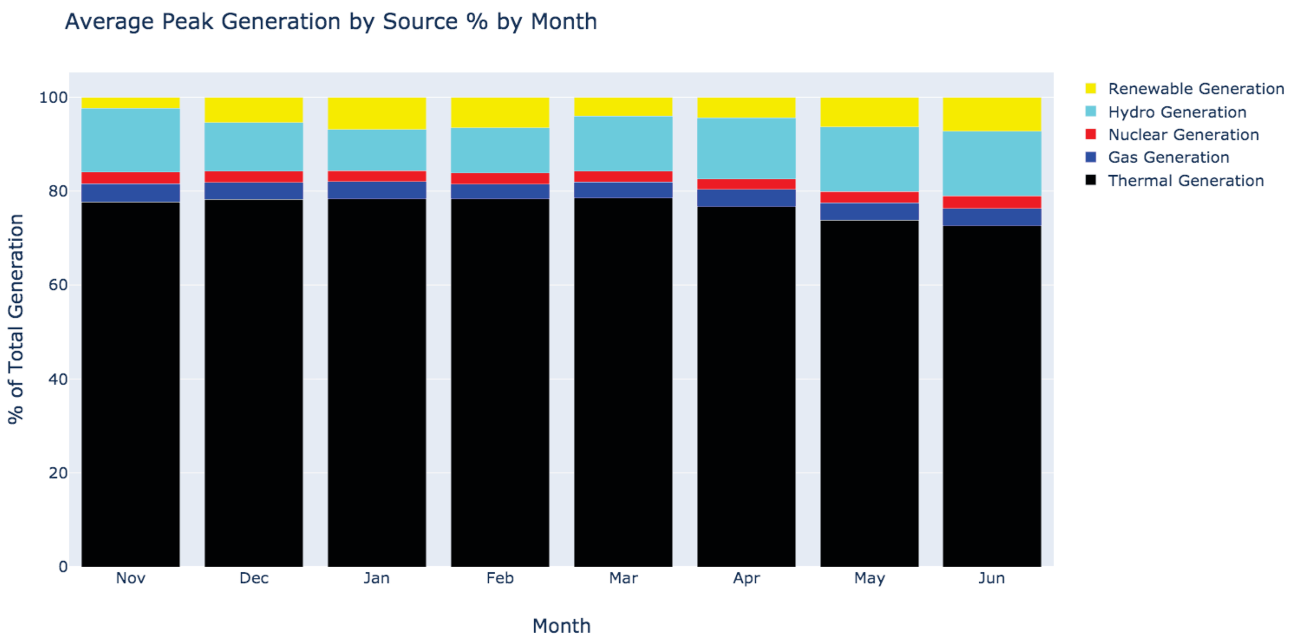


Figure 22- Average peak generation by source percentage and month



Note: Increase in RE in January and February is not because RE generation has increased in absolute terms, but because peak has actually shifted to daytime, when RE is also high. This is not the case for other months when peak is in the evening, when there is no solar.

4. ToD-based data to examine future RE integration capabilities

India's high RE ambitions require careful planning for balancing the grid in real-time. While studies such as Greening the Grid (GtG) (NREL, POSOCO, Berkeley Lab, 2017) have examined 2022 scenarios for 175 GW, they relied on 2014 data, that too estimated for RE generation. With the tracker, with mid-2019 actual (real-time) data, we can take stock of the ability of the Indian grid to absorb additional solar power at an all-India level, meaning we assume perfect inter-state transmission capability to absorb RE that may be concentrated in selected regions.

Given the "must-run" status of RE, to the extent technically feasible, other generation must back down when RE grows, while balancing demand. The alternates are storage, or throwing away RE, i.e., "curtailment".

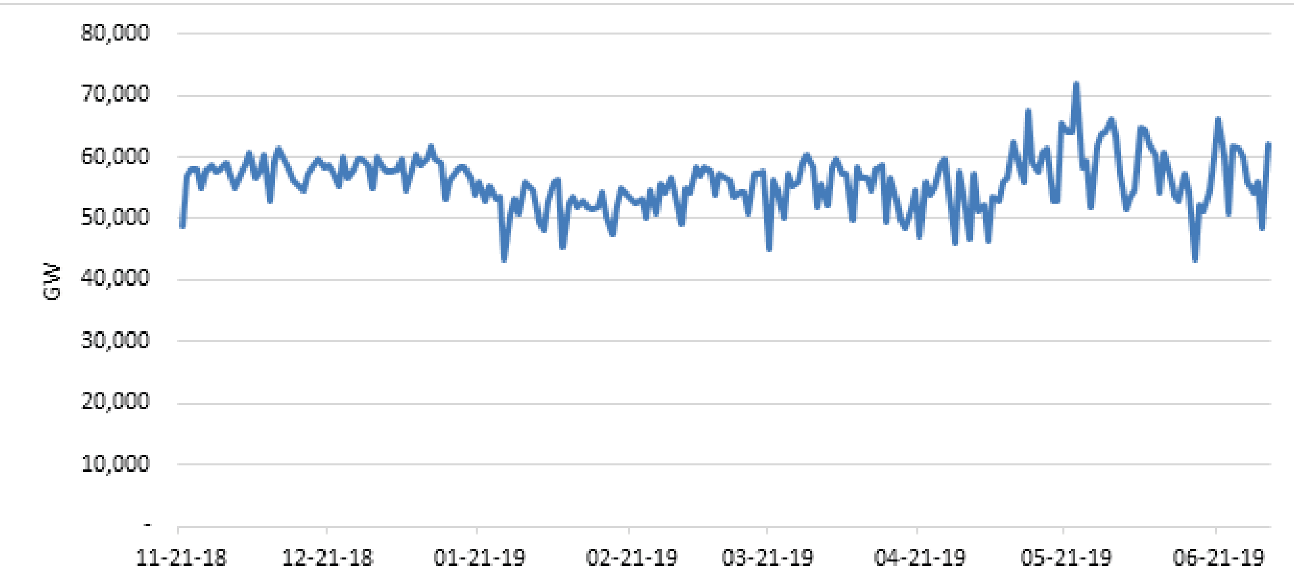
Coal power plants are expected to lower their output down to 55%, termed flexing, and this represents one of the largest means of adjusting to variations in RE. As we have seen, while technically hydro can switch on/off quickly, its actual operations are more complex due to a combination of competing demands for water supply, overflows after the monsoon, etc. Thus, we assume, for this first order calculation, that only 50% of actual hydro output at any given time period can be switched off (due to, say, a rise in RE), and all of gas-based power can be switched off if required. Coal is not expected to switch off and back on within a single day.

Using the tracker data, we perform the following calculation to estimate system slack to absorb more solar power:

1. Calculate the lowest thermal output each day between 11 AM and 2 PM.
2. Determine the maximum thermal output within +/- 24 hours.
3. Calculate the percentage output the aggregate coal fleet is operating at as the low found in Step 1 (low divided by high).
4. Take the difference between this factor and daily 55% output, with an estimated correction of 5% because the highest output found in Step 2 may not represent the capacity online at that time period, and simply the output at that time, which will always be a little lower than the capacity. Stated another way, this corrects for the fact that all coal plants will not be outputting at 100% of capacity at the time of maximum found within 24 hours.
5. Convert this buffer (percentage) into GW available from additional flexing down coal can perform, and add 50% hydro plus all gas respectively running at that time to determine system buffer to absorbing more solar.

Figure 23 shows the results. We see that we have a current slack of about 45 GW, some days a little more.

Figure 23- Maximum additional RE that can be incorporated in the grid before curtailment kicks in



How long will this last? This depends on two main factors. First, what is the growth of solar? Second, what is the growth of demand mid-day? We can estimate demand growing by perhaps 10 GW annually. Solar has historically grown 10 GW grid scale, plus a little more behind the meter ("rooftop"). However, current targets require almost 25 GW of solar growth annually, and ambitious plans for 2030 require even higher annual growth. Thus, the current system might only have a few years of ability to absorb growing RE before we need major changes, including storage as well as pricing signals that reflect grid conditions and encourage time-of-day based consumption.

Note, for this calculation, we have not considered any rise in alternate "must-run" supply, which would include coincident wind power and nuclear power. On the other hand, there is scope for shifting off-peak demand to the mid-day, especially with the rise of solar pumps.

5. Recommendations for data

Granular data helps better understand the role of various generation sources in balancing the grid and how generation capacities vary over time (by time of day as well as seasonally). Key learning from the data include:

1. In the winters, the gap between the maximum and minimum generation is higher. Thus, the winter season provides a greater opportunity for load shifting, helping maintain a smoother generation profile and operate power plants at a steadier PLF, with better optimisation of which plants operate as well.
2. Hydro generation increases significantly after March, approaching a "must-run" equivalent by the late monsoon period.
3. As summers approach, we find a significant increase in minimum daily demand. Often the focus is on the maximum demand, but minimum demand will also become important in future with a high RE generation, which will force plants to run at lower PLF's.
4. The daily peak shifts from mid-day to evening in March and subsequently by May shifts to late night.

This tracker represents the best available granular supply data in India. However, even more granular data (at a state level, separating different RE types [wind, solar, biomass, mini-hydro], etc.) will enhance analyses. Time series data will help examine trends (multi-year), and such data should be made available by grid operators.

References

NREL, POSOCO, Berkeley Lab. (2017). *GREENING THE GRID.*
Power, M. o. (2019). Retrieved from MERIT: www.meritindia.in

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