RAMPING UP THE RAMPING CAPABILITY

India's Power System Transition

GREENING THE GRID PROGRAM
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RAMPING UP THE RAMPING CAPABILITY

India's Power System Transition

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EXECUTIVE SUMMARY

The Indian power system is going through a period of transformation with plans for renewable energy to be integrated at a large scale over the next decade. Increasing thrust is being given to flexible operation of existing generating resources. Ramping is one of the key attributes of flexibility. With implementation of national level security constrained economic dispatch (SCED), the national power system operator of India (POSOCO) has started to observe occasional constraints in ramping capability obtained from generators under SCED, which could get further aggravated with more variable renewable energy (VRE). This paper focuses on complexities of ramping and the challenges with high shares of renewables in the Indian context.

List of Acronyms

ADGP	achievable degree of generator performance
CAISO	California Independent System Operator
CERC	Central Electricity Regulatory Commission
CPUC	California Public Utility Commission
EIM	energy imbalance market
FRP	flexible ramp product
IDGP	interval degree of generator performance
ISGS	interstate generation station
ISO	independent system operator
MISO	Midwest Independent System Operator
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
POSOCO	Power System Operation Corporation
RCP	ramp capability product
ReEDS	Regional Energy Deployment System
RRAS	reserve regulation ancillary services
SCED	security constrained economic dispatch
VRE	variable renewable energy

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Table of Contents

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

List of Tables

List of Figures

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

1 Introduction

Imagine driving a car on a terrain with plains and steep slopes with sharp hairpin bends. The job of the driver is relatively easy while driving on plains as a steady speed would be sufficient to cover the distance. But what happens when the car climbs up the slope with the same speed? The car would start to slow down and fall back unless the car is accelerated to balance the opposing gravitational forces. Similar is the case with power systems where power system operators are required to ensure a balance between load and generation to maintain the constant frequency of the grid, and, therefore, ensure reliable delivery of power. They do this by dispatching least-cost generation at the same rate as load subject to various operational constraints. This is traditionally achieved either by changing the generation of many large, slower-moving plants, dispatching a few fast-ramping plants, or a combination of these. Any imbalance impacts the frequency as well as tie-line flows in the system. It becomes more challenging during the time when load is ramping up fast and the generation needs to be adjusted at the same rate.

Present-day power systems are undergoing transformations toward higher penetrations of renewables, and, therefore, the main objectives of power system operators are also undergoing a transition. This transition is toward balancing supply with a slightly modified version of load, termed the net load, which includes the generation of variable renewable energy (VRE). In balancing net load as opposed to only load, there are new considerations. For instance, the periods when load is increasing and VRE generation is decreasing could require conventional generators to respond at a faster rate than traditional requirements to compensate for lost supply from renewable energy (Figure 1); however, the ability of a power system to respond to such periods could be limited due to various reasons, the result of which could be load curtailment, VRE curtailment, or reliability concerns, such as frequency violations. Anticipating the ramping needs of the system in real time requires considering potentially new scenarios such as these to avoid periods of ramp scarcity.

For example, with more VRE and without nontraditional methods, the on-bar conventional generation decreases, which means the responsibility of providing ramp comes to fewer generators. Whatever the reason, any additional ramping requirement in real time is met by the residual ramp capability of the on-bar conventional generation or the use of nontraditional methods such as demand response or new technologies such as battery storage. With more VRE in the system, there is more uncertainty in the ramp requirement and the residual ramp capability to meet this uncertainty could be limited with less conventional generation on-bar. Further, government policies and directives in many countries are phasing out coal/nuclear generation (CIGRE 2020). This phase out may lead to scarcity of ramping capability in real-time operations. It is therefore important to assess the requirements of the system, the capability of the existing fleet, and to take operational and long-term measures to ensure sufficient ramping capability exists. Another important aspect of ramping is its inclusion in the schedules. Further, changing the direction of ramp during ramping in one direction is challenging, like the challenge of turning a vehicle at hairpin bends. Apart from ramping, acceleration and jerk are equally important for the system operators. All these factors make it difficult for the system operators to correctly incorporate the exact ramping profile in the schedules, which is done in actual practice with some trade-offs.

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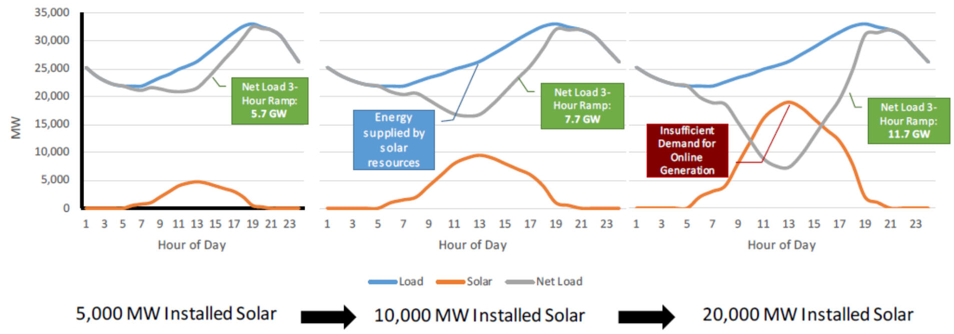

Figure 1. Example of increasing solar resources leading to increased ramping requirements

(Source: NERC, 2019 Long-Term Reliability Assessment)

The Indian power system is going through a period of transformation with plans for renewable energy to be integrated at a large scale over the next decade. Further, with implementation of national-level security constrained economic dispatch (SCED), the national power system operator of India, POSOCO, has started to observe constraints in ramping capability obtained from generators under SCED, which could get further aggravated with more VRE (POSOCO, 2020). This report focuses on complexities of ramping and the challenges with high share of renewables in Indian context. This report also reviews the experience of different power systems around the world in accounting for, acquiring, and managing the ramping capabilities as a means for balancing supply and demand. The report concludes with a suggested pathway for India to plan for ramping related issues in the future.

2 Ramp Rate: An Essential Flexibility Attribute

Flexibility is defined as *the ability of a resource, whether any component or collection of components of the power system, to respond to the known and unknown changes of power system conditions at various operational timescales* (Ela et al. 2014). Every power system needs flexibility to operate but differs in the requirement, which is based largely on the load profile. Accordingly, every power system has built generation and transmission resources and developed market products matching its requirements for flexibility; however, the addition of renewables has the potential to increase the need for flexibility to manage the uncertainty and variability associated with weather-dependent generation resources. This additional flexibility, manifested in market products or operational practices, could come from various sources, such as demand response, energy storage, altering transmission operation, and renewable energy curtailment. But it is likely that thermal and hydro generators, which form the bulk of the generation assets in India, will balance this requirement in the near- to mid-term. These generators can increase flexibility through various parameters (Text Box 1), which have the potential to be altered by either operational practices or retrofits (Cochran et al.).

Test Box 1. Flexibility Attributes of Generators

Minimum Generation Levels: Also referred to as minimum turn down level or technical minimum in Indian context, defined as the minimum output that the generator can sustain continuously. It is expressed as percentage of maximum rated capacity.

Ramp Rate: It measures how quickly a plant can change its output. It is generally calculated as the capability of a unit between its minimum and maximum level. It is expressed as percentage (of unit rating) per minute.

Startup/Shutdown Time: Time required to move from nonoperational state (cold, warm, hot) to operational state and vice versa. It is expressed in minutes/hours.

Minimum up/down time: Minimum length of time the plant must stay in an operational state before taking offline and vice versa. It is expressed in minutes/hours.

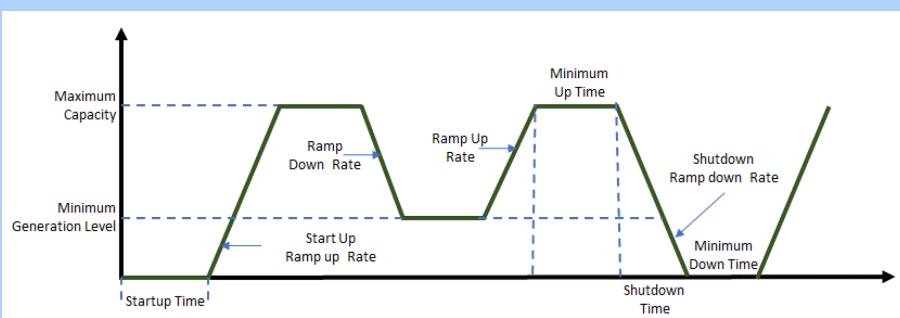

Figure 2. Flexibility attributes of generators

Source: Adapted from Agora 2017

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Ramping is a key flexibility attribute which has acquired significance in recent years. It has also been identified as an important reliability service by North American Electric Reliability Corporation (NERC) and an important attribute for managing power systems with high penetration of renewables in various renewable integration studies around the world. Some systems have developed specific market products to procure necessary ramping services, and some are providing incentives to the generators to improve ramping performance as discussed in the subsequent sections.

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3 Ramping in the Context of the Indian Power System

According to Government of India targets, 175 GW of VRE (100 solar, 60 wind, 10 biomass, and 5 small hydro) capacity is planned to be achieved by 2022, which will be increased to 450 GW by 2030 (Prime Minister's Office 2019). The ramping requirements have increased over the years, as shown in Figure 3 and with these targets, the ramping requirements for India are also expected to increase and so is the uncertainty of net load. The increased requirement for ramping is primarily being met by the thermal fleet (Figure 3), which was mostly operating as base load around a decade back. While contribution of other generation sources towards ramping is yet to increase commensurately, it is observed that hydro plants have been providing faster ramp down in recent years, matching their ramp up capabilities (Figure A- 8). Additional plots showing changes in ramping over the years are included in Appendix A.

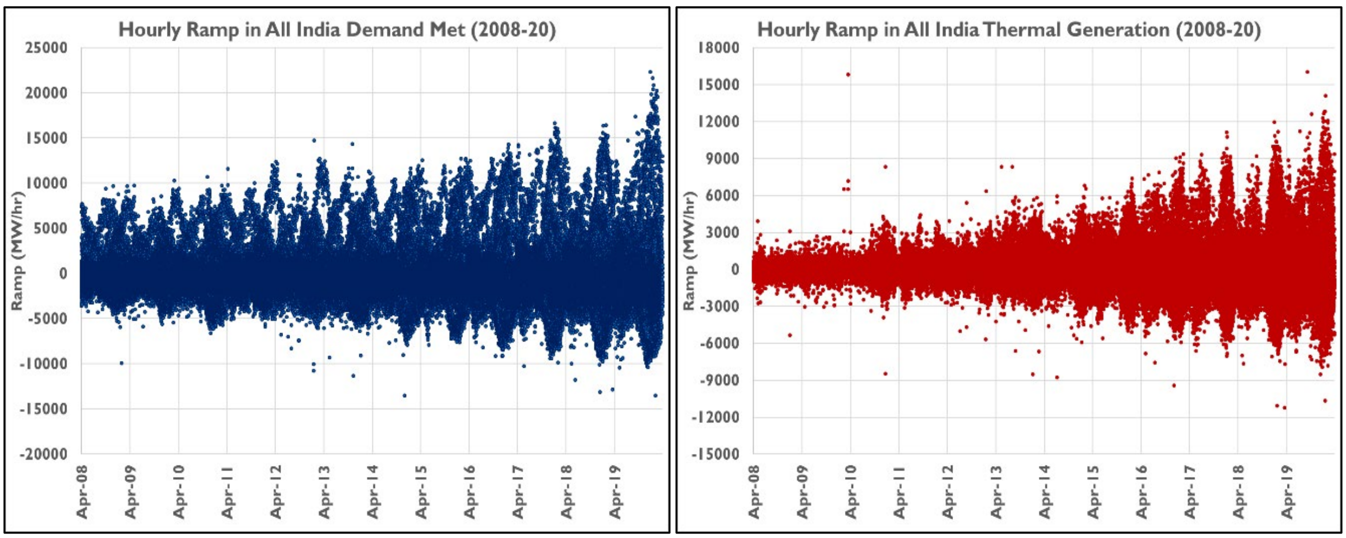

Figure 3. Hourly ramp rates of demand and thermal generation in India from 2008–2020

(Source: POSOCO)

The Government of India renewable energy targets have led to several technical planning studies that have identified power system ramping to be a potential issue for further research and planning efforts (GTG National Study 2017; NEP 2018; CEA 2019; CPI 2019). For instance, the National Electricity Plan (Generation) has stressed on the importance of having fast ramping capability for large-scale renewable energy in the grid (NEP 2018). The study estimated that the ramping requirements to balance net load for 2021-2022 would be higher than those required for only balancing load (Figure 4). Specifically, that there are more periods of time where the ramping demands of the system are above 6,000 MW/hour than if the system was without VRE. It has also concluded that the additional capacity required for 2022–2027 should be preferably from flexible sources of generation to meet the peaking, balancing, and ramping requirements of the grid.

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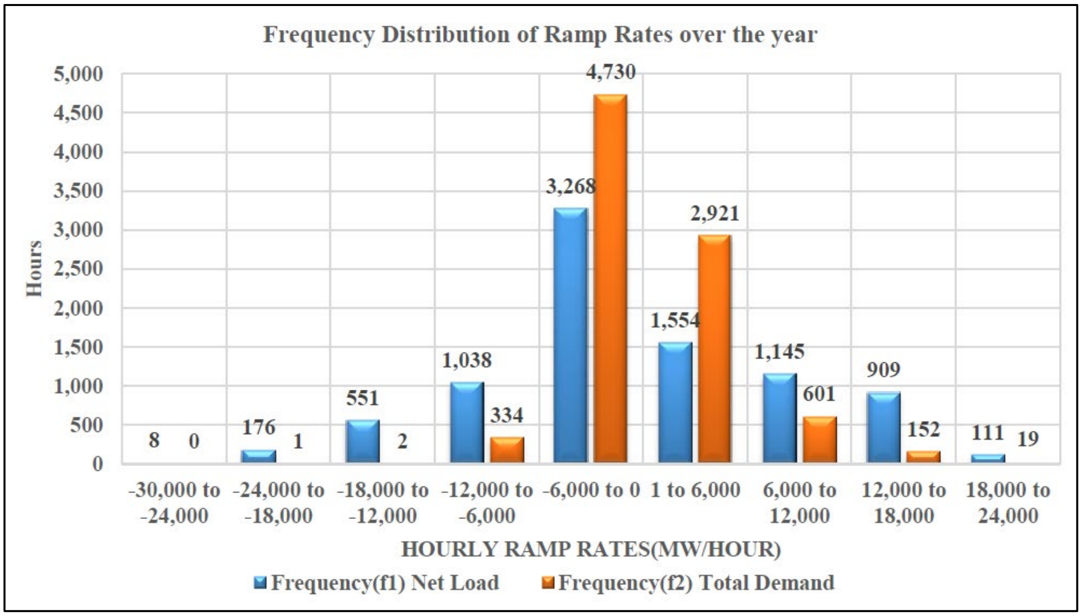

Figure 4. Projected ramp rates frequency distribution in India in 2022 as per the National Electricity Plan, CEA

(Source: CEA 2019)

Additionally, a study examining 15-minute operations for 2022 concluded that, when Government of India targets of 160 GW of wind and solar are met, for 0.6% of the year, net load up-ramps exceed 25 GW/hour, greater than any hour in a scenario with 2016 levels of VRE (No New VRE), and peak at almost 32 GW/hour (GTG National Study 2017). This is manageable, provided all the machines provide at least 1% ramp rate. The study by Central Electricity Authority on the flexible operation of thermal plants for integration of renewable generation has also concluded that the net load ramp is manageable with all plants providing at least 1% ramp rate. This is assuming that entire capacity on-bar would contribute to ramping. This expectation needs to be tempered as only plants which are yet to reach their maximum or minimum generation levels would contribute to ramping. Another analysis from Climate Policy Initiative estimates India's ramping requirements to increase by three to four times from 2017 to 2030 in various scenarios with a much wider spread (CPI 2019).

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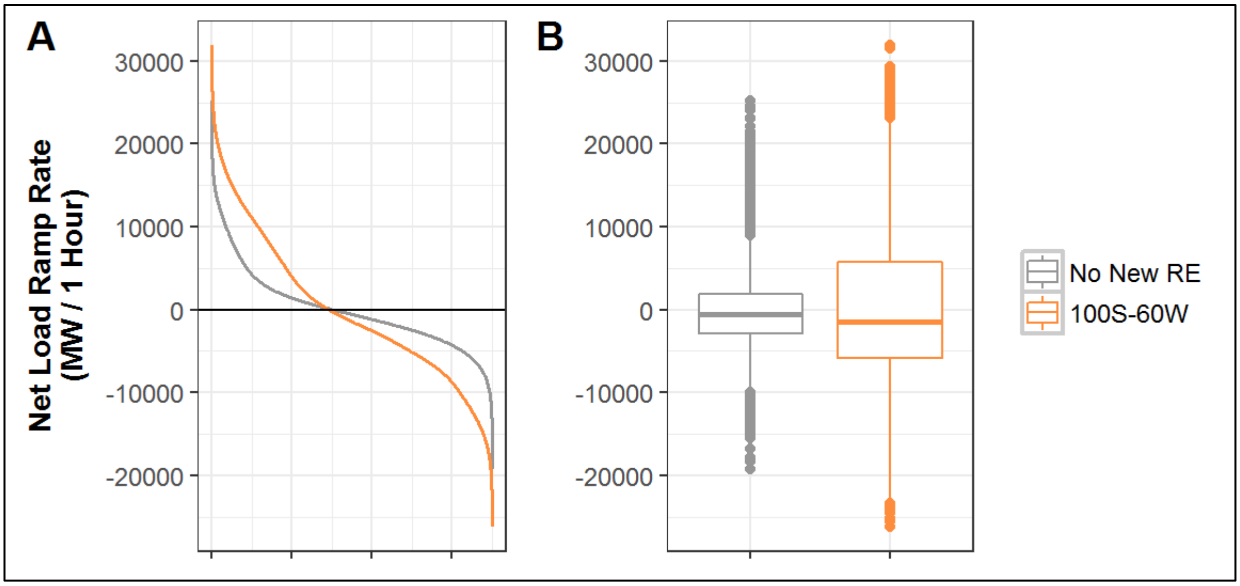

Figure 5. Net load ramps for the annual operations of two scenarios in 2022. No New RE represents a scenario with 2016 levels of RE, and 100S-60W represents a scenario where Government of India targets of 160 GW wind and solar are met.

(Source: GTG National Study)

These studies have used models that simulate operations at either 1-hour or 15-minute time steps with an assumption of all generators providing 1% ramp rates; however, in practice, this level of availability is often otherwise, and operators are faced with the challenges such as insufficient ramping capability, delay in ramping, and so on. The following sections give details on the status of system ramping challenges and solutions in India.

3.1 Regulatory Provisions

The existing provisions of Central Electricity Authority (Technical Standard for Construction of Electrical Plant and Electrical Lines) in India requires thermal generators to be capable of providing 3%–5% ramp rate.

7 (4)-The design shall cover adequate provision for quick start up and loading of the unit to full load at a fast rate. The unit shall have minimum rate of loading or unloading of 3% per minute above the control load (i.e. 50% MCR). For supercritical and ultra-super-critical units, minimum rate of loading or unloading shall be 5% per minute above the control load (i.e., 50% MCR).”

On the other hand, Indian Electricity Grid Code recommends one per cent per minute or as per manufacturer’s limits.

5.2(i) -The recommended rate for changing the governor setting i.e., supplementary control for increasing or decreasing the output (generation level) for all generating units, irrespective of their type and size, would be one (1.0) per cent per minute or as per manufacturer’s limits.

Any imbalance between demand and generation including variability of renewables in India is being managed through dispatch of Reserve Regulation Ancillary Services (CERC 2015). There is no exclusive product for procurement of ramping as of now. Implementation of automatic generation control interstate generating stations across the country is in progress, after which secondary reserves would be used to handle the imbalances along with ancillary services (CERC 2019).

Although the technical provisions require generators to be capable of providing ramp rate between 3%–5%, the actual performance of the thermal generators has been much less than this. Generators in India declare their block-

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wise ramp rates to the system operator for scheduling purposes which is generally in the range of 1%. In addition, thermal generators which fall under the ambit of Regulation Reserve Ancillary Services (RRAS) declare ramp rates, which were around 0.5%–0.8% until March 2020.

In order to incentivize thermal generators to provide more ramping capability, Central Electricity Regulatory Commission (CERC) came out with regulations to financially incentivize generators to provide ramping capability beyond the threshold of 1% and to penalize in case of failure to provide 1%, in terms of return on equity.

"Proviso (iii)to regulation 30(2) of CERC (Terms and Conditions of Tariff) Regulations, 2019 (applicable to generators whose tariff is determined by CERC)

"in case of thermal generating stations with effect from 1.4.2020:

a) Rate of return on equity shall be reduced by 0.25% in case of failure to achieve the ramp rate of 1% per minute;

b) An additional rate of return on equity of 0.25% shall be allowed for every incremental ramp rate of 1% per minute achieved over and above the ramp rate of 1% per minute, subject to ceiling of additional rate of return on equity of 1%.

These regulations require the National Load Despatch Centre to assess the ramping capability of individual generators based on which, incentive/penalty (Table 1)shall be applicable to these generators. Accordingly, the guidelines were issued by National Load Despatch Centre for assessment of ramping capability of individual stations (POSOCO 2020). These guidelines assess the ramping capability based on the ramp rate declared, scheduled and achieved by the generator. A summary of the ramping capability assessment process is given below:

1. Calculate proportion of blocks (Td) out of total (Tm) in a period, in which the ramp up/down rate declared by interstate generation stations (ISGS) is 1% per minute or more (i.e., Td/Tm).
2. Calculate number of blocks (D) out of declared blocks (Td), in which ISGS is scheduled by regional load dispatch center with ramp up/down rate of ≥1 % /min.
3. Calculate proportion of blocks (E) out of scheduled blocks (D), where ISGS has achieved actual ramp up/down rate ≥scheduled ramp rate (when it is ≥1%/min) i.e., (E/D).
4. Calculate proportion of blocks (F) out of scheduled blocks (D), where ISGS has achieved actual ramp up/down of ≥1%/min when scheduled ramp rate is ≥1%/min i.e., (F/D).
5. Calculate actual average ramp rate in the blocks when scheduled ramp rate is 1%/min or more.

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Table 1. Generators Ramping Performance Criteria in India

<table>
<tr><td colspan="3">Td/Tm < 0.85</td><td>reduction in return on equity by 0.25%</td></tr>
<tr><td rowspan="7">Td/Tm ≥0.85 and</td><td>D < 60*M</td><td></td><td>no additional return on equity</td></tr>
<tr><td rowspan="2">D ≥60*M</td><td>E/D < 0.75</td><td>no additional return on equity</td></tr>
<tr><td>E/D ≥0.75</td><td>Additional return on equity (%) = (Greatest Integer (annual average ramp rate) –1)*0.25%

(Ceiling of 1%)</td></tr>
<tr><td colspan="2">D < 90*M</td><td>no reduction in return on equity</td></tr>
<tr><td rowspan="2">D ≥ 90*M</td><td>F/D ≥0.75</td><td>no reduction in return on equity</td></tr>
<tr><td>F/D < 0.75</td><td>reduction in return on equity by 0.25%</td></tr>
</table>

With this incentive/penalty regime for ramp rates coming into effect on April 1, 2020, interstate thermal generators have started declaring ramp rates of 1% for the purpose of scheduling and Regulation Reserve Ancillary Services/SCED. For performance measurement, this scheme utilizes 15-minute injection recorded in interface energy meters, which serve as the datum for commercial settlement.

3.2 Operational Experience

An assessment of actual ramping capability of all generators in India, including intrastate and interstate generators, reveals that around 35% of coal-fired units provide at least 1% ramp and the rest provide ramping in the range of 0.5%–0.7% (Figure 6) (POSOCO, 2018). Many pilots have been taken up in India to demonstrate ramping capability of up to 3% in thermal power plants (IGEF 2018; GTG-RISE 2019; CEA 2019).

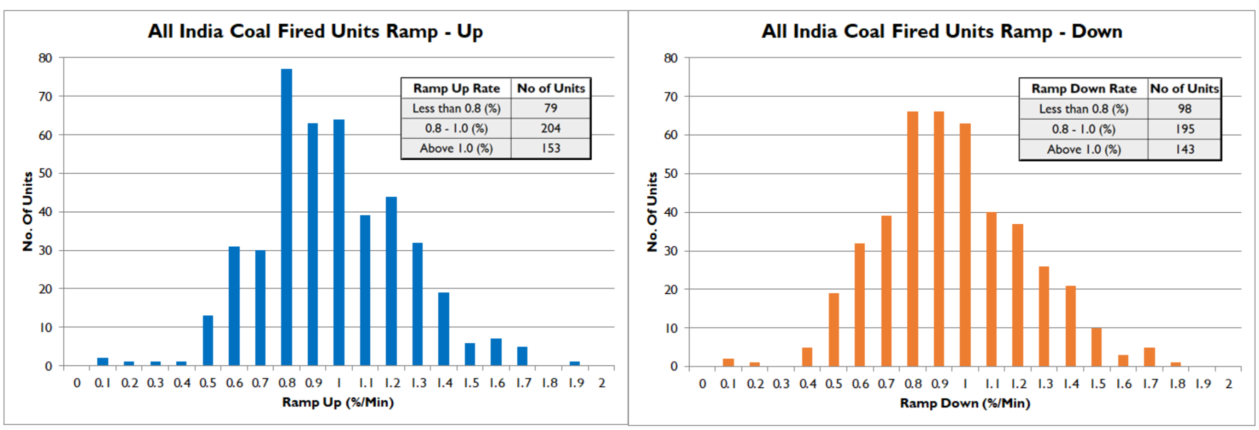

Figure 6. Maximum ramp capability distribution of coal-fired generating stations in India

Source: POSOCO'S Report on Analysis of Ramping Capability of Coal-Fired Generation in India

Additionally, efforts to improve the efficiency of operations in India include a pilot on SCED at the national level, which has been implemented by POSOCO since April 1, 2019. All the thermal ISGS, which are regional entities and whose tariff is determined or adopted by the CERC, are participating in this pilot. CERC has expanded the scope of SCED from June 1, 2020 onward to allow intrastate generators and independent power producers to join SCED. As of August 2020, the total capacity, which is part of SCED, stands at 56 GW. SCED is an optimization

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mechanism for the dispatch of generating units to meet demand based on minimizing total variable cost of generation subject to technical and operational constraints. Ramp rate is one of the constraints that is being honored during this optimization process. While improvements in terms of reduction of variable cost of generation and ease of generator operations (lesser requirement of ramping from individual generators) are observed, there is a significant reduction in the amount of total ramping capability available during certain periods. The data from April–December 2019 for this pilot project was analyzed by POSOCO where it was found that the leftover up margin (Installed Capacity-Schedule) in ISGS after SCED scheduling, which is also referred as available spinning reserve in Indian context, is being consolidated in the higher variable cost generators. The availability of these reserves is being constrained by the ramping capability of generation units. Therefore, a reduction in the cumulative reserve quantum constrained by ramp is being observed after the SCED optimization process. It is also observed that typically, ramp constrained reserve (i.e., reserve that can be activated within next 15 minutes) is approximately one-third of the total spinning reserve.

Post-implementation of SCED, the cheaper generators are generating at their maximum capacity, and the costlier generators are either turned off or operating at their technical minimum. This has reduced the number of generators providing reserves in both directions at any instance. Although the ramping requirements based on requisition by various states are satisfied in SCED, the responsibility of providing ramping in either direction amongst generators is more concentrated to few generators. Delay in ramping by any generator leads to considerable shortfall in real time.

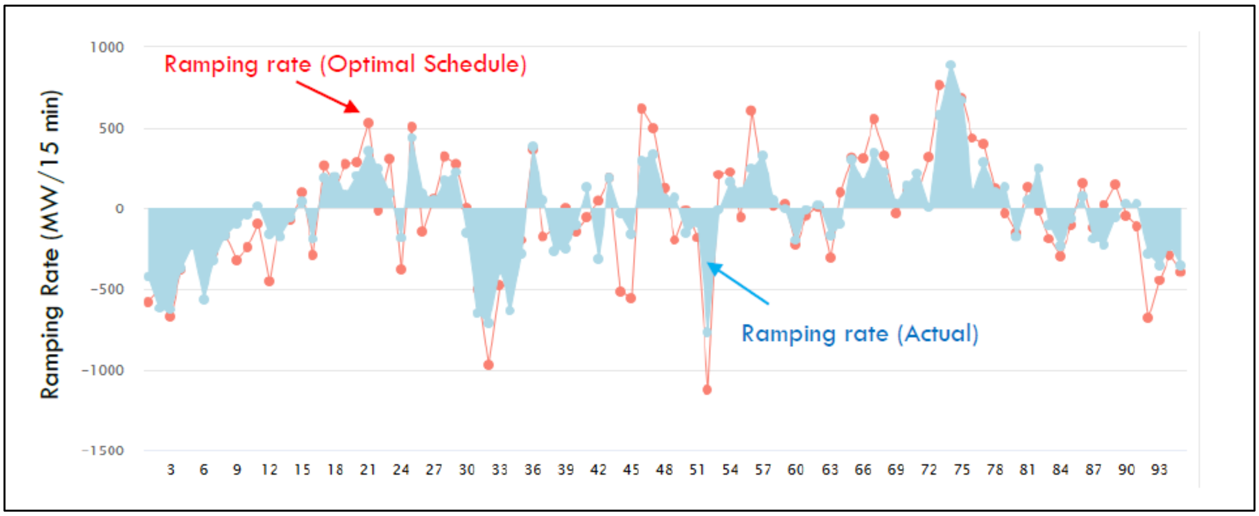

Figure 7. Ramping in optimal schedule and actual (all-India)—typical day (96 15-minute time blocks)

Source: (POSOCOs "Detailed Feedback Report on SCED Pilot")

The shortfall in available ramping was also observed during certain time blocks especially during evening and morning when the ramp requirement is very high (Figure 7). This has led to infeasibility in the SCED algorithm in certain time blocks. Figure 8 shows the average block-wise pattern of infeasibility due to ramp during the SCED pilot. It can be inferred from the figure than the ramp up infeasibility during the evening is considerably higher than other hours.

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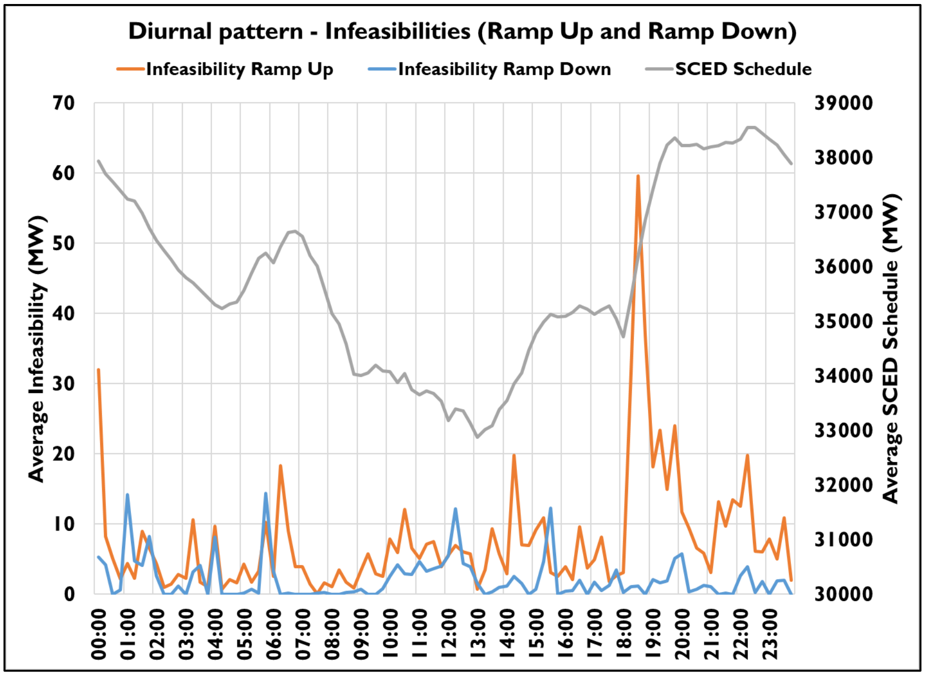

Figure 8. Infeasibilities (ramp up/down)—diurnal pattern in India

Source: (POSOCOs "Detailed Feedback Report on SCED Pilot")

The ramp-related infeasibilities are being resolved by making it a soft constraint. The penalty price was chosen as one-third of the highest variable cost initially and is currently kept at 25% of the highest variable cost based on operational experience. These penalty prices only resolve the issue encountered during the optimization stage but in the real time operations there is an actual shortfall of ramping which could adversely impact the frequency and tie-line flows. Figure 9 shows the shortfall in ramp in SCED observed on one sample day.

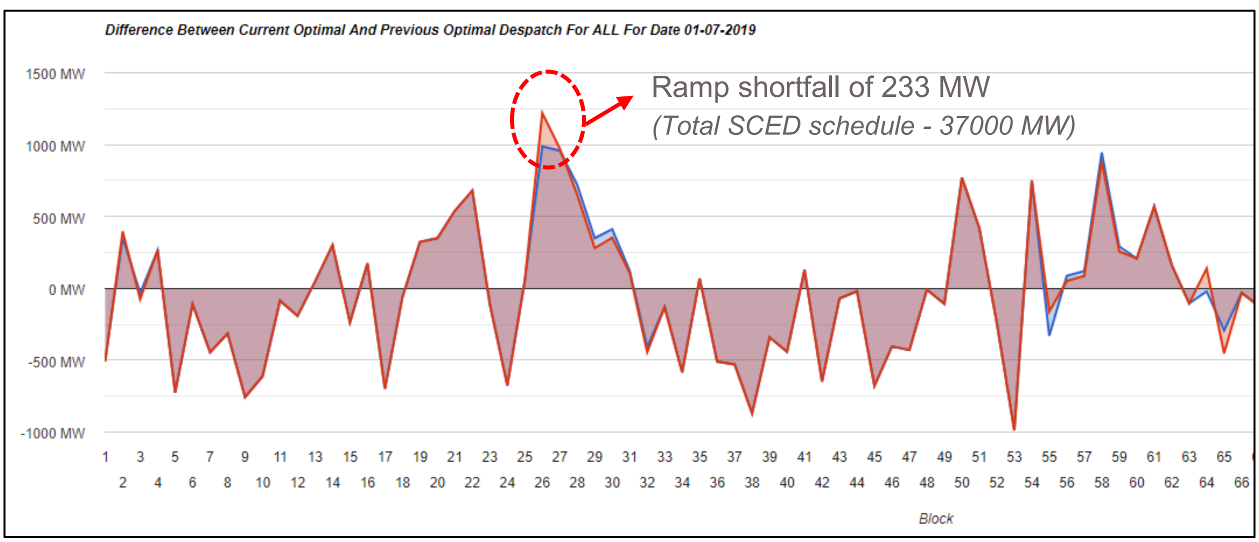

Figure 9. Infeasibility case study India—system ramp (National)

Source: (POSOCOs "Detailed Feedback Report on SCED Pilot)

Unprecedented demand ramp rates of the order of 3,000 to 4,000 MW/min were observed (Figure 10)during the 9 p.m. 9 min. event on April 5, 2020, where people of India switched off their lights at 9 p.m. for 9 minutes on the appeal of the Prime Minister of India to show solidarity and confidence in the nation's collective fight against the

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novel coronavirus. These high ramp rates were managed by the Indian system operators with the help of fast-ramping hydro and gas generation. Although hydro generators are considered a fast-ramping resource, their governor response is limited by the droop settings. During this event, the system operator changed the droop settings of some hydro generators from normal range of 4%–5% to 1%–2%. The lowering of governor droop settings means faster response in the event of frequency change which was beneficial in managing these events. The normal droop settings may be revisited to get faster response from the generators with high penetration of renewables, especially during events, which would require faster ramping from conventional generation such as solar eclipse, cyclone, and so on.

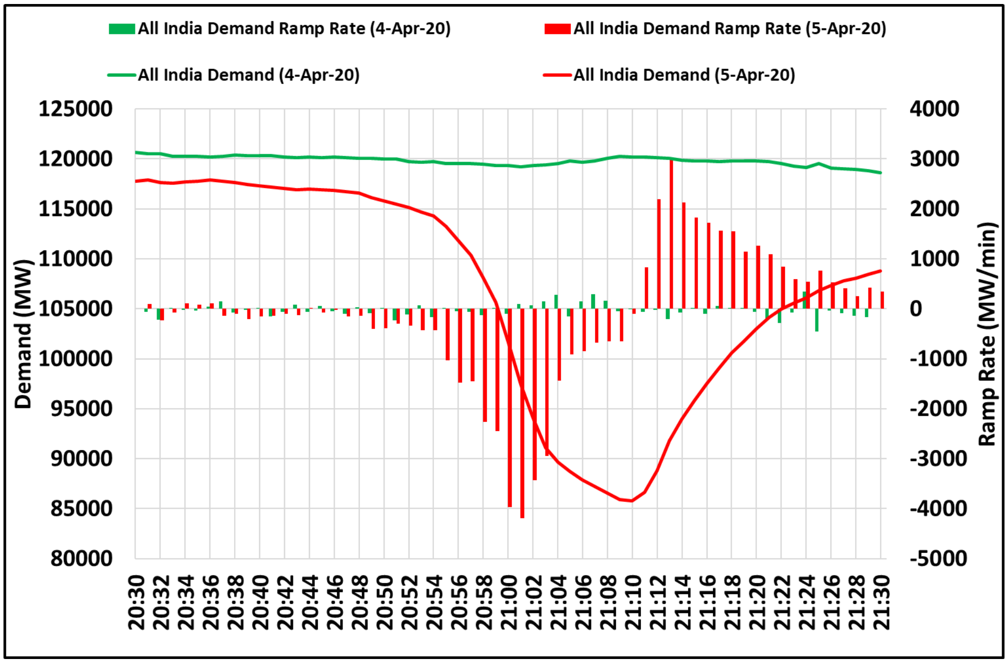

Figure 10. Demand and ramp rates trend during the lights-off event

Source: (POSOCOs report on "Pan India Lights Off Event (9 PM 9 Minutes) on 5th April 2020")

For the regulated generation capacity, which is shared by many beneficiaries, sharing of ramping capability becomes particularly challenging for regional load dispatch centers, which are coordinating the scheduling activity. The requisitions given by beneficiaries are moderated to ensure generators get an operationally feasible schedule, that is, limits like ramp rates, technical minimum, declared capability, are honored; however, market platforms, like power exchanges are yet to factor ramp rates as a constraint either in the day-ahead market or the real-time market. For market transactions, it is the responsibility of the generators to structure their offers in a manner such that all limits are satisfied. From a physical perspective, although ramp capability of thermal generators is assumed constant over their generation range in the scheduling process, it depends on factors like generation level, number of mills in service etc. The ability of generators to follow scheduled ramps strictly also depends on the preparation time available to generators before dispatch.

Another aspect associated with ramping, which is to be appreciated, arises due to the scheduling, metering, and settlement philosophy. While the load curve, generation, and ramping are all continuous curves, they have to be discretized into 15-minute average MW blocks for the purpose of scheduling and settlement (Figure 11). The average MW drawn or injected by any entity during any 15-minute time block should be equal to their schedule in the corresponding time block. The interface meters record the energy exchanged for each time block from which the average MW is derived. The relationship between the ramping in the actual generation, which is a continuous line versus the ramping in average MW schedule, which is a staircase, introduces complications in assessment of available ramping reserves in the scheduling timeframe. The ramp rate that can be scheduled, therefore, instead of

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straightforward 1%, becomes a function of the schedule in previous time blocks. Further, any change in the direction of ramping between consecutive time blocks creates an additional constraint while scheduling. Modeling this dependence mathematically and incorporating it into scheduling and optimization logic adds another layer of complexity and is usually a trade-off from practical considerations. While the scheduling is based on 15-minute average MW values, the power plant operator needs to convert it suitably to the generating unit load set points as well as the ramp rate. There is no unique solution for these set points which needs to be varied within the 15-minute time block, too.

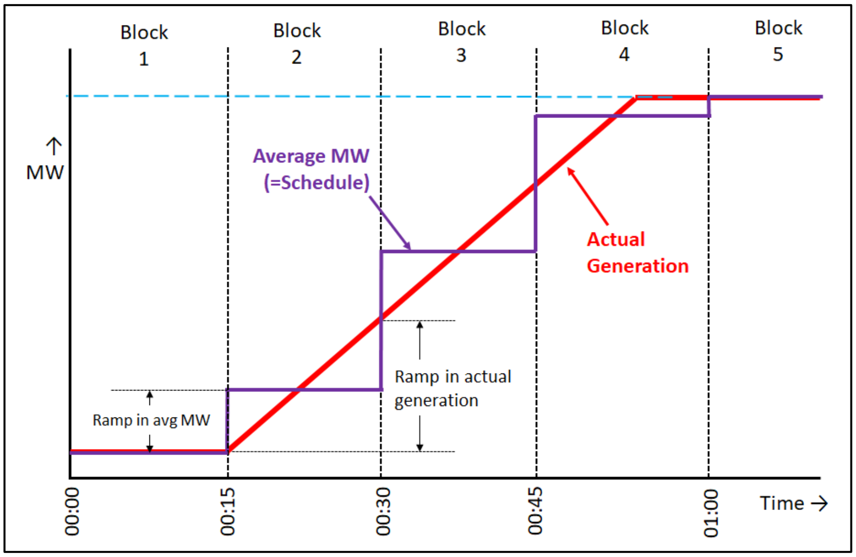

Figure 11. Illustration of ramp in average MW schedule

4 Ramping-Related Practices Around the World

Over the years, the ramping needs of the power system were limited to changes of load and the systems were designed to cater to those changes only. Most of the ramping needs of the systems were catered by fast-ramping generators, such as hydro, gas and so on, or through interconnection. Thermal generators were required to operate at baseload at most of the time, and hence were designed and operated with less flexibility. The general default ramp rate in these cases was around 1% per minute or even less. Any shortfall in actual ramping is reflected in the frequency which results into activation of reserves/ancillary services and in some cases even led to manual control of loads. The aspect that block scheduling, although facilitating markets, fails to accurately represent the physical characteristics of load or generation, and results in significant regulation burden, has been recognized and reported (ORNL 2003). Over the years, the expectation of consumers to get round-the-clock quality power have led to improved reliability standards which has forced the systems to find ways to meet the ramping needs. Further, the transition to clean energy has also increased the deployment of VRE generation around the world. The variability and uncertainty of VRE has added another dimension to the ramping needs of the system (AEMO 2020; CAISO 2016; Agora 2015; Huber 2014). The changing needs and changing technology have enabled thermal generators to provide higher ramp rates.

Insufficient ramping capability may lead to imbalance between generation and load. This may impact the frequency adversely and, in some cases, cause curtailment of either load or renewable energy. These issues creep into the system slowly over a matter of months or years, and hence need to be diagnosed early to ensure sufficient measures are taken in time to address them. Therefore, the first step is to identify ramping concerns, if any. The increasing penetration of nondispatchable resources in the United States raised the concerns regarding insufficient ramping capability. For example, the California Independent System Operator (CAISO) started experiencing ramping and over supply concerns especially during the times when such resources were meeting large portion of the demand. Further the changing generation mix, environment regulations leading to coal generation retirements, distributed generation, and so on, raised reliability related concerns which led to the constitution of Essential Reliability Services Task Force by NERC. The Essential Reliability Services Task Force has developed guidelines to provide balancing areas with methods to identify the ramping concerns with increasing penetration of non-dispatchable resources. The first step is to perform prescreening process based on various parameters of the forecasted operating conditions such as minimum load, amount of non-dispatchable resources, maximum regulation up/down, maximum net load increase/decrease and contingency reserves. A more detailed analysis based on Control Performance Standard (CPS1) (NERC Reliability Standard BAL-001-2) is done if the balancing area fails the prescreening test (NERC 2016). The criteria for prescreening (Level 1) is based on the contribution of nondispatchable resources during constrained operating conditions and in cases where Level 1 screening results indicates concern, additional (Level 2) analysis is done considering how much resources can be brought online/offline within one to three hours to cover the requirements. The CPS1 evaluation will also identity the hours of the day where ramping is a concern for the balancing area.

4.1 Ramping Capability of Various Resources

On average, the coal-based power plants around the world have ramp rates within the range of 1%–4% per minute, combined cycle gas turbines are between 2%–4%, and open cycle gas turbines are within the range of 8%–12%. State-of-the-art coal-based plants can even achieve ramp rates of up to 6% per minute, whereas state-of-the-art combined cycle gas turbines can achieve 8%–10%, and open cycle gas turbines up to 15% (Agora 2017; EPPSA 2015). In Denmark, thermal power plants are either built or retrofit to provide 4% ramp rate. Retrofit measures in Germany (Boxberg and Walsum Power Plant) allowed power plants to achieve ramp rates up to 6%. The new Belchatow II Unit1 in Poland can provide a ramp rate of 2%–6%. Nuclear plants are generally considered inflexible, but they also offer some flexibility in countries like Germany and France (Agora 2015). Internal combustion engines can provide fast ramping of around 100% (IRENA 2019). Hydro generators can provide ramp rates of the order of 10%–30% per minute; however, this flexibility may be restricted at times due to various environmental constraints. The fixed-speed pumped storage hydro plants can also provide the response

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rate within this range but adjusting their load in pumping mode is a challenge (MWH 2009). On the other hand, the output of variable speed pumped storage hydro can also be adjusted in the pumping mode. Emerging technologies such as battery energy storage systems and demand response have the potential to contribute to the ramping needs of the system. Battery energy storage systems can provide the full response within a second (PNNL 2019) making them suitable for providing operating reserves (GTG, Grid Integration Toolkit 2019). Demand response can also provide very fast response, but its availability is limited and varied. Figure 12 shows the technology specific ramp rates for thermal generators around the world.

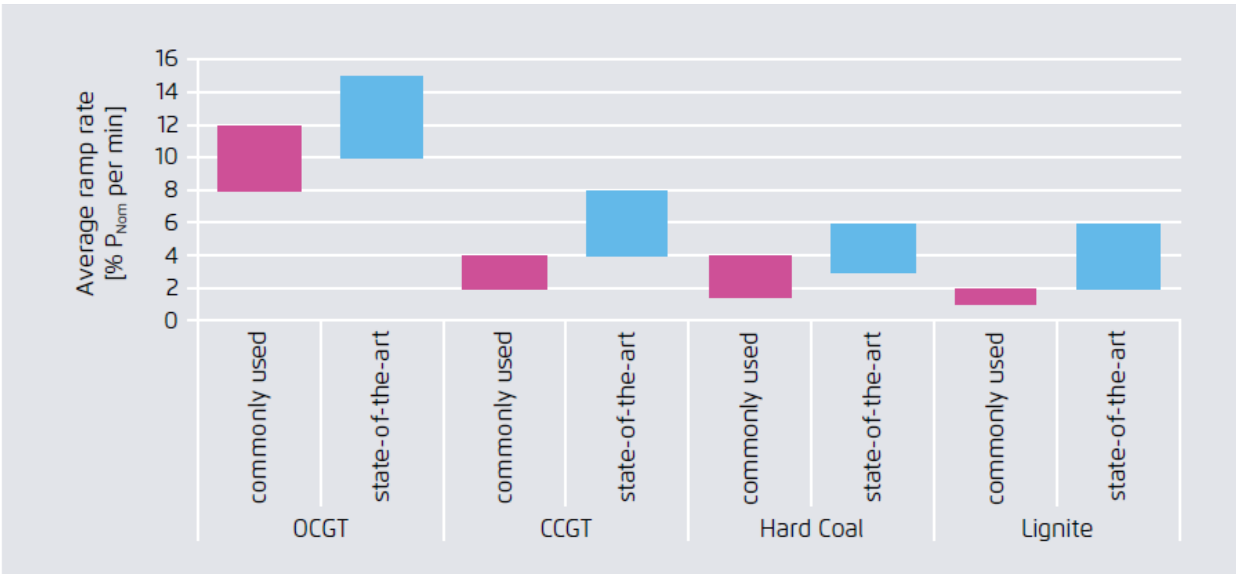

Figure 12. Technology-specific ramp rates around the world

(Source: Agora Energiewende (2017): Flexibility in thermal power plants – With a focus on existing coal-fired power plants)

Information on the actual ramping capability of generators in the United States is limited. A study by the National Renewable Energy Laboratory (NREL) for the PJM, CAISO, and WAPA systems based on publicly available hourly data indicates the thermal generator ramping within 1%–1.2% (Kirby 2014). The Regional Energy Deployment System (ReEDS), a capacity expansion model developed by NREL for the U.S. power sector, assumes 4% ramp rate for coal and 5%–8% for gas generation (NREL2018).[1] In South Africa, most of the generators provide ramp rates between 0.1%–0.7% (Agora 2017).

4.2 Options to Meet Ramping Requirements

Ramping response could either be mandated through grid code provisions, procured through markets or a combination of both. In most regions, ramping availability has evolved over time as new requirements have been realized. The National Electricity Rules of Australian Energy Market Commission requires generators to provide 3 MW/min or 3% per min, whichever is lower (AEMC 2020). The grid code of E.ON Netz, Germany, requires generators to be capable of providing at least 1% per minute ramp rate (E.ON Netz 2006). EirGrid (Ireland) Grid Code, mandates ramping capability of at least 1.5% of registered capacity per minute when the unit is in the normal dispatch condition (EirGrid 2020). Northern Ireland grid code requires generators to be able to provide at least 3% ramp rate in hot conditions (SONI 2018). The standard ramp rate for coal-fired thermal generators in Denmark is 4% for open cycle gas turbines 3% and for gas-fired power plants 9% (Jiawei Wang et al.). The

[1] NREL has also developed a ReEDS-India model for use in long-term power system planning for India. Preliminary analysis using this tool can be found in Rose et al. 2019.

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transmission code of Energy Market Authority of Singapore requires generating units providing contingency reserve should at least be capable of providing 10% per minute (EMA 2014).

A lot of systems around the world can manage their present ramping needs from regulation reserves and ancillary services provided by their existing generation fleet. In Europe and the United Kingdom, various categories of reserves are held by the control areas to manage imbalance between load and generation. Regulatory mandates to provide higher ramp rates, generation retrofit to improve flexibility, availability of fast ramping hydro, reserves and ancillary services, reserves sharing, and a robust interconnection provides European countries and the United Kingdom ways through which they can fulfill their ramping requirements (Triple 2015). Over the years, there has been a downward change in temporal resolution of ancillary services and load and batteries are allowed to participate in these markets in some countries (Bowler et al.).

Recently, EirGrid and System Operator of Northern Ireland have defined new ramping services under the DS3 program. These ramping services are namely RM1, RM2, and RM3, defined to cover three distinct product-time horizons (i.e., 1 hour, 3 hours, 8 hours). This was based on an analysis that showed that even with capacity adequacy, the ramping adequacy is unlikely with high levels of wind penetration. The payment toward these services is based on available volume, payment rate, scaling factor, and duration. The fast reserve in the United Kingdom is procured by the system operator via competitive monthly tendering process from the providers who can start delivery within 2 minutes of instruction, deliver at least 25 MW at a ramp rate of more than 25 MW/minute and sustain that level for a minimum of 15 minutes In addition, in the United Kingdom, some portion of general operating reserves are procured to manage the additional variability caused by wind and solar generation.

In most U.S. markets, ramp rates are included in the offers made by the generators, although this can vary depending on the market product. Any imbalance in the system leading to area control error or frequency deviation is generally compensated by dispatching regulation reserves. However, with increasing renewable penetration, handling imbalances on account of insufficient ramping capability through regulation reserves may obscure any signal in real time prices regarding ramping requirements. In fact, holding more regulation reserve for ramping may reduce the resources in real time dispatch and may cause some price spikes in real time due to resource shortage (CAISO 2015). Hence, CAISO and the Midwest Independent System Operator (MISO) have come up with unique products to procure ramping capability.

The mechanism for the ramping products in CAISO and MISO is somewhat unique to other reserve products, in that there is no exclusive offer from a generator made for ramping capability. Instead, the opportunity cost of each provider is calculated as the difference between energy bid price and the local marginal price, which is considered for calculating the clearing price for the ramp product. In MISO, the ramp capability product (RCP) is co-optimized with energy and ancillary services. The payments towards RCP is made at the clearing price of ramp products. In CAISO, flexible ramping product (FRP) procured in 15- and 5-minute markets is settled at the market clearing price for that market. Any difference between FRP procured in 15- and 5-minute markets is settled at the 5 minutes market FRP price. The Figure 13 below shows the concept behind MISOs ramping product. The energy ramp constraint is depicted in red, whereas the blue depicts the ramp capability constraint. With only energy ramp constraints, the dispatch at t3 would be based on the netload at t2 and t3. With ramping capability constraint, the dispatch at t3 would additionally include sufficient margin in the resources to ramp up/down to the range of potential at t5.

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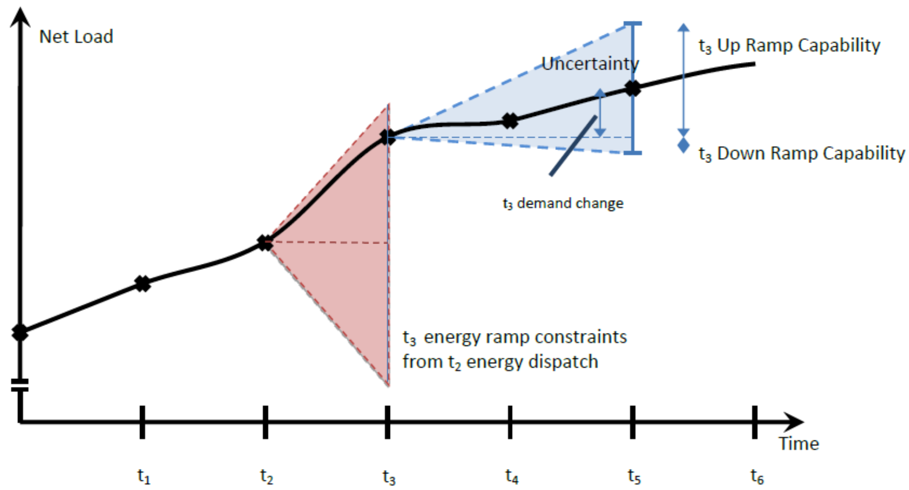

Figure 13. Graphical representation of ramp capability requirements in MISO

(Source: Ramp Capability Product Design for MISO Markets)

4.3 Performance Measurement

Performance measurement is the ability of the ISOs or market operators to measure the actual ramping achieved by the generators and compare it with the declared ramp rates. In many markets around the world, ramp capabilities are mandated by grid codes. For example, the generating units in Ireland and Northern Ireland are required to demonstrate the ramp capabilities in accordance with grid codes. The performance of RM1, RM2, and RM3 services in Ireland is assessed based on the unit's ability to follow a synchronization dispatch instruction except demand-side units. If the unit gets delayed in synchronizing 15 minutes after the start synchronizing time, the transmission system operator issues a failure to follow notice. The demand-side units performance is assessed based on the response, time and duration. In Australia, the ancillary service providers are required to be certified in accordance with the guidelines of Australian Electricity Market Operator, which includes ramp rate as one of the parameters. The transmission code of New Zealand requires reserves to be tested for its capability in accordance with the system operation manual.

FERC Order 755 requires wholesale market operators in the United States to include market-based payments for regulating reserve performance, lost opportunity costs for all regulating reserve capacity prices, and incentives and rules for accuracy. In PJM, this led to a tripling of fast-moving resources available for frequency regulation. Because these resources can respond to signals more quickly and accurately, PJM was able to lower its regulation requirements. Order 784 expands the incentives for high-performance resources by requiring public utilities to also consider speed and accuracy in assessing regulation resources. U.S. ISOs have several calculations for measuring ramp performance. CAISO has detailed guidelines for testing regulation, spin, and nonspin ramp rate. Availability of contracted and self-provided ancillary services can be verified by the CAISO by unannounced testing of resources, by auditing of response to CAISO dispatch instructions, and by analysis of the appropriate meter data or interchange schedules. The capability of any resource providing regulation is tested by CAISO using energy management system data by moving a resource's output over the full range of its regulation capacity within a 10-minute period. MISO, on the other hand, calculates performance factor and ramp factor for making the payments. Performance factor is an energy mileage-based calculation that measures how closely a resource follows dispatch instructions across a market hour based on its offered ramp rate. Ramp factor represents the ratio that the time-weighted real-time ramp rate deviates from the day-ahead ramp rate. PJM calculates an hourly performance score that reflects a regulation resource's accuracy in increasing or decreasing its output to provide frequency regulation service in response to PJM's dispatch signal. The calculations are done for each 10 seconds but averaged over a 5-minute period to determine a composite performance score per resource. PJM also monitors the real time performance of the generator through its Generator Performance Monitor (GPM) logic. This model

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calculates the interval degree of generator performance (IDGP) and achievable degree of generator performance (ADGP), which is used to modify the bid ramp rate in case of underperformance. IDGP is a measure of responsiveness of a generator to energy dispatch instructions in MW terms, whereas ADGP calculates the response in the last 10 SCED intervals to calculate the expected performance of the generator. The value of ADGP will be lie between zero and one; however, a floor of 0.75 is applied to the lower value.

$$IDGP_i = \frac{AUgen_t - AUgen_{t-1}}{Ugen_t - AUgen_{t-1}}$$

where,

$AUgen_t$: Actual unit output for interval t

$Ugen_t$: SCED dispatch signal for interval t

$$ADGP_i = \sum_{i=0}^{N-1} EWF_{t-1} \times IDGP_{t-1}$$

$$EWF_{t-1} = \left(1 - \frac{1}{N}\right)^{\alpha}, \text{i} = 0,1,\ldots,\text{N} - 1$$

$$Achievable\_Ramp\_Rate = ADGP \times Bid - in\_Ramp\_Rate$$

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5 Ramping Considerations from Resource Adequacy to Dispatch: Case Study of CAISO

Initial efforts in the United States to consider ramping requirements in resource adequacy started in 2013–14 by CAISO and the California Public Utility Commission (CPUC) with Flexible Resource Adequacy Criteria and Must-Offer Obligation initiative. This was largely driven by the CAISO studies indicating requirements of flexible capacity with 33% renewable portfolio standards, future retirements of significant amounts of once-through cooling generation units and rapidly growing levels of distributed generation. In 2015, CPUC adopted a flexible resource adequacy requirement which requires load-serving entities to demonstrate 90% of their monthly flexible capacity requirements in the year-ahead process and 100% of their flexible capacity requirements in the month-ahead process.[2] The flexible capacity needs at the resource adequacy level are developed through CAISO's annual Flexible Capacity Study, where the flexible capacity need is defined as the quantity of economically dispatched resources needed by CAISO to manage grid reliability during the largest 3-hour continuous ramps in each month. Resources are considered as flexible capacity if they can ramp up or sustain output for 3 hours. These flexible capacity needs of the system are determined for up to 3 years into the future. The ISO-wide flexibility needs are calculated as follows:

$$Flexibility\ Need_{MTH_y} = Max\left[\left(3RR_{HR_x}\right)_{MTH_y}\right] + Max\left(MSSC, 3.5\% * E\left(PL_{MTH_y}\right)\right) + \varepsilon$$

where

$Max[(3RR_{HRx})_{MTHy}]$ = Largest 3-hour contiguous ramp starting in hour x for month y

E(PL) = Expected peak load

MTHy = Month y

MSSC= Most Severe Single Contingency

ε = Annually adjustable error term to account for load forecast errors and variability methodology

The assessment process has the following broad steps:

1. Load and net load forecasts are calculated based on expected and existing grid-connected wind and solar resources, CEC (CAISO 1-in-2 MID-MID) hourly load forecast from integrated energy policy report and actual load of current year.
2. Maximum 3-hour net load ramps plus contingency reserve are calculated for each month. This gives the monthly flexible capacity requirements, which are divided into various categories based on the system's operational needs:
   - Base Flexibility: Largest 3-hour secondary net load ramp. Secondary net load ramp is calculated as the largest net load ramp that is distinct from the daily maximum net load ramp.
   - Peak Flexibility: Difference between 95% of the maximum 3-hour net load ramp and the largest 3-hour secondary net load ramp

[2] CPUC resource adequacy obligations are applicable to all load-serving entities within CPUC's jurisdiction, including investor-owned utilities, energy service providers, and community choice aggregators. Based on the study done by CAISO, each load-serving entity receives its allocation, which they have to comply by annual and monthly filling with CPUC.

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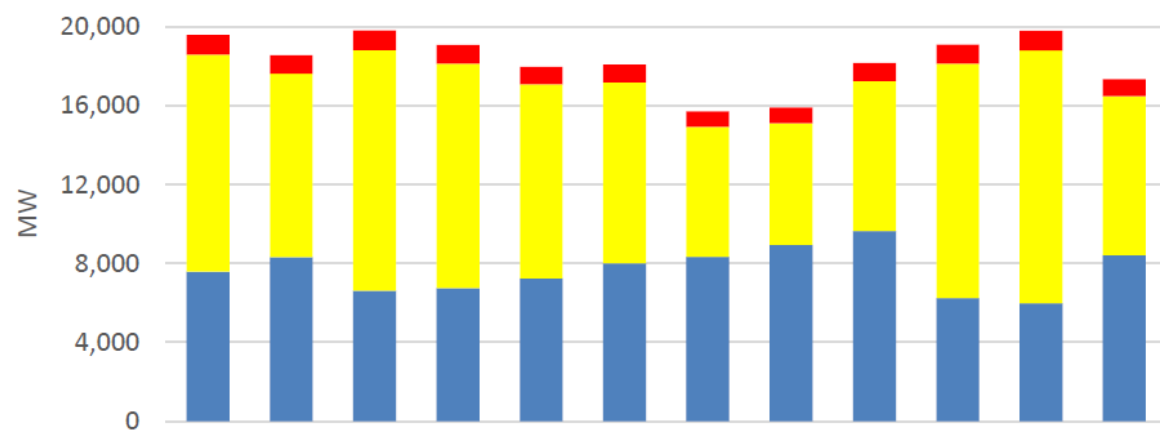
- o Super-Peak Flexibility: Five percent of the maximum 3-hour net load ramp of the month

3. The distributions of both the largest 3-hour net load ramps for the primary and secondary net load ramps are analyzed to determine appropriate seasonal demarcations.
4. The seasonal requirements are calculated as a simple average of the percent of base flexibility needs for all months within a season.
5. Each local regulatory authority's contribution to the flexible capacity need is calculated based on their contribution to the maximum three-hour net load ramp

CAISO also declares a specific 5-hour period during which flexible capacity counted in the peak and super-peak categories will be required to submit economic energy bids into the ISO market. This period is called the Seasonal Must-Offer Obligation Period. This period is determined based on the analysis of net load curves to coincide with the maximum three-hour net load ramp. The calculation of flexible capacity needs for each category for 2021 is shown in Figure 14.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Super-Peak Flexibility	980	929	992	954	899	905	786	795	909	955	991	868
Peak Flexibility	11,025	9,310	12,216	11,369	9,845	9,188	6,589	6,163	7,635	11,893	12,838	8,071
Base Flexibility	7,592	8,336	6,624	6,765	7,243	8,012	8,350	8,950	9,640	6,254	5,987	8,421

Figure 14. CAISO system-wide flexible capacity monthly calculation by category for 2021

(Source: CAISO report on Final Flexible Capacity Needs Assessment for 2021)

CAISO has also implemented FRP, which requires a certain quantum of 5-minute ramping capability in both directions to ensure sufficient flexible ramping capacity in real time 15- and 5-minute markets (CASIO Market Operations BPM 2020). This was introduced as CAISO observed that the unit commitment in real-time lacks sufficient ramping capability and flexibility to handle real-time system load and supply changes with high renewable energy penetration (CAISO, 2015). FRP is modeled as a constraint on both sides in these markets. The ramping needs for the system are calculated based on the expected ramp and uncertainties in the net system demand of the current and the next interval. The incremental up and down uncertainty requirements are calculated based on a rolling 30-day hourly net forecast error with separate calculations for weekends and holidays.

CAISO also performs a flexible ramping sufficiency test as a part in the Energy Imbalance Market (EIM) (CAISO, EIM, BPM 2019). An EIM entity is required to demonstrate sufficient ramping capability for each 15-minute interval in each hour. EIM entity must pass all four 15-minute interval tests to pass the hourly flexible ramping sufficiency test for the given ramp type. This test calculates the ramping requirement as a combination of net demand uncertainty, forecasted change in demand, diversity benefit factor, net import capability, net export

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capability, and flexible ramp credit. Figure 15 provides a schematic representation of ramp checks at various stages of power system operation in CAISO.

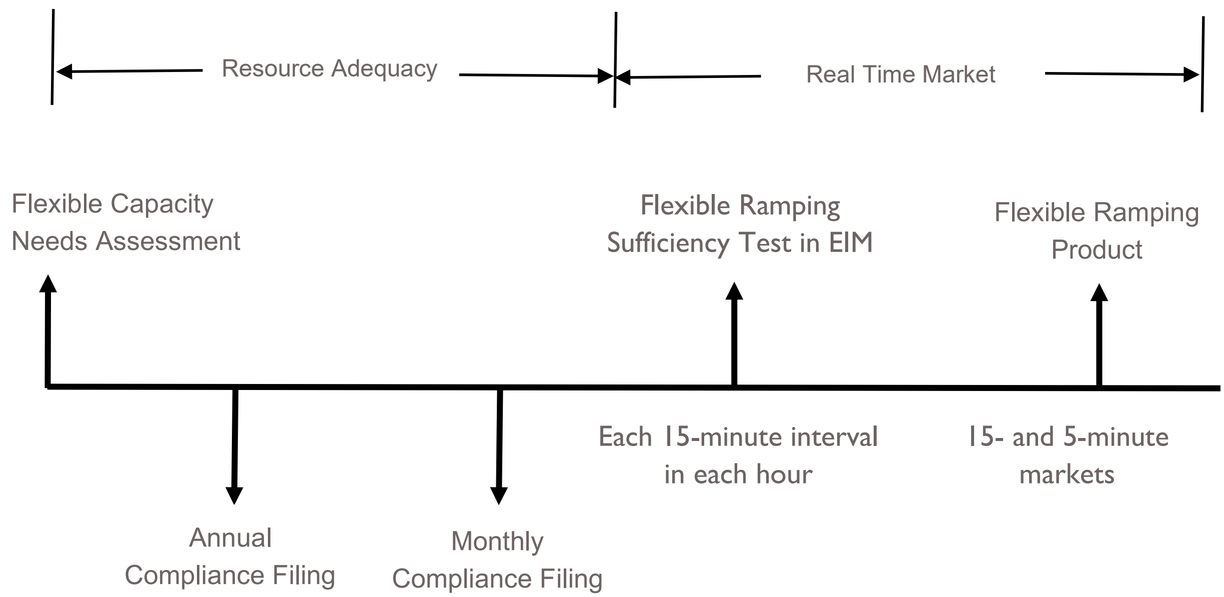

Figure 15. Schematic representation of ramping requirement assessment, compliance, and procurement in CAISO

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6 Pathway for India

The Indian power system is different from other power systems in many ways. It has a decentralized system of scheduling and dispatch with a thin overlay of centralized systems applications (SCED, Ancillary Services) and a small percentage of energy transacted through markets. Hence, balance needs to be maintained between the market-based solutions and mandatory requirements for achieving the desired ramping requirements. Based on the literature survey, it appears that the provisions in the Central Electricity Authority standards are close to the average capabilities of existing plants around the world. Because the declaration of actual ramping capability by different generators under the ancillary services is less than the standards, it is important that these standards are enforced at the interconnection stage and in the long run through periodic testing at both central and state levels. Incentives and penalties for ramping performance have already been included in the tariff of the interstate generators by CERC. Similar provisions can be made at the state level and included in the power purchase agreements with merchant power plants. Ramping-related issues may become more visible with high penetration of renewables. It is therefore important for state control areas to assess flexible capacity needs and ensure resource adequacy considering these flexibility requirements.

Suitable framework may also be considered where emerging technologies such as energy storage, demand response, and so on, can also provide ramping services. The experience of SCED has showed ramping as a constraint during the pilot phase at many instances. Typically, ramp-constrained15-minute reserve is around 20%–30% of the total spinning reserve. It is therefore important to consider multiperiod optimization so that a look-ahead ramp is available for many time blocks rather than only the immediate next time block. With experience, security-constrained unit commitment may also be adopted, which can ensure adequacy of ramping and spinning reserves margin. The requirement to maintain minimum 15-minute reserve in both directions in addition to spinning reserves could be introduced. This can be modeled as a constraint in SCED and security-constrained unit commitment, which would then be used for obtaining secondary regulation through automatic generation control and would also help in avoiding instances of ramp shortfall. Depleted secondary reserves and shortfall would be replenished by dispatching tertiary reserves. Factoring of ramp constraints in the day-ahead market, as well as the real-time market, is another area to be examined.

As India moves in the direction of higher renewable energy absorption and initiatives, such as 24 x 7 power supply, agriculture load shifting to the high solar generation period, electrification of loads, and so on, the issue of ramp flexibility would become more and more important. Unlike reactive power requirement, which is local and needs to be supplied by local resources, ramping requirement is system-wide but needs to be provided in a dispersed manner or it would lead to an adverse impact on tie-line flows.

The understanding of ramp and its importance is evolving among various stakeholders, and so are the market and regulatory mechanisms. The challenges associated with ramping will occupy center stage and keep practitioners and researchers engaged for a long time to come.

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Appendix A. Changes in Ramping Over the Years in India

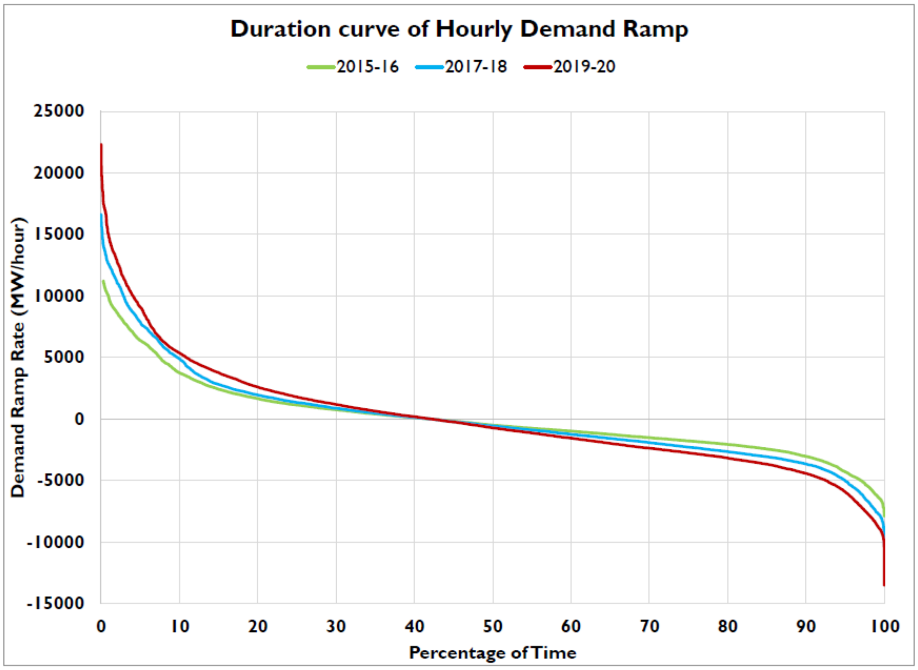

Figure A- 1. Hourly demand ramp duration curve for India from 2015 to 2020 (alternate years)

(Source: POSOCO)

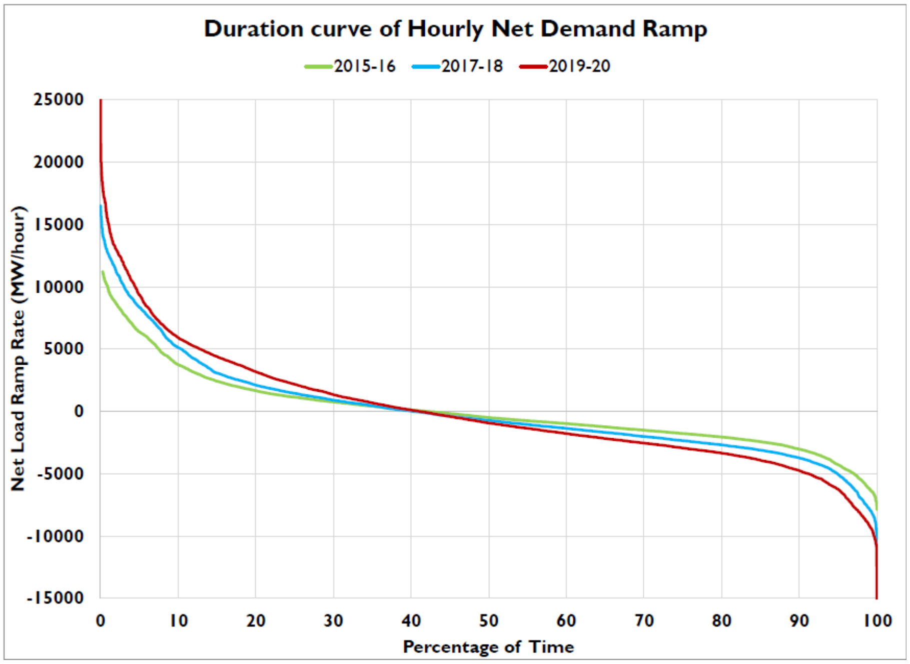

Figure A- 2. Hourly net demand ramp duration curve for India from 2015 to 2020 (alternate years)

(Source: POSOCO)

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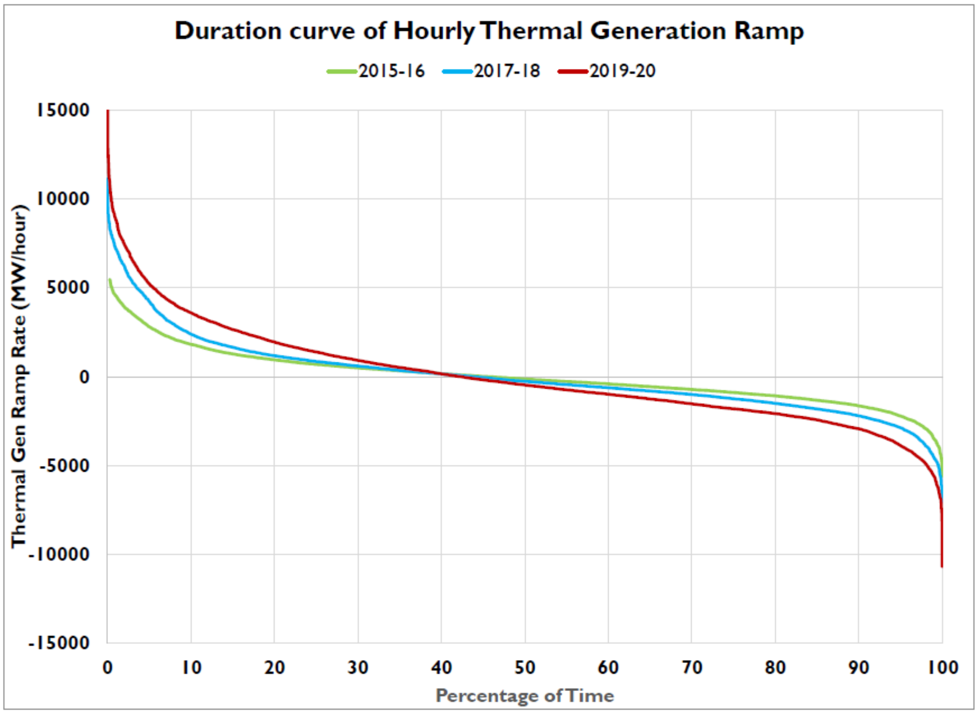

Figure A- 3. Hourly ramp duration curve for thermal generation in India from 2015 to 2020 (alternate years)

(Source: POSOCO)

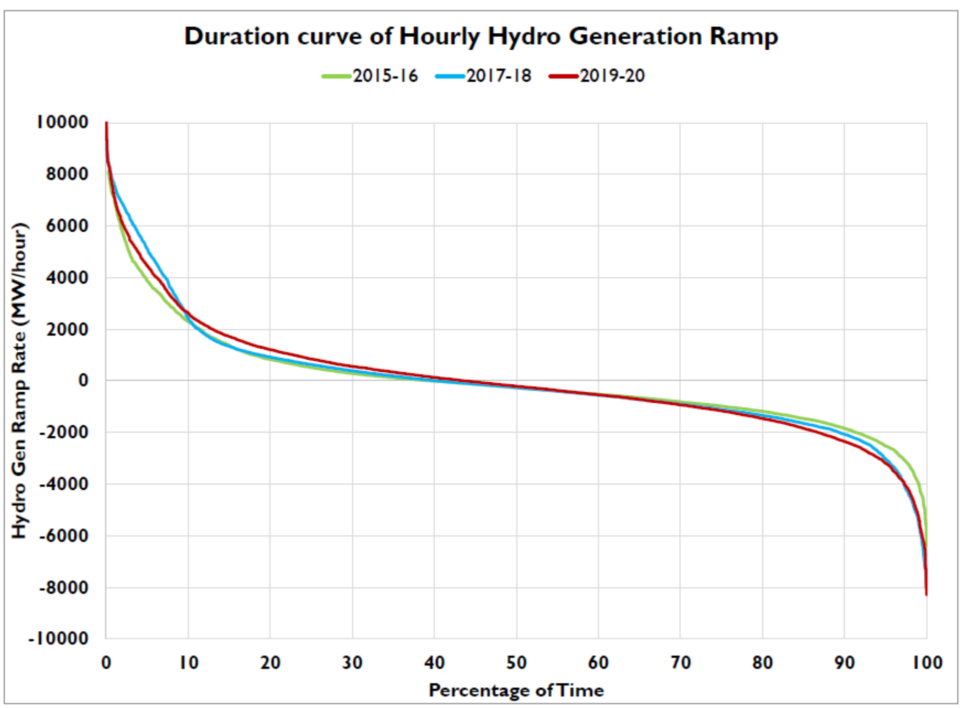

Figure A- 4. Hourly ramp duration curve for hydro generation in India from 2015 to 2020 (alternate years)

(Source: POSOCO)

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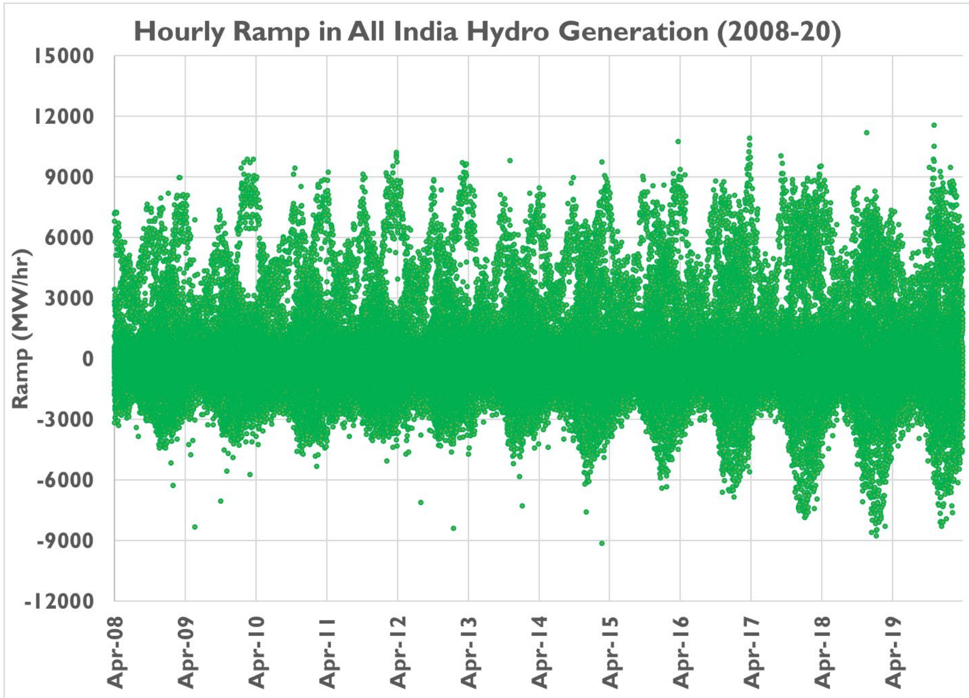

Figure A- 5. Hourly ramp for hydro generation in India from 2008 to 2020

(Source: POSOCO)

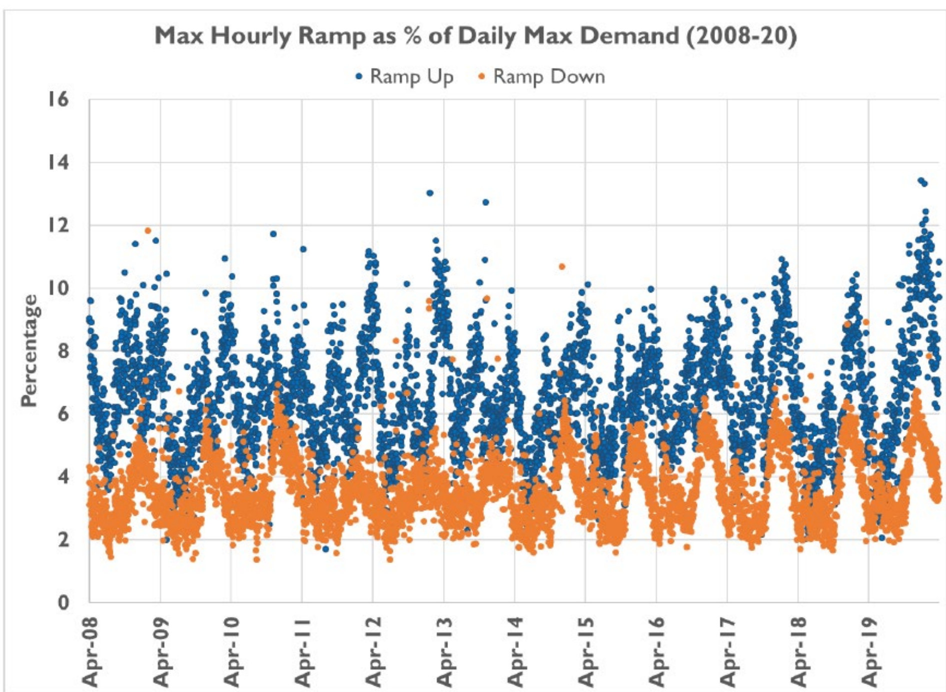

Figure A- 6. Maximum hourly ramp as percentage of daily maximum demand in India from 2008 to 2020

(Source: POSOCO)

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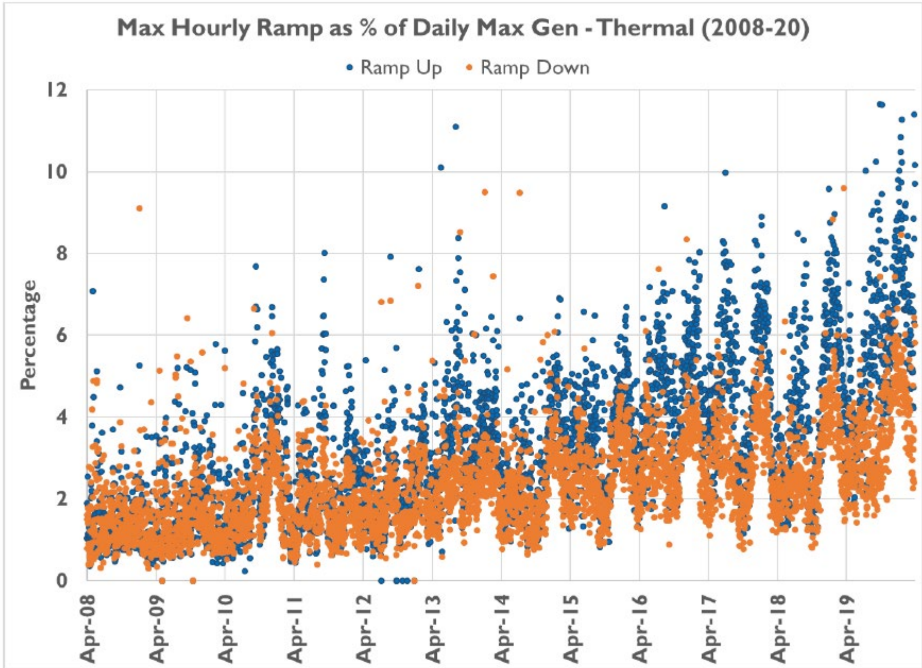

Figure A- 7. Maximum hourly ramp as percentage of daily maximum thermal generation in India from 2008 to 2020

(Source: POSOCO)

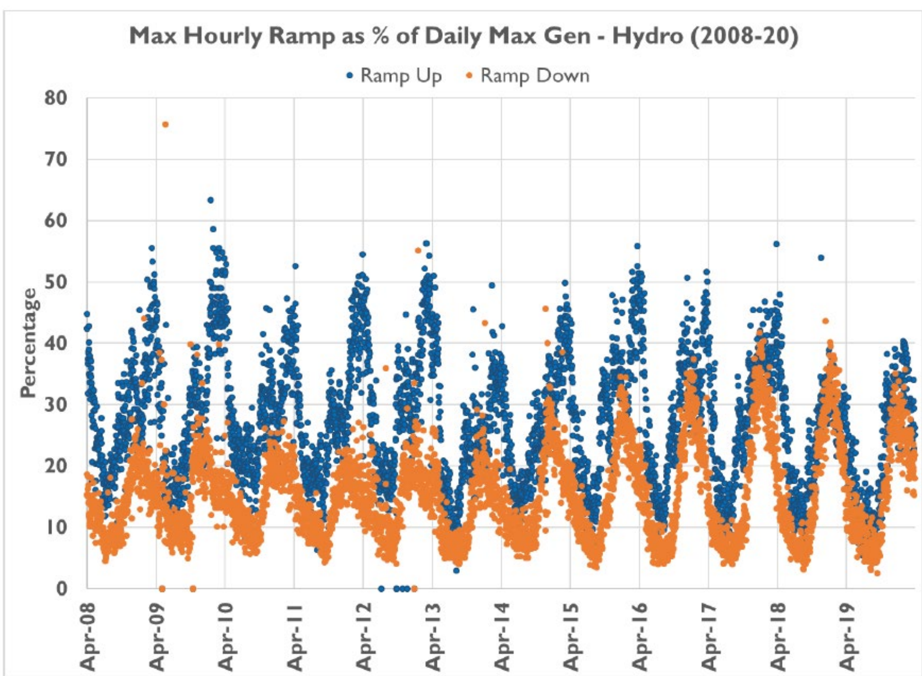

Figure A- 8. Maximum hourly ramp as percentage of daily maximum gas generation in India from 2008 to 2020

(Source: POSOCO)

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