GOVERNMENT OF INDIA
MINISTRY OF POWER

OPENING MARKETS, DESIGNING WINDOWS, AND CLOSING GATES

India's Power System Transition - Insights on Gate Closure

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India's Power System Transition - Insights on Gate Closure

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ABSTRACT

This report explores the concept of gate closure, the time at which market participants must submit their final bids and offers for electricity. Gate closure is typically considered a minor feature of market design, but its implementation could be pivotal to how power markets will operate under high penetrations of renewable energy. This report analyzes global experiences with gate closure, and then reviews the unique benefits, challenges, and other considerations that will impact the implementation of gate closure in the Indian electricity market.

List of Acronyms

ACER	Agency for the Cooperation of Energy Regulators
AEMC	Australian Energy Market Commission
CERC	Central Electricity Regulatory Commission
DC	Declared Capacity
DOE	U.S. Department of Energy
ERCOT	Electric Reliability Council of Texas
EU	European Union
ISGS	interstate generating station
ISO	independent system operator
LTA	Long-Term Access
MTOA	Medium-Term Open Access
MW	megawatt
MWh	megawatt-hour
NEM	National Energy Market
NLDC	National Load Despatch Centre
NREL	National Renewable Energy Laboratory
NYISO	New York Independent System Operator
RRAS	Reserve Regulation Ancillary Services
RLDC	Regional Load Despatch Center
RTC	real-time commitment
SCADA	Supervisory Control and Data Acquisition
SCED	Security Constrained Economic Dispatch
SCUC	security-constrained unit commitment
SLDC	State Load Despatch Centre
STOA	Short-Term Open Access
TSO	transmission system operator
URS	Un-Requisitioned Surplus
WEM	Western Australia Wholesale Electricity Market

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1 Introduction

Picture the last time you traveled via commercial airline. When you received your boarding pass, you may have observed a notation informing you the time at which the doors closed or boarding ended. This time was likely 15-30 minutes before the actual departure time for your flight. With all passengers on board and eager to reach their destination, why must the airplane wait to depart?

In fact, the short window of time between the completion of boarding and the plane's departure is crucial to ensuring a safe flight and orderly air traffic. After the aircraft's doors close and the flight deck crew completes its preflight checklist, the pilot contacts air traffic control for clearance to push back from the gate. Air traffic control is responsible for coordinating the sequence of departures for all flights. Although airline dispatchers usually request a particular routing from air traffic control more than an hour before takeoff, the final minutes before the aircraft leaves the gate provide an opportunity for air traffic control, the flight dispatcher, and the pilot to make last-minute adjustments based on updated weather conditions, runway usage, and airspace dynamics. During this time, the flight dispatcher also provides final information about passenger count, cargo loading, and aircraft and fuel weights, which the pilot and first officer use to adjust takeoff settings and speed (Collier and Smith 2017; Midkiff, Hansman, and Reynolds 2004).

Just as the airline industry allows time between final boarding and takeoff for operations that enable preflight planning and the safe release of each flight, many wholesale electricity markets employ a similar period of preparation time between the close of the bidding period and the dispatch of electricity. This period is known as gate closure.

This paper explores the concept of gate closure, including rationale, design features, and considerations for implementation. The paper then reviews the wide range in gate closure design, including in-depth descriptions in example markets. The paper concludes with an assessment of design considerations for gate closure in the India power sector, where gate closure is being considered for implementation with the adoption of real-time markets.

1.1 Gate Closure in Electricity Market Design

Indian power system stakeholders are deliberating a move toward creating electricity markets closer to real time. The value of real time market operations could be significant in respect to grid reliability and optimal operations, particularly with an increasing share of variable renewable energy in the generation mix. One element under consideration is a proposal to introduce gate closure in the Indian power system, which may have broad market implications and presents a number of important issues needing thorough examination, including:

- Purpose of gate closure in the electricity market
- The duration or period of the gate closure
- The nature of gate closure (i.e., day-ahead/intraday, rolling/fixed window)
- Time interval of rolling gate closure
- Impact on system security assessments and planning
- The layers of gate closures across various jurisdictional seams
- Ease of operations for stakeholders in generation, transmission, distribution, and trading
- Risk diversification and mitigation

- Impact on electricity market prices and volatility
- Impact on system costs (i.e., balancing and transaction costs).

This report first explores many of these issues in the global context, drawing from the experience of power systems in which gate closure has been considered, implemented, or revised. We then discuss the unique benefits, challenges, and other considerations that will impact the implementation of gate closure in the Indian electricity market.

1.2 What Is Gate Closure?

In a wholesale electricity market, gate closure refers to the time at which market participants must submit their final bids and offers for electricity.[1] Following gate closure, no further trades may take place unless certain circumstances apply. Gate closure is typically presented as a minor feature of market design. Yet, its implementation could be pivotal to how power markets will operate under increasing penetrations of renewable energy in the generation mix.

At some point before real time, contracts (i.e., dispatch schedules) must be finalized for a predetermined upcoming delivery or settlement period. Gate closure is the point at which the finalization occurs. After gate closure, forward-looking data, such as physical information and contract volumes for the predetermined delivery period, are frozen. The system operator takes over the responsibility for balancing supply and demand through available reserves or ancillary services, thereby ensuring reliability, security, and the economic optimization of power system operations.

Historically, vertically integrated utilities balanced supply and demand along a continuum. The system operators in the utilities set schedules day-ahead to allow slower ramping thermal plants to come online, and the operators could continue to adjust schedules based on physical capabilities of the plants against improved load forecasts and contingencies. In many power systems, these adjustments could continue up through delivery of power, the end point in this continuum.

The introduction of centralized platforms for markets, in which a market operator creates schedules and dispatch set points based on the marginal costs of delivering energy, presented an opportunity to improve competition among generation and reduce costs of operations. Yet, one aspect of this evolution has the potential to decrease efficiency—the interruption of seamless least-cost balancing up through delivery. With markets, the requirement for gate closure emerges. Market operators must fix and communicate the dispatch set points, the point that, in many jurisdictions, occurs one hour before the delivery of energy. Between gate closure and delivery, system operators rely on a separate set of resources, such as regulating reserves, to ensure readiness to maintain balance. Regulating reserves are not subject to the least-cost economic optimization that occurs within the real-time market. If the deployment of the reserves is co-optimized with energy markets, this inefficiency is minimized. Yet, the inherent division of energy from ancillary services creates potential opportunities for suboptimal dispatch compared to a seamless vertically integrated operation. Shortening the time interval between gate closure and dispatch allows more opportunity to balance supply and demand economically through the market, reducing the need for regulation reserves.

[1] In this paper, we refer to market participants as electricity buyers (e.g., scheduled loads or load-serving entities, such as distribution utilities) and sellers (e.g., generators).

Definitions: Time Horizons for Power System Operations

Gate closure occurs within the broader context of power system operations, including unit commitment and dispatch:

Unit commitment (also known as scheduling) is the practice of ensuring a generator is committed and available when needed. Unit commitment reflects the time period needed to start up a generator so that the plant is synchronized to the grid. Many system operators make decisions about which units to commit one day ahead to allow time for plants that have slower start-up times.

Dispatch refers to the frequency with which power system operators change generation set points among available generators to deliver energy (e.g., hourly or subhourly).

Gate closure is the time at which participants in a wholesale electricity market submit their final bids and offers. At this point, the power system operator uses the most recent actual data (operational and market) to begin the set point calculation and communication process. Gate closure can occur at a particular time (e.g., at 1000 on the day before delivery), or it can be defined with reference to each dispatch period (e.g., one hour before each dispatch period). Some systems use both approaches. For example, power systems with day-ahead and real-time markets may define both an initial and a final gate closure time (van der Veen and Hakvoort 2016):

- ***Initial gate closure time***: The time at which market participants must submit their initial bids and offers (or the time at which the load serving entity must provide its initial energy schedule) to the system operator. Initial gate closure frequently occurs the day before energy delivery and defines the unit commitment and dispatch schedule for the following day.
- ***Final gate closure time***: The time at which final bids and offers (or the energy schedule) must be submitted for the real-time market. Power systems that define both an initial and a final gate closure time may allow market participants to submit updates to their initial bids, offers, or schedules before the final gate closure time.

Figure 1 illustrates an example of how these processes might integrate with a power system with day-ahead unit commitment, 15-minute dispatch periods, and gate closure one hour in advance of delivery.

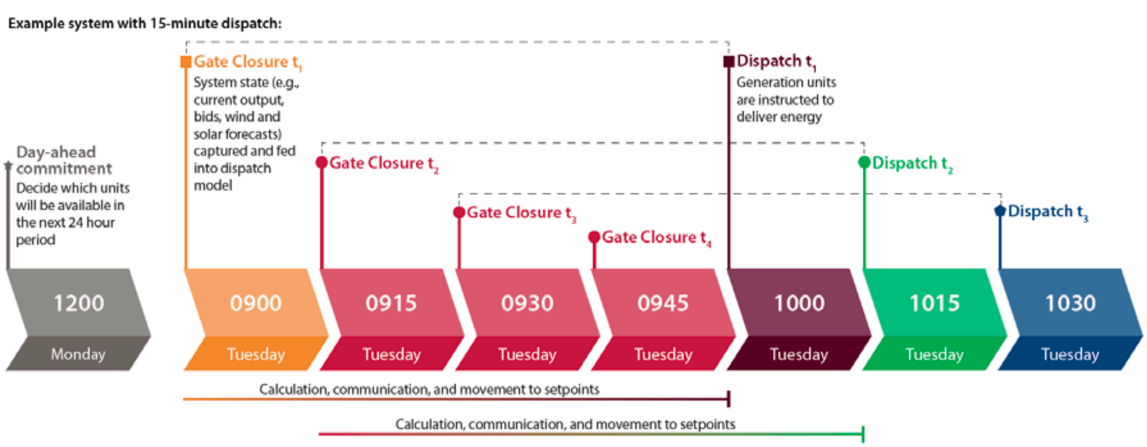

Figure 1. Example of unit commitment, gate closure, and dispatch processes for a hypothetical power system

In this illustrative case, dispatch occurs every 15 minutes, and gate closure occurs one hour prior to dispatch.

2 The Rationale for Gate Closure

Fundamentally, gate closure is a bid-scheduling tool. Its implementation is intended to benefit a variety of power sector stakeholders. Gate closure provides:

- Time for the system operator to compare the energy demand forecast with the schedules submitted by all generators in the system. The system operator uses this data to identify reliability issues, determine the need for ancillary services (including reserves), and take action accordingly (Elexon 2018).
- Generators and other balancing resources (e.g., demand response) a prescribed amount of time to finalize their physical outputs based on contracted volume, notify the system operator of their expected output, and reach their new specified dispatch setpoints.

Without gate closure in the real-time market, electricity markets have two general alternatives for scheduling generation: 1) committing units during the day-ahead schedule and not allowing rebidding by market participants following the close of the day-ahead market; or, 2) allowing generators to submit revisions to their day-ahead bids at any time until dispatch. The former approach potentially impacts the cost of system operations, because it prevents economic updates to schedules based on conditions nearer to real-time, with the likely results of increasing the forecasting error and requiring more reserves than would be needed if economic dispatch could occur closer to real-time (see the "The Importance of Gate Closure in Power Systems With Higher Levels of Variable Renewable Energy" text box).

The latter approach also has potential cost implications. For example, before 2015, the Australian Energy Market Commission (AEMC) found circumstantial and statistical evidence that some generators were engaging in deliberately late re-bidding behavior in certain regions of Australia's National Energy Market (NEM), in which market participants may rebid until dispatch (Australian Energy Market Commission 2015). AEMC linked late bidding with price volatility[2] and an increase in the price of forward contracts as market participants sought to pay a premium to hedge this volatility. While gate closure does not necessarily prevent deliberately late rebidding (it simply shifts the deadlines for late rebids earlier), it can help to address the resulting price spikes by giving demand-side resources (including demand response) and fast-start generation an opportunity to respond to the higher price.

[2] Price spikes could occur, for example, if a generator rebid at a high price capacity it had previously offered at a low price and did so too close to dispatch for other generators to respond with their own adjustments.

3 Defining the Length of Time Between Gate Closure and Dispatch

Perhaps the most crucial design decision in gate closure implementation is the length of time between gate closure and dispatch. Generally, a trade-off exists between balance planning accuracy (i.e., unit commitment or scheduling) and market efficiency, with the former being favored by a longer interval and the latter being favored by a shorter interval (ACER 2018c; Competition Economists Group 2014; van der Veen and Hakvoort 2016). System operators might prefer a longer window between gate closure and dispatch to ensure they have adequate time to balance supply and demand while maintaining an appropriate reserve margin. Conversely, market participants might prefer gate closure closer to dispatch so they can react to changing market or plant conditions and submit bids and offers that are more likely to reflect real-time circumstances. However, some generators may be more flexible than others in their ability to respond as time approaches real time; thus, short gate closure windows might favor fast-moving units over less flexible ones.

Some considerations might place a lower bound on a power system's desired gate closure interval. One major determinant of the length of the gate closure interval is a power system's generation mix. Longer gate closure intervals (e.g., several hours to day-ahead) may be necessary in systems that rely on slower-starting or slower-ramping thermal units as the marginal electricity supplier. On the other hand, shorter gate intervals are possible in power systems with a large capacity of fast-starting units. Facchini, Rubino, Caldarelli, and Di Liddo (2019) provide an example of how gate closure can change to reflect an evolving generation mix:

> In the United Kingdom, historically the [gate closure (GC)] has been calibrated on the time needed to the marginal provider to supply its service. For this reason, the UK moved the GC from 3.5 to 1 h before real time…because of the progressive substitution of the coal generation with other form of more flexible plants - Combined Cycle Gas Turbine (CCGT) - that allowed for the management of energy imbalances closer to real time. This reflects the different timing required to warm up and operate those two different types of plants: about 3 h for coal plants and 5 up to 30 min (depending on efficiency and on generation capacity) for gas fired plants.

Beyond the generation resource mix, the availability of greater computing power and improved modeling also influence the gate closure interval. The gate closure interval must be long enough to allow the system operator to run the security constrained unit commitment and dispatch models, then transmit dispatch instructions to generators. Historically, power system operators may have relied upon relatively long gate closure intervals to allow sufficient time to conduct power flow calculations and determine reserve requirements; with modern technologies, those calculations can be done faster.

Studies are just beginning to emerge regarding the impact of gate closure interval on electricity prices. In cases where no rules are in place to ensure bids are made in good faith, some studies have raised concerns that defining gate closure at a fixed time will enable generators to engage in late bidding, which can enable these generators to influence market price, as previously discussed (Competition Economists Group 2014); however, recent analysis provides evidence that the United Kingdom's 2002 decision to shorten the gate closure interval from 3.5 hours to 1 hour before dispatch had the effect of reducing short-term price volatility in the wholesale market (long-term price volatility has not been impacted) (Facchini et al. 2019). The authors of that report attribute this impact to the ability of shorter gate closure intervals to facilitate more accurate short-term forecasting of electricity demand.

Notably, global experience has demonstrated a general trend toward power systems shortening the interval between gate closure and dispatch. Power systems in Alberta, Singapore, and the United

Kingdom all shortened their gate closure intervals in the early 2000s (Competition Economists Group 2014; Facchini et al. 2019). The Western Australia Wholesale Electricity Market (WEM) is currently evaluating a rule change that would reduce the interval between gate closure and dispatch from 2 hours to 30 minutes (Economic Regulation Authority 2019). In its 2015 comments on the revised draft Network Code on Electricity Balancing, the European Agency for the Cooperation of Energy Regulators also recommended that gate closure be set "as close as possible to real time in order to ensure that the balancing energy bids reflect the real time value of balancing energy to the highest possible extent" (ACER 2015). Beyond enhancing market flexibility, reducing the interval between gate closure and dispatch has important benefits for renewable energy integration, as discussed in the "The Importance of Gate Closure in Power Systems With Higher Levels of Variable Renewable Energy" text box.

Available documentation indicates that decisions related to changing the length of the gate closure interval in the systems discussed above have been based primarily on qualitative rather than quantitative analysis. However, interest in quantitative analysis of gate closure options is growing; in an effort to inform current discussions regarding the harmonization of balancing gate closure time in the European Union (discussed further in the "Harmonizing Gate Closure Across Borders: A Case Study from the European Union" text box), Petitet et al. (2019) recently developed a first-of-its-kind study comparing the operational costs of different gate closure intervals. The study found that 60-minute gate closure resulted in lower operational costs as compared to a 15-minute gate closure in the simulated system.

Singapore's Rationale for Moving from 2-Hour to 65-Minute Gate Closure

When Singapore's power system reduced its gate closure from 2 hours to 65 minutes, the market operator cited additional benefits of a short gate closure interval (Market Administration 2005). Reducing the gate closure interval would enable market participants to react to changing market or plant conditions closer to real time by offering more capacity of online generating units if prices were forecast to be high due to shortages in the market. This would in turn help moderate price spikes in supply-constrained situations (this would not be the case if offline units have to be brought online, as they generally take two hours to start up). Additional justifications for a shorter gate closure interval included: 1) encouraging more responsive bidding based on most recent market information; 2) reducing any given generator's risk by allowing it to correct sudden changes to its physical position closer to real time; and 3) reducing the need for a generator to justify offer variations.

3.1 Changes to Bids and Offers

Different power systems define different rules regarding the extent to which changes are allowed after gate closure. Most of these rules are driven by reliability considerations. Some power systems define acceptable operational reasons for schedule changes after gate closure (Competition Economists Group 2014). For example, Alberta allows repositioning of the asset to serve the stand-by operating reserves market or to manage physical or operational constraints. Other power systems (Electric Reliability Council of Texas [ERCOT], New Zealand, Singapore) allow changes for physical reasons, such as a forced outage.

The Importance of Gate Closure in Power Systems With Higher Levels of Variable Renewable Energy

Around the world, several power systems with growing levels of variable renewable energy resources, such as solar and wind, have taken steps to decrease the amount of time between gate closure and dispatch within their power systems.

Gate closure can influence the ability of a power system to use renewable energy forecasts, which are an important tool for increasing power system flexibility and enabling efficient integration of variable renewable energy to the grid. Like electricity demand, solar and wind resources are variable (their output changes over all timescales) and uncertain (their output cannot be predicted with perfect accuracy). Solar and wind power forecasting can help mitigate these twin challenges. The accuracy of solar and wind power forecasts—as well as demand forecasts—depends on their time horizon, with forecast errors decreasing significantly closer to real-time dispatch (CIGRE 2006; Holttinen et al. 2016).The combination of frequent dispatch and short gate closure allows for more frequent generation schedule updates based on the best available forecasts. These frequent updates reduce uncertainty and also reduce the need for reserves and the cost of operating the power system. Studies of the Western Interconnection in the United States have shown that the need for regulation reserves decreases as the dispatch interval and renewable energy forecast lead time decrease, as illustrated in Figure 2 (King, Kirby, Milligan, and Beuning 2011). Reserve requirements decrease even further as the size of the balancing footprint increases, from individual balancing area authorities, to regional aggregations of balancing area authorities, to interconnection-wide.

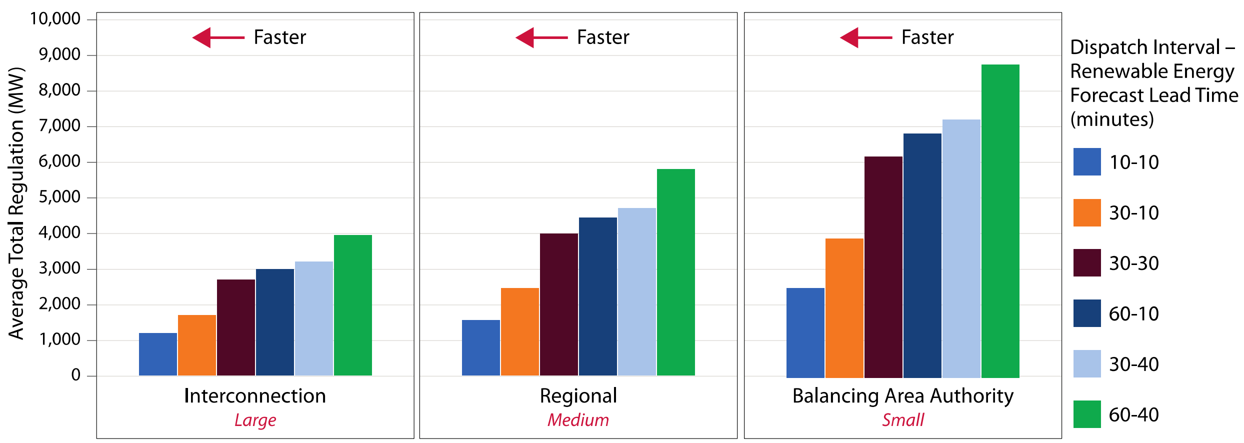

Figure 2. The need for regulation reserves decreases as power system operations become "big" (i.e., the size of the balancing footprint increases) and "fast" (i.e., the dispatch interval and renewable energy forecast lead time decrease).

Figure adapted from King, Kirby, Milligan, and Beuning 2011

Reducing the gate closure interval can also decrease the total reserve requirement. Several power systems around the world allow renewable energy generators to participate in electricity markets. In these systems, wind and solar generators offer their generation into the day-ahead and (if available) intraday markets, using the best-available generation forecasts to inform their bids. Because forecast accuracy improves as the horizon between the forecast and real time decreases, shortening the gate closure interval reduces forecast error. It also can reduce costs; a recent study of the power systems of Denmark, Finland, and Portugal provides evidence that reducing gate closure from day-ahead to two hours before dispatch has the potential to reduce imbalance costs associated with wind energy production by 30% and 50% in the Portuguese and Nordic markets, respectively (Holttinen et al. 2016).

Ideally, gate closure, forecasting horizon, and dispatch interval align within an electricity market to maximize the economic benefits of achieving fast operations. For example, 15-minute renewable energy forecasts—while very accurate—will provide the most value if the dispatch or gate closure interval is also 15 minutes, so the power system operator can use the most recent forecasts to inform decisions. That said, many power systems (especially those with growing levels of variable renewable energy) may benefit from an incremental approach in which the gate closure, dispatch interval, and the renewable energy forecasting horizon are shortened periodically to allow time for the entities involved in electricity markets to adjust their information infrastructure and institutional practices. The pace of change is also influenced by availability of data and experience conducting accurate forecasting. Singapore, the United Kingdom, and Western Australia are power systems that have, or are considering, shortening their gate closure intervals over time (Economic Regulation Authority 2019; ELEXON 2002; Market Administration 2005).

4 Gate Closure Around the World

Globally, gate closure takes as many forms as electricity markets themselves, and its implementation reflects the unique institutional structure, resource composition, and geography of each power system. Figure 3 shows the interval between gate closure and dispatch in several countries with wholesale energy markets. At the extremes, market participants in the Nord Pool market in Germany may trade until the moment of dispatch, while in the New England Independent System Operator's service area, gate closure occurs between 1600 and 1800 the day before dispatch. More commonly, gate closure ranges from five minutes to approximately two hours ahead of dispatch.

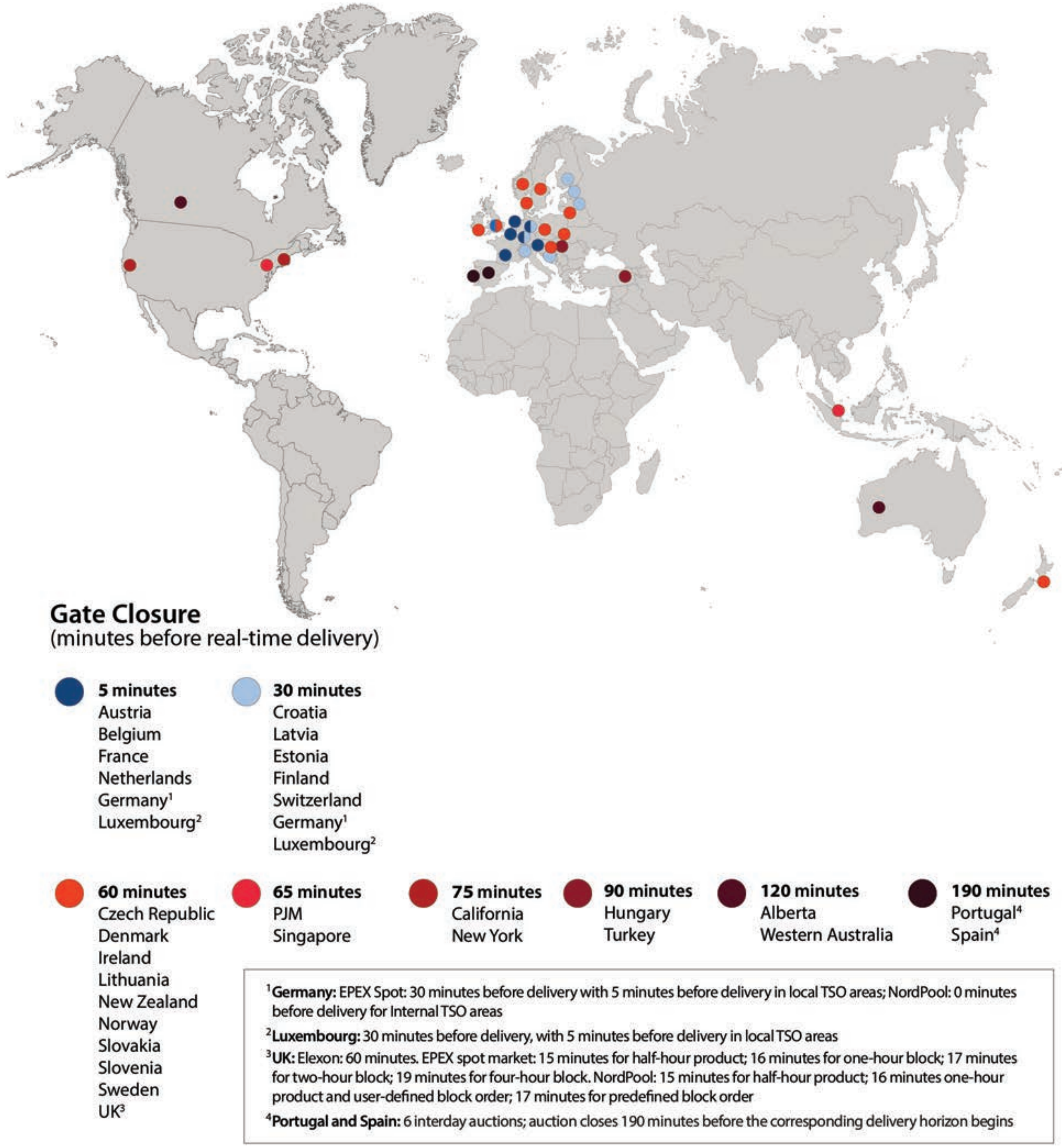

Figure 3. Gate closure in electricity markets around the world

See Appendix A for data sources.

Not all wholesale electricity markets implement gate closure. For example, to address the late rebidding behavior previously discussed, AEMC contemplated but ultimately dismissed the option of introducing gate closure into the NEM (AEMC 2015).[3] The Commission recognized that introducing gate closure would have the potential to result in positive outcomes; however, it ultimately decided against

[3] Australia has two energy markets: the NEM and the WEM. Unlike the NEM, the WEM has implemented gate closure (120 minutes in advance of dispatch).

implementing gate closure to allow the market its maximum flexibility to "reach efficient outcomes that reflect changing conditions" (ibid.).

Gate Closure in Germany

In Germany, the implementation of an imbalance pricing system (which enacts a charge on market participants who deviate from their schedules) incentivizes market participants to balance as close as possible to real time. The relatively short gate closure times in Germany's markets reflect this feature of the system. For Nord Pool power exchange participants, the gate closure is effectively zero minutes. EPEX SPOT Market provides a power exchange with a 30-minute and 5-minute gate closure:

> Electricity traded for a delivery on the same or on the following day on single hours, 15-minute periods or on block of hours. Each hour, 15-minute periods or block of hours can be traded until 30 minutes before delivery begins; and until 5 minutes before delivery within the respective control zones. Starting at 3pm on the current day, all hours of the following day can be traded. Starting at 4pm on the current day, all 15-minute periods of the following day can be traded. (EPEX SPOT 2019)

To facilitate short gate closure, the transmission system operators in Germany conduct re-dispatching ex ante to avoid transmission constraints and keep sufficient spinning reserves.

Harmonizing Gate Closure Across Borders: A Case Study from the European Union

Beyond its utilization within particular power systems, gate closure can also apply to power and energy trade across borders. The gate closure window for trades that take place between two or more markets need not be the same as the gate closure for transactions within each of the participating systems.

Recent experience from the European Union (EU) provides one example of how a group of power systems can define and implement gate closure to facilitate cross-border trade. In the EU, market participants in each bidding zone (which sometimes—but not always—are delineated by the national borders of the EU member states) submit orders for cross-zonal capacity allocations and are continuously matched with contracts to deliver this electricity. To coordinate and harmonize this process, the EU has established regulations that require intraday cross-zonal gate closure times to be set for each bidding zone border. The regulations specify that the chosen gate closure times must meet two objectives:

- "[Maximize] market participants' opportunities for adjusting their balances by trading in the intraday market as close as possible to real time; and,
- [Provide Transmission System Operators] and market participants with sufficient time for their scheduling and balancing processes in relation to network and operational security" (ACER 2018a).

To implement these regulations, the EU Agency for the Cooperation of Energy Regulators (ACER) recently adopted a decision to set the intraday cross-zonal gate closure time for all bidding zone borders to 60 minutes before the start of the relevant intraday market time unit (i.e., dispatch period) on the bidding zone border (ACER 2018b). The market time unit to which gate closure will ultimately be applied is the longer of the two market time units on either side of the border. For example, if one system dispatches every 15 minutes and its neighbor dispatches every 30 minutes, the intraday cross-zonal gate closure time will occur 60 minutes before each period in the 30-minute dispatch system. ACER's decision also allows one exception: the gate closure time will be 30 minutes across the Estonia-Finland border, as both Estonia and Finland conduct gate closure internally on a 30-minute basis.

ACER considers the 60-minute gate closure time conservative with respect to the amount of time needed by transmission system operators and market participants to schedule and balance their systems reliably (ACER 2018c); however, ACER acknowledges the conservative gate closure as being justified in lieu of uncertainty related to the implementation of concurrent electricity balancing regulations in the EU, which will, for example, harmonize the imbalance settlement period across the EU to 15 minutes by 2021. As the system operators and market participants gain experience with the integrated balancing market under these new regulations, ACER encourages the adoption of a gate closure closer to real-time, with the goal of improving market liquidity and reducing the need for more expensive balancing services.

5 From Gate Closure to Dispatch: Case Study from the New York Independent System Operator

In this section, we walk through a detailed example of the process used by the New York Independent System Operator (NYISO) between gate closure and dispatch in its real-time market. Gate closure in NYISO occurs 75 minutes prior to each operating hour. Figure 4 shows the operational time frame. This figure and the discussion that follows are adapted from NYISO's *Transmission and Dispatch Operations Manual* (NYISO 2018).

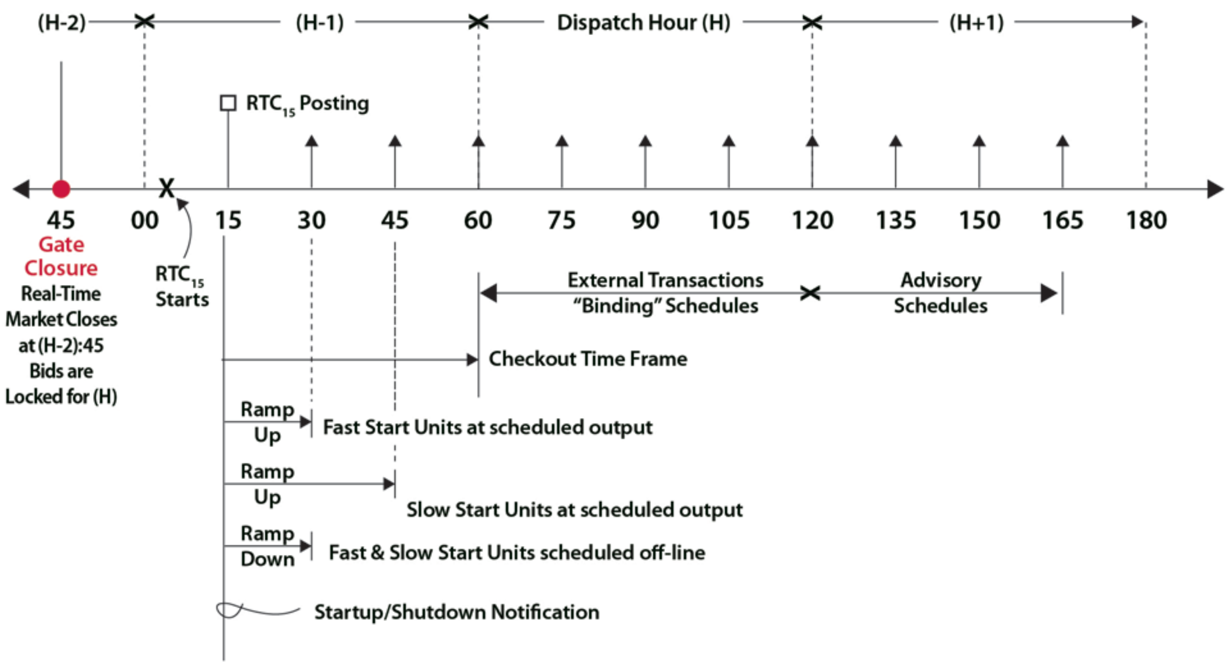

Figure 4. Operational timeline for NYISO's real-time commitment (RTC) market

Adapted from NYISO 2018

1. **Gate closure (75 minutes prior to the operating hour):** Bidding for the dispatch hour (H in Figure 4) closes. The system operator collects the accepted bids from the day-ahead market, as well as real-time supply offers, transactions, regulation bids, and constraints. In their supply offers, generating units provide information (including minimum run time, minimum down time, max starts and stops per day, response rate, duration, start-up time, minimum generation, and upper operating limit) that help to define the ability of particular units to respond within the gate closure period. In addition, suppliers must specify the unit operating mode of their units as fixed (i.e., their output cannot be changed from the in-hour schedule) or flexible, as well as whether they are independent system operator (ISO)-committed (economically-selected) or self-committed (price taker).

2. **Real-time commitment begins (60 minutes prior to the operating hour):** NYISO executes the real-time commitment (RTC_{15}), a multiperiod security-constrained unit commitment (SCUC) and dispatch process. RTC_{15} co-optimizes to simultaneously solve for load, operating reserves, and regulation service on a least-as-bid production cost basis over the following 165-minute optimization period (10 points separated by 15-minute intervals). NYISO:

   - Updates the power system grid model based on the latest transmission outage schedules (including forced outages)

- Updates the load forecast based on the latest load information
- Accepts any updated reserve requirements
- Accepts the day-ahead schedules and firm transaction schedules, as well as the hour-ahead generation bids and firm transaction bids
- Accepts the telemetered phase shifter and tap settings from Supervisory Control and Data Acquisition (SCADA) with adjustments made for known schedule change.

Each RTC_{15} run produces the following outputs:

- Binding unit commitment and de-commitment instructions for periods beginning at 15 minutes (for resources that can respond in 10 minutes) and 30 minutes (for resources that can respond in 30 minutes) after the scheduled posting time of each RTC_{15} run. For example, units that submit a 30-minute startup time will receive a binding startup notification from the RTC that posts its results 30 minutes before the scheduled start of the units.
- Advisory commitment guidance for the remainder of the optimization period
- Binding schedules for External Transaction schedules to begin at the start of each quarter hour
- Calculated transmission losses as part of the power flow solution for each time interval for each load zone.

During RTC_{15}, NYISO also conducts the Supplemental Resource Analysis, a process used to commit additional resources outside of SCUC and RTC to ensure sufficient resources are available to meet forecasted load and reserve requirements.

3. **Posting of real-time results (45 minutes prior to the operating hour):** accepted bids, offers, transactions, regulation bids, and constraints are publicly posted into the Market Information System, which is the interface between NYISO and market participants. This posting serves as a notification for suppliers to start or shut down their units. The posted information includes:
    - Revised generator schedules for the next hour
    - Revised firm transaction schedules for the next hour
    - Market participant actions
4. **Reserve pick-up (approximately 10 minutes prior to the operating hour):** NYISO monitors the area control error and load trends and identifies and mitigates deficiencies in generation or transmission security violations. NYISO or the transmission owner may request out-of-merit generation; for example, for security, during communication failures, or if RTC_{15} did not successfully run.

6 Gate Closure for India's Electricity Market

With its unique characteristics and behavior, the Indian electricity market is one of the most dynamic electricity markets in the world. A coordinated multilateral scheduling and dispatch model has been in place since 2001. This approach encourages competition and at the same time maintains necessary coordination to ensure reliability. Power system operation is optimized through cooperation of agents in a multilateral trade structure. In the Indian power system, reliability assessments are carried out by the system operator on transmission corridors and disseminated in the public domain, aiding in the administration of the market. The economic decisions by buyers and sellers, located in different regions, are formulated into contracts considering grid security and reliability. These contracts are coordinated and implemented by the system operator in the form of schedules.

Indian electricity stakeholders have expressed a need to increase the frequency of market opportunities available for market participants to balance their portfolios (CERC 2018b). Achieving this objective would entail shortening the time between procurement period closure and real-time dispatch. The introduction of gate closure may allow enhanced valuation of the product and, notably, the foregone value of the capacity in other market segments, thereby enhancing flexibility and reducing risk.

6.1 Flexibility in the Indian Electricity Market

An important aspect of the Indian electricity market is the decentralized nature of scheduling and dispatch decisions. This approach gives freedom and choice to the load serving entities (i.e., state utilities, also known as distribution companies) to revise capacity requisitions, as well as allow inadvertent deviations from schedule within limits if grid conditions permit. It borrows from the basic philosophy of homeostatic control, proposed by Schweppe et al. (1980), in which the supply (generation) and demand (load) respond to each other in a cooperative fashion and are in a state of continuous equilibrium to the benefit of both the utilities and their customers. The revision windows for different contracts (i.e., long-term, medium-term, and short-term) have been specified in the Indian Electricity Grid Code. Further, in case of transmission congestion, there is inter se priority in the curtailment of contracts, with Bilateral Short-Term contracts having lowest priority, then Day-Ahead Power Exchange Spot Market contracts, followed by Medium-Term Open Access (MTOA) Contracts. Long-Term Access (LTA) contracts have the highest priority.

6.2 Continuum of Contracts

Presently, the electricity market in India comprises physical delivery only contracts between generating resources and load serving entities. These contracts have to be intimated to the respective load dispatch centers a day in advance. The Indian Electricity Grid Code lays the foundation for the scheduling and dispatch process as a continuum of different long-term, medium-term, and short-term contracts, as well as close-to-real-time windows and products across the spectrum of stakeholders. In case of complex systems like power systems, it is likely that the cessation of challenges at one level will result not in the steady state, but in a move to some other level of dynamic state; however, the common thread throughout the range of continuum is a strategic goal of ensuring reliability, security, and economy in the electricity grid, from planning to operations to settlement.

6.2.1 Windows Available for Various Market Products

Open access in interstate transmission was introduced in 2004 along with the initiation of bilateral transactions. Subsequently, in 2008, collective transactions through the power exchanges were also introduced. Over the years, the various products available and the associated processes have undergone changes depending on the requirements of the market. Market conditions, such as liquidity and prevailing (or likely) prices, drive the preferences of market participants in terms of choice of different products in different windows to balance the portfolio. These windows can be categorized as short-term, medium-term, or long-term. The various Indian electricity market products, along with their timelines for delivery in the current market design, are depicted in Figure 5.

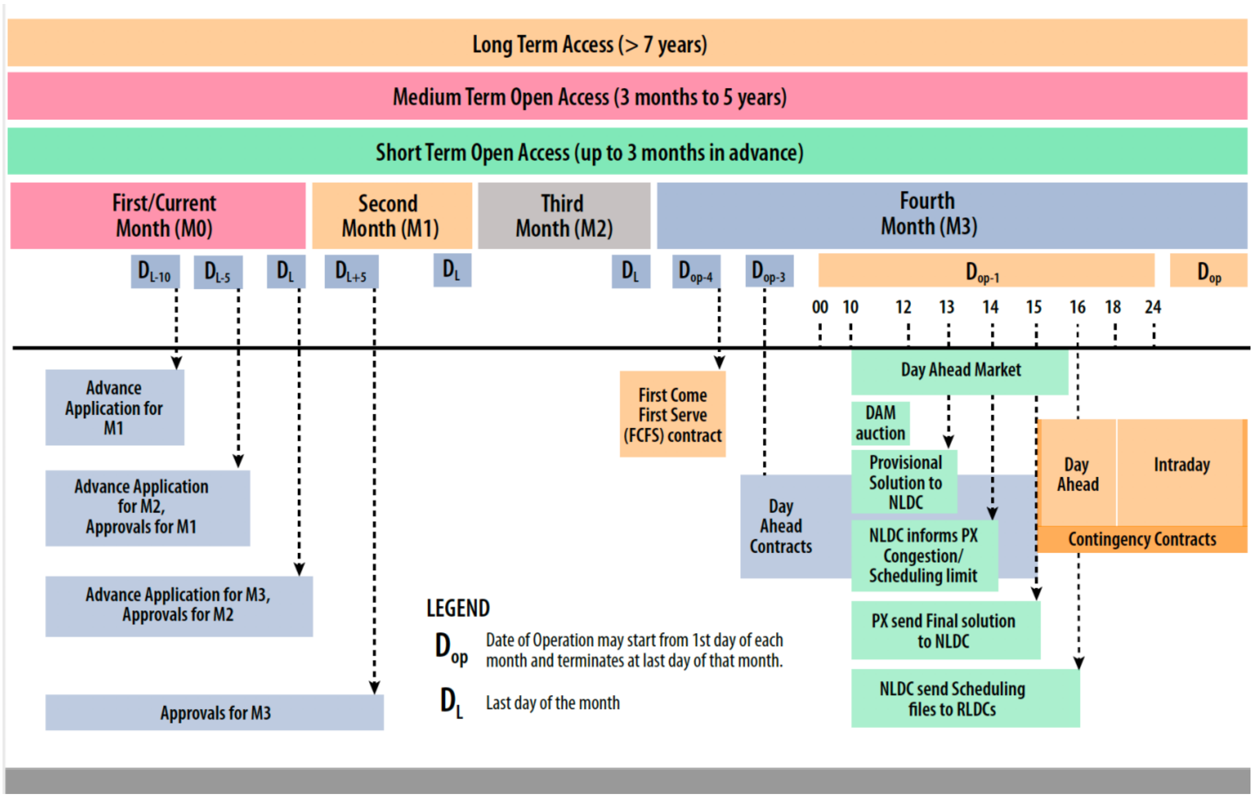

Figure 5. Electricity market products in India

Source: POSOCO

The longest window available in the current Indian Electricity Market is the LTA, which refers to the right for market participants to use the interstate transmission system for a period exceeding seven years. An MTOA grants market participants the right to use the interstate transmission system for a period equal to or exceeding three months but not exceeding five years. After LTA and MTOA, the next window available is that of Short-Term Open Access (STOA), applying to the period up to three months in advance. The different products available in the STOA in different time frames are as follows:

- The window for application for Advance STOA-Bilateral product to respective the RLDC is three months in advance but approved one month at a time. In case of congestion in Advance STOA-Bilateral product, electronic bidding is conducted by the respective Regional Load Dispatch Center (RLDC).
- The next window for application for first-come, first-serve STOA-Bilateral product occurs four days prior to day of operation. The processing is done on a first-come first-serve basis for transactions commencing and terminating in the same calendar month.
- The applications received within three days prior and up to 1500 hours of the day immediately preceding the day of operation is treated with the same priority as the day-ahead STOA-Bilateral product; however, the processing of a day-ahead STOA-Bilateral application is done only after processing of the collective transactions of the power exchanges, a sort of mutually exclusive window.

- The double-sided closed-bid auction is done for every time block in 96 time blocks of 15 minutes in the Day-Ahead Market through the Power Exchanges. The auction window is from 1000 hours-1200 hours. The final clearing result is communicated at 1500 hours to the National Load Despatch Centre (NLDC).
- The window for Contingency STOA-Bilateral product is opened after 1500 hours of the day immediately preceding the day of operation. All Contingency STOA-Bilateral applications received up to 1800 hours are clubbed together with the same priority. If the Contingency STOA-Bilateral application is received in intraday, subject to approval, the scheduling of the transaction commences within 91 minutes after application is received.

The summary of windows available in the Indian Electricity market is depicted in Figure 6. The windows are, at times, mutually exclusive (i.e., no two windows or electricity market products are open at the same time for the same delivery period). When a new window for a particular product is opening, it is accompanied by a closing of the preceding window of another product. Therefore, each window of different products offers a new opportunity to the market participants to balance through a portfolio of products, thereby enhancing grid security and reliability.

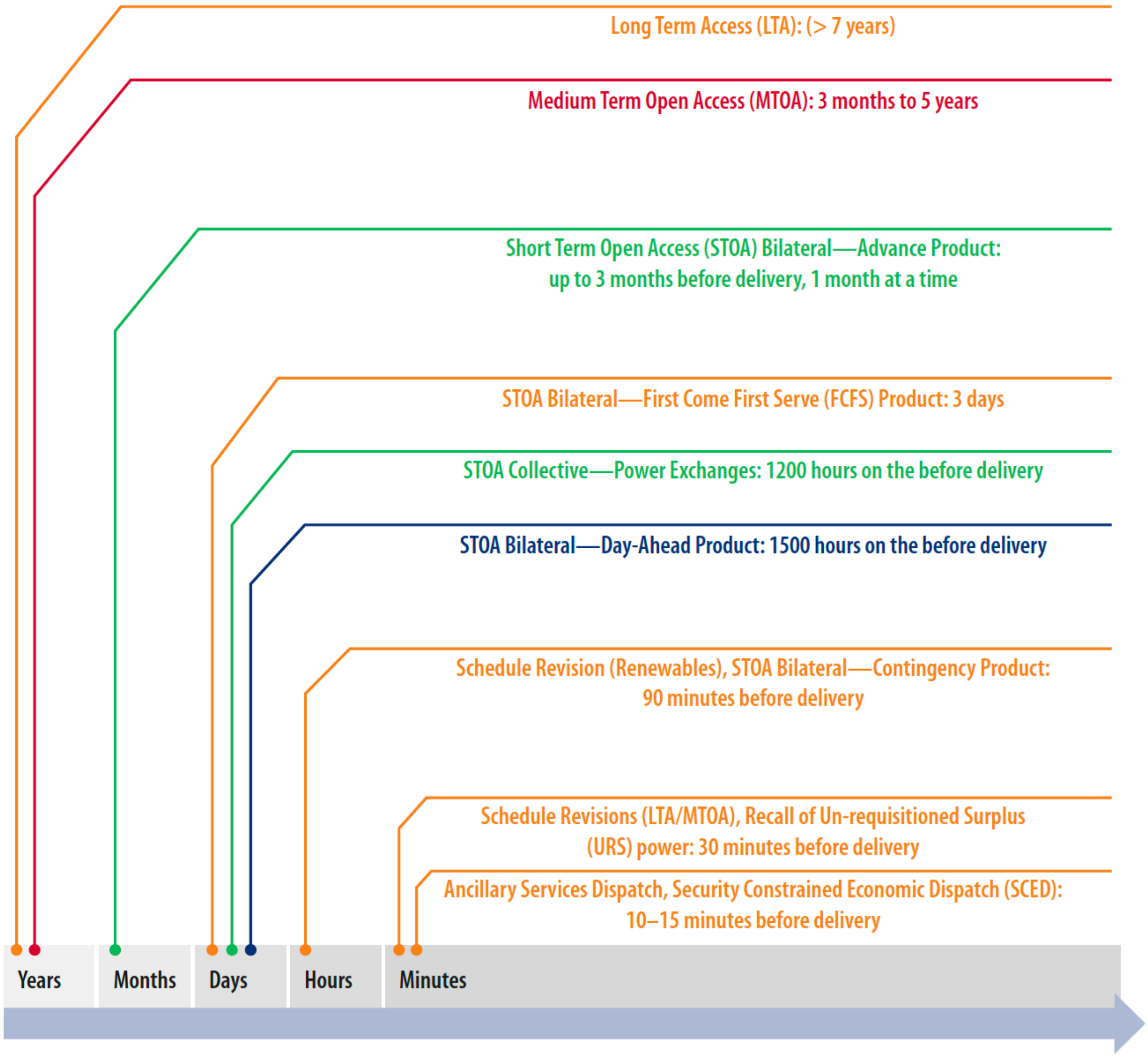

Figure 6. Gates and windows in the Indian electricity market

Source: POSOCO

The available transfer capability in the interregional transmission corridors would be honored in all time frames while scheduling trades in different windows.

6.3 Scheduling Framework

Figure 7 illustrates the current approach to day-ahead and intraday scheduling in India's electricity market.

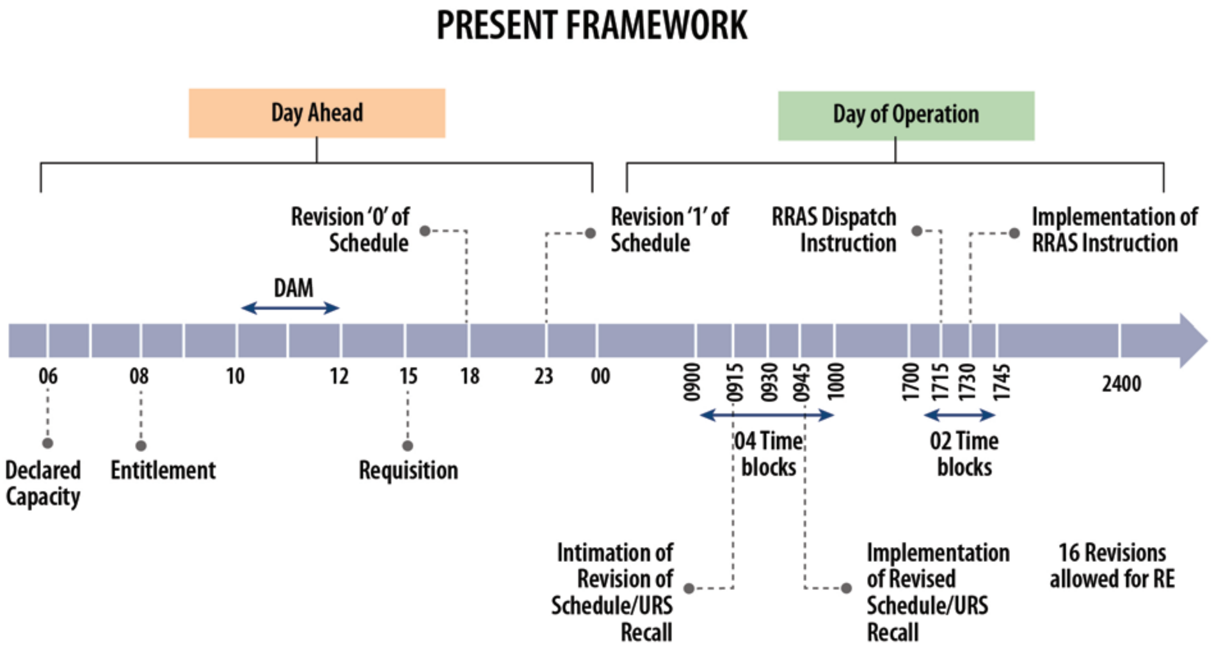

Figure 7. Current scheduling framework for India's electricity market

Source: POSOCO

6.3.1 Day-Ahead Scheduling

In the present framework mandated in the Indian Electricity Grid Code, each interstate generating station (ISGS) submits its declared capacity (given in megawatts [MW]) and generation (DC, given in megawatt-hours [MWh]) capabilities foreseen for the next day (i.e., 0000 hrs to 2400 hrs for 96 blocks of 15 minutes duration each) to the respective Regional Load Despatch Center (RLDC). By 0800 hours, each State Load Despatch Centre (SLDC) submits to its respective RLDC the ISGS shares (MW and MWh) to which the state is entitled during the following day at 15-minute intervals.

The load serving entity communicates its consent for the sale of unrequisitioned generating capacity to the ISGS at least 24 hours before 0000 hrs of the day of operation (i.e., the day of dispatch). In the meantime, the submission of bids and offers in the power exchanges for day-ahead market is done from 1000-1200 hrs on the day before dispatch. The requisition in each of the ISGS in which the states have long term, medium term, bilateral interchanges, approved short term bilateral interchanges are communicated to the respective RLDC by 1500 hrs.

The scheduling request of day-ahead collective transactions in power exchanges is communicated by the NLDC to the respective RLDCs by 1600 hrs. The interchange schedule (i.e., Revision 0, in MW, after deducting the apportioned estimated transmission losses) is communicated by RLDC to each regional entity by 1800 hrs.[4] The modifications, if any, in view of grid conditions have to be communicated by the respective SLDC, ISGS, or regional entity to RLDC by 2200 hrs. At 2300 hours, the RLDC communicates the final generation/drawal schedule for the next day (i.e., Revision 1) to the respective SLDC, ISGS, or regional entity.

[4] As defined in the Indian Electricity Grid Code, regional entities are those within an RLDC control area whose metering and accounting are done at the regional level. RLDCs conduct scheduling for regional entities.

6.4 Intraday Scheduling and Dispatch

There are many instances throughout the day of operation when either a regional entity or load dispatch center may initiate revisions in the schedules on account of various contingencies. As per the Grid Code, at present, there are various provisions for revision in schedules effectively up to 31 minutes before the dispatch period. A regional entity (including a renewable energy generator) can initiate a revision in its DC and STOA (Bilateral) injection schedule if a forced outage occurs. In case of a STOA contingency application, ISGSs can revise their schedules, with changes implemented within up to 91 minutes after the application is received.

Based on real-time conditions, NLDC issues the instructions for Reserve Regulation Ancillary Services (RRAS) Up/Down schedule to each ISGS. Once added to the generation schedule, the revision is operationalized, at the earliest, from the time block starting 15 minutes after issue of the dispatch instruction. A pilot project on Security Constrained Economic Dispatch (SCED) has been deployed, effective April 1, 2019. The SCED schedule is incorporated by the ISGS before the start of the delivery block. Further, RLDCs can revise schedules on their own in case of bottleneck in evacuation of power from ISGS, transmission constraints, and in the interest of better grid operation.

6.5 Context for Gate Closure in India

6.5.1 Regulatory Mandate and Initiatives

The Ministry of Power notified a scheme on *Flexibility in Generation and Scheduling of Thermal Power Stations to reduce the cost of power to the consumer* in which it emphasized that suitable provision for gate closure for operationalizing the scheme may be provided by the Appropriate Commission (Ministry of Power, Government of India 2018).

The Central Electricity Regulatory Commission's (CERC's) *Discussion Paper on Re-designing Real Time Electricity Markets in India* suggests that the intraday/real-time market design for India needs to incorporate the concept of gate closure for guaranteeing firmness and sanctity of schedules in intraday trades (CERC 2018b). Figure 8. shows the preliminary concept for gate closure as outlined in this paper. CERC's *Discussion Paper on Designing Market for Tertiary Ancillary Services in India* also highlighted the importance of gate closure in the proposed market-based ancillary services mechanism (CERC 2018a).

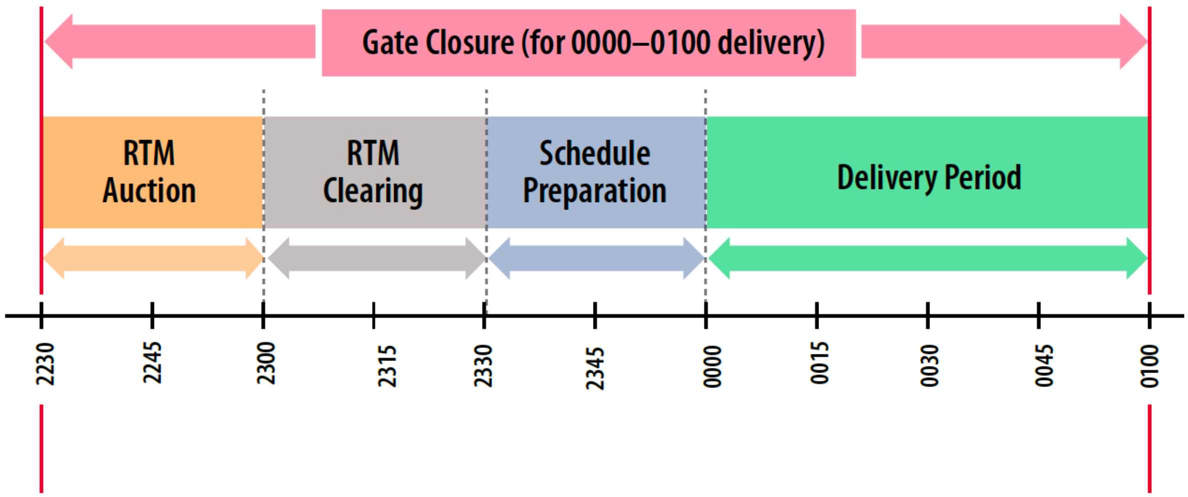

Figure 8. Concept of gate closure, as per CERC staff paper

Source: CERC 2018b

The Power System Operation Corporation (POSOCO) *Consultation Paper on Security Constrained Economic Despatch of ISGS Pan-India* emphasized that with the large number of participants, there are requests for revisions in schedule on an almost continuous basis (POSOCO 2018). This reality can create challenges in real-time assessment of the hot and cold reserves available in the system. To efficiently implement the proposed optimization process at the regional and national level, the introduction and timing of gate closures may play an important role. Conceptually, prior to gate closure, the flexibility of revising the schedules is with the market participants; post gate closure, the system operators take over and prepare for the predetermined delivery period. Gate closure time is intended to be implemented to enable a thin centralized layer of optimization over the present decentralized scheduling. This optimization could also extend to tertiary reserves where more opportunities for co-optimization of energy, ancillary services, and reserves are being considered.

The Forum of Regulator of India deliberated the concept of gate closure (Forum of Regulators 2018a). The Forum endorsed the recommendation of the Technical Committee for the introduction of a real-time market with gate closure and requested CERC to take the idea forward. It was also reiterated that automation of the process and preparedness of the stakeholders, especially distribution companies and power exchanges, were essential requisites to the success of the framework.

The Forum of Regulators *Sub-Group Report on Introduction of Five Minute Scheduling, Metering, Accounting and Settlement in Indian Electricity Market* recognized that with coordinated multilateral scheduling processes, the various activities, such as rescheduling of undispatched surplus and tripping of power system elements, may be contributing to overlap with the schedule modifications being carried out by the concerned RLDC (Forum of Regulators 2018b). The available reserve quantum is thus changing continuously, and simultaneous ancillary service dispatch has added another dimension of complexity to the process with potential parallel changes by the NLDC (for ancillary services) and the RLDCs (schedules).

CERC's *Report of the Expert Group Volume – II "Review of the Principles of Deviation Settlement Mechanism (DSM), Including Linkage with Frequency, in the Light of Emerging Markets* recommended the need for introduction of gate closure concept in the scheduling process so that the system operator has clarity of the quantum of reserve and resources at hand at any given point of time CERC 2017). This would facilitate better optimization of the scheduled dispatch and the real time ancillary dispatch.

The POSOCO *Report on Reserve Regulation Ancillary Services (RRAS) Implementation in Indian Grid - Half Year Analysis and Feedback* emphasized that improved co-optimization of the scheduled dispatches and the real-time ancillary services dispatch needs to be formulated (POSOCO 2016). The report also highlighted another limitation of the absence of gate closure in the extant RRAS Regulations (i.e., that the original beneficiaries have the right to recall unrequisitioned power from ISGSs any time as per the provisions of the regulations). Therefore, the ownership and rights remain with the original beneficiary, and original beneficiaries should continue to pay the fixed charges. This market design has created a perverse incentive for load serving entities to take a passive approach and avoid keeping reserves on bar. In order to maintain grid security, NLDC and the RLDCs will try to keep spinning reserves in the system, and they will utilize this reserve as per their requirement. The beneficiary gets a refund of fixed charges despite a passive approach. To alleviate these issues, some amendments in the scheduling timelines prescribed in the Grid Code may be necessary. POSOCO suggested that the process of revision of ISGS schedules may be examined afresh considering Day-Ahead Market, 24 x 7 Market, sale by ISGS and ancillary services, among other considerations. In physical terms, the concept of gate closure may also facilitate more efficient system balancing through a thin layer of centralized scheduling over decentralized scheduling by the constituents.

7 Considerations Going Forward—Perspectives from India

> ***Successful Gate Closure Implementation in India***
>
> Essential considerations for successful implementation of gate closure in any typical power system include:
>
> - Primary control
> - Secondary control through automatic generation control
> - Different types of reserves (e.g., fast and slow) with sufficient quantum (either mandatory or through market)
> - Market design and regulatory framework
> - Robust communication and IT infrastructure
> - Skilled workforce and capacity building.

In India, with the current majority of generation resources being coal based, generators need to receive dispatch instructions at least 15 minutes in advance. As a result, a reduction of gate closure to anything less than an hour may create new challenges for system operators, even if the transition to five-minute scheduling and settlement occurs. In the future, as new market products with newer attributes are introduced in light of the evolving power system, gate closure could mitigate some of these challenges. Hourly gate closure complements current renewable energy forecasting practice in India, as granular solar irradiance data is available on a 30-minute basis. It could also help to ensure adequate time is available for suitable technology upgrades for more than 6,000 market participants at the interstate level. With operationalization of retail-level competition and new market participants such as aggregators, the current market dynamics are likely to change significantly, including consideration of new market arrangements with real-time market and gate closure.

In a large grid like India, there are **multiple regional-level control areas** for the purpose of scheduling and energy accounting. All buyers and sellers in a regional-level control area are treated as **nested control areas** within that respective regional-level control area and are clubbed together into a separate group. **Scheduling, energy accounting, and settlement** for the individual transactions for **nested (embedded) control areas** are handled by the respective states. Cooperation and commitment of the internal control areas are essential; otherwise, the combined control performance of national control area can easily be worse than the sum of individual regional and state level control areas. Hence, the **seams between different control areas and jurisdictions** would be an important consideration for introduction of gate closure concept.

Considering the predominance of thermal generation in India, communication infrastructure, forecasting granularity challenges, the seams between different jurisdictions, limitations of granular weather data information technology upgradation, newer products in marketplace, decentralized scheduling and dispatch model, international experience, complexity of contracts, available windows and products; hourly (versus a shorter time frame) gate closure could potentially support greater efficiency and optimization with the Indian electricity market. In order to ensure all market participants benefit from the use of this mechanism with gate closure, the concept would also likely need to be introduced via an amendment of the Indian Electricity Grid Code to ensure market clarity, ability to operationalize, and compliance. Further, efficient and effective implementation of gate closure approach would likely require parallel introduction of related state grid codes via the State Electricity Regulatory Commissions.

References

ACER (Agency for the Cooperation of Energy Regulators). *Recommendation of the Agency for the Cooperation of Energy Regulators No 03/2015 of 20 July 2015 On the Network Code on Electricity Balancing*. July 2015. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Recommendations/ACER Recommendation 03-2015.pdf.

ACER. (2018a). Annex I: Intraday cross-zonal gate opening and gate closure times in accordance with Article 59 of Commission Regulation (EU) 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management.

ACER. *Decision of the Agency for the Cooperation of Energy Regulators No 04/2018 of 24 April 2018 on All Transmission System Operators' Proposal for Intraday Cross-Zonal Gate Opening and Intraday Cross-Zonal Gate Closure Times.* April 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Individual decisions/ACER Decision 04-2018 on IDCZGTs.pdf.

ACER. *Intraday Cross-Zonal Gate Opening and Gate Closure Times*. July 2009. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0001:0014:EN:PDF

AEMC (Australian Energy Market Commission). *Bidding in Good Faith, Final Rule Determination*. December 2015. https://www.aemc.gov.au/sites/default/files/content/815f277c-a015-47d0-bc13-ce3d5faaf96d/Final-Determination.pdf.

CERC (Central Electricity Regulatory Commission). *Report of the Expert Group (Volume II): Review of the Principles of Deviation Settlement Mechanism (DSM) Including Linkage with Frequency in light of Emerging Markets*. New Delhi. December 2017. http://www.cercind.gov.in/2018/Reports/ASB.pdf.

CERC. *Discussion Paper on Designing Market for Tertiary Ancillary Services in India*. New Delhi. September 2018. http://www.cercind.gov.in/2018/draft_reg/DP.pdf.

CERC. *Discussion Paper on Re-designing Real Time Electricity Markets in India*. New Delhi. July 2018. http://www.cercind.gov.in/2018/draft_reg/RTM.pdf.

CIGRE. *Electric Power System Planning with the Uncertainty of Wind Generation*. 2006. https://e-cigre.org/publication/293-electric-power-system-planning-with-the-uncertainty-of-wind-generation.

Cochran, Jaquelin, Michael Milligan, and J. Katz. "Greening the Grid: Sources of Operational Flexibility." Golden, CO: NREL. NREL/FS-6A20-63039. May 2015. https://www.nrel.gov/docs/fy15osti/63039.pdf.

Collier, Mike, and Steve Smith. "The Flight Dispatch Process." Presented at the Cross Polar Working Group, May 30-June 1 2017. Washington, D.C. https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/systemops/ato_intl/documents/cross_polar/CPWG23/CPWG23_Brf_AAL_Dispatch_Process.pdf.

Competition Economists Group. *International review of rebidding activity and regulation*. December 2014. https://www.aemc.gov.au/sites/default/files/content/1694f30d-2165-4e5a-b464-e28de02d02e9/CEG-International-review-of-rebidding-activity-and-regulation-Final-report.PDF.

Economic Regulation Authority. "Rule Change: RC_2017_02." Accessed February 8, 2019. https://www.erawa.com.au/rule-change-panel/market-rule-changes/rule-change-rc_2017_02.

Elexon. "The Electricity Trading Arrangements: A Beginner's Guide." February 2019. https://www.elexon.co.uk/documents/training-guidance/bsc-guidance-notes/beginners-guide-2/.

Elexon. "Modification Report - Modification Proposal P12: Reduction of Gate Closure from 3.5 Hours to 1 Hour." Last modified September 29, 2010. https://www.elexon.co.uk/mod-proposal/p012-reduction-of-gate-closure-from-3-5-hours-to-1-hour/.

EPEX SPOT. "Intraday market with delivery on the German TSO zone." Accessed February 8, 2019. https://www.epexspot.com/en/product-info/intradaycontinuous/germany.

Facchini, Angelo, Alessandro Rubino, Guido Caldarelli, and Giuseppe Di Liddo. "Changes to Gate Closure and its impact on wholesale electricity prices: The case of the UK." *Energy Policy* 125 (February 2019): 110–121. https://doi.org/10.1016/J.ENPOL.2018.10.047.

Forum of Regulators. "Minutes of the 63rd Meeting of the Forum of Regulators." New Delhi. April 9, 2018. http://www.forumofregulators.gov.in/Data/Meetings/Minutes/63.pdf.

Forum of Regulators. *Sub-Group Report on Introduction of Five Minute Scheduling, Metering, Accounting and Settlement in Indian Electricity Market*. February 2018. http://www.forumofregulators.gov.in/Data/Reports/5.pdf.

Holttinen, Hannele, Jari Miettinen, Antonio Couto, Hugo Algarvio, Luis Rodrigues, and Ana Estanqueiro. "Wind power producers in shorter gate closure markets and balancing markets." 2016 13th International Conference on the European Energy Market (EEM) (pp. 1–5). IEEE. June 6-9 2016. https://doi.org/10.1109/EEM.2016.7521309.

King, J., B. Kirby, M. Milligan, and S. Beuning. *Flexibility Reserve Reductions from an Energy Imbalance Market with High Levels of Wind Energy in the Western Interconnection*. Golden, CO: NREL. NREL/TP-5500-52330. October 2011. https://www.nrel.gov/docs/fy12osti/52330.pdf.

Market Administration, E. M. C. Gate Closure Reduction, Pub. L. No. EMC/BD/07/2005/14(b), Chapter 6, section 10.4; Appendix 6A. January 2006. https://www.emcsg.com/f311,9288/EMC_246-EMA-wg_revised.pdf.

Midkiff, Alan, R. John Hansman, and Tom G. Reynolds. *Air Carrier Flight Operations*. Cambridge, MA: MIT/ICAT. July 2004. https://dspace.mit.edu/bitstream/handle/1721.1/35725/FlightOpsICATfinal2.pdf.

Ministry of Power Government of India. "Scheme on Flexibility in Generation and Scheduling of Thermal Power Stations to reduce the cost of power to the consumer." August 2018. https://powermin.nic.in/sites/default/files/webform/notices/Merit Order operation.pdf.

New York Independent System Operator. *Manual 12: Transmission and Dispatch Operations Manual*. July 2019. https://www.nyiso.com/documents/20142/2923301/trans_disp.pdf/9d91ad95-0281-2b17-5573-f054f7169551.

Pelland, Sophie, Jan Remund, Jan Kleissl, Takashi Oozeki, and Karel De Brabandere. "Photovoltaic and Solar Forecasting: State of the Art." October 2013. http://iea-pvps.org/index.php?id=278.

Petitet, Marie, Marie Perrot, Sébastien Mathieuc, Damien Ernstc, Yannick Phulpina. "Impact of gate closure time on the efficiency of power systems balancing." June 2019. https://www.sciencedirect.com/science/article/pii/S0301421519301223

POSOCO (Power System Operation Corporation Limited). *Report on Reserve Regulation Ancillary Services (RRAS) Implementation in Indian Grid - Half Year Analysis and Feedback*. New Delhi. November 2016. https://posoco.in/download/half-year-feedback-to-cerc/?wpdmdl=8916.

POSOCO. *Consultation Paper on Security Constrained Economic Dispatch of ISGS Pan India*. New Delhi. September 2018. https://posoco.in/download/consultation-paper-on-security-constrained-economic-dispatch-of-isgs-pan-india/?wpdmdl=19708.

Schweppe, F. C., Tabors, R. D., Kirtley, J. L., Outhred, H. R., Pickel, F. H., & Cox, A. J. (1980). Homeostatic Utility Control. IEEE Transactions on Power Apparatus and Systems, PAS-99(3), 1151–1163.

van der Veen, Reinier, and Rudi Hakvoort. "The electricity balancing market: Exploring the design challenge." *Utilities Policy* 43 (December 2016): 186–194. https://doi.org/10.1016/J.JUP.2016.10.008.

Appendix A: Data Sources for Figure 3

Alberta

Alberta Electric System Operator. "Guide to understanding Alberta's electricity market." Accessed August 6, 2019. https://www.aeso.ca/aeso/training/guide-to-understanding-albertas-electricity-market/.

Australia (WEM)

Economic Regulation Authority. "Rule Change: RC_2017_02." Accessed February 8, 2019. https://www.erawa.com.au/rule-change-panel/market-rule-changes/rule-change-rc_2017_02.

Austria

EPEX SPOT. "Intraday market with delivery on the Austrian TSO zone." Accessed August 6, 2019. https://www.epexspot.com/en/product-info/intradaycontinuous/Austria.

Belgium

EPEX SPOT Belgium. "EPEX SPOT CIM." Accessed August 6, 2019. https://www.belpex.be/trading-clearing/belpex-cim/.

California

California ISO (Independent System Operator). "Market processes and products." Accessed August 6, 2019. http://www.caiso.com/market/Pages/MarketProcesses.aspx.

Croatia

ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

Czech Republic

OTE. "Daily Market-Spot Market Index." Last modified August 20, 2019. http://www.ote-cr.cz.

Denmark

Nord Pool. "Price Development." Accessed August 6, 2019. https://www.nordpoolgroup.com/.

Estonia

Nord Pool. "Price Development." Accessed August 6, 2019. https://www.nordpoolgroup.com/.

Finland

Nord Pool. "Price Development." Accessed August 6, 2019. https://www.nordpoolgroup.com/.

France

EPEX SPOT. "Intraday market with delivery on the French TSO zone." Accessed August 6, 2019. https://www.epexspot.com/en/product-info/intradaycontinuous.

Germany

ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018.

https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

EPEX SPOT. "Intraday market with delivery on the German TSO zone." Accessed August 6, 2019. https://www.epexspot.com/en/product-info/intradaycontinuous/germany.

Nord Pool. "Price Development." Accessed August 6, 2019. https://www.nordpoolgroup.com/.

Hungary
Hungarian Power Exchange. "HUPX Intraday market." https://hupx.hu/en/product/id.

Iberian Peninsula (Portugal and Spain)
ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

OMI-Polo Español S.A. "Intraday Market." Accessed August 6, 2019. http://www.omel.es/en/home/markets-and-products/electricity-market/our-electricity-markets/intraday-market.

Ireland
Single Electricity Market Committee. *Quick Guide to the I-SEM*. https://www.semcommittee.com/sites/semc/files/media-files/ISEM quick guide_1.pdf.

Latvia
Nord Pool AS. "Price Development." Accessed August 6, 2019. https://www.nordpoolgroup.com/.

Lithuania
ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

Luxembourg
ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

Netherlands
EPEX Spot. "EPEX SPOT Intraday in the Netherlands." Accessed August 6, 2019. https://www.epexspot.com/en/product-info/intradaycontinuous/the_netherlands.

New Zealand
Electricity Authority. "Electricity Industry Participation Code Amendment (Shortened Gate Closure and Revised Bid and Offer Provisions) 2017." Accessed August 6, 2019. https://www.ea.govt.nz/code-and-compliance/the-code/amendments/2017-code-amendments/.

Norway
Nord Pool AS. "Price Development." Accessed August 6, 2019. https://www.nordpoolgroup.com/.

New York
NYISO (New York Independent System Operator). *Manual 12: Transmission and Dispatch Operations Manual*. July 2019. https://www.nyiso.com/documents/20142/2923301/trans_disp.pdf/9d91ad95-0281-2b17-5573-f054f7169551.

PJM
PJM. "PJM Real-Time Energy Market." October 2018. https://pjm.com/-/media/training/nerc-certifications/gen-exam-materials-feb-18-2019/training-material/02-generation/2-4-real-time-energy-market.ashx?la=en.

PJM. *PJM Manual 11: Energy and Ancillary Services Market Operations, Revision 106*. May 2019. https://www.pjm.com/-/media/documents/manuals/m11.ashx?la=en.

Poland
ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

Romania
ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

Singapore
Energy Market Authority. "Singapore Electricity Market Rules: Appendix 6A, Market Operations Timetable." January 2019. https://www.emcsg.com/f283,7867/Appendix_6A_Market_Operations_Timetable_1Jan19.pdf.

Slovakia
ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

Slovenia
ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

Sweden
Nord Pool AS. "Price Development." Accessed August 6, 2019. https://www.nordpoolgroup.com/.

Switzerland

EPEX SPOT. "Intraday market with delivery on the Swiss TSO zone." Accessed August 6, 2019. https://www.epexspot.com/en/product-info/intradaycontinuous/switzerland.

Turkey

Enerji Piyasaları İşletme A.Ş. "Spot Electricity Market: Phases." Accessed August 6, 2019. https://www.epias.com.tr/en/intra-day-market/phases.

United Kingdom

ACER and Council of European Energy Regulators. *Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017-Electricity Wholesale Markets Volume*. October 2018. https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/MMR 2017 - ELECTRICITY.pdf.

ELEXON. "Glossary Term: Gate Closure." Accessed August 6, 2019. https://www.elexon.co.uk/glossary/gate-closure/.

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