Ramp Capability Dispatch and Uncertain Intermittent Resource Output

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Rutgers Center for Research in Regulated Industries
Advanced Workshop in Regulation and Competition
31st Annual Western Conference
Hyatt Regency, Monterey, California, June 27-29, 2018

6-21-2018

Revised 7-17-2018

Abstract

Between 2011 and 2015 the MISO and California ISO developed the concept of ramp capability dispatch with the expectation that it could be used to reduce the cost of accommodating higher levels of intermittent resource output, while also improving the reliability of the transmission system. The introduction of ramp capability dispatch was expected to accomplish this by enabling better management of the ramp capability needed to balance variations in intermittent resource output. While the fundamental concepts underlying ramp capability dispatch are relatively simple, achieving the intended objective of reducing the cost of accommodating higher levels of intermittent output while maintaining historical levels of transmission reliability, depends on selection of appropriate values for some critical parameters and the workability of a number of implementation choices and compromises.

This paper does not discuss the details of the ramp capability dispatch model formulation which are discussed in many other papers, but instead focuses on explaining the operating challenges that motivated the development of ramp capability dispatch, then turns to a discussion of the initial efforts to address the ramp problem thru changes in real-time unit commitment decisions before turning to a discussion of how ramp capability dispatch design is expected to improve the ability of system operators to balance variations in intermittent resource output and key design choices that potentially impact the performance of ramp capability dispatch designs.

We then turn in Section VI to empirical analysis of the performance of the initial ramp capability designs. Both the MISO and California ISO implemented their ramp capability dispatch designs in 2016, so historical performance data are available to use in assessing the effectiveness of their implementation choices and to identify implementation problems. Because these designs are directed at better managing the response of the transmission system and generation resources to uncertain net load using a number of parameters to account for that uncertainty, it was anticipated that elements of

the initial designs and implementation choices would require adjustments based on operating experience. Now that these designs have been in operation for a year or more, we are able to assess performance, discuss the potential need for changes in the MISO and California ISO implementations and summarize the lessons learned for other ISOs facing similar operational challenges. This paper begins the process of reviewing the performance of ramp capability dispatch designs using publicly available data but also refers to the results of analyses by the MISO and California ISO which often draw upon additional non-public data. Essentially it it noteworthy that all of our empirical analysis is based solely on an analysis of publicly available interval level price data and thereby illustrates the ability of market participants and regulators to examine ISO performance in LMP markets using these price data.

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Executive Summary

The growth in intermittent electricity generation resources over the last several years has created new operational challenges for system operators in many regions. As intermittent generation resources become a substantial portion of the generation mix supplying energy, the net-load (load minus intermittent resource output) that system operators must meet by adjusting the output of dispatchable resources becomes more difficult to forecast accurately. The system operator must have enough dispatchable resources to balance not only predictable changes in load, interchange and scheduled generator output, but also to balance unpredictable variations in intermittent resource production.

The growth of intermittent generation means that system operators must at times accommodate thousands of megawatts per hour of variations in intermittent resource output. This paper examines the introduction of a new dispatch concept – called ramp capability dispatch -- to address system operators' need to have enough ramp capability available in real-time to balance both expected and unexpected variations in net load. It focuses on the conceptual design and results of the initial implementation of a ramp capability dispatch by two system operators -- CAISO and MISO -- focusing on lessons learned to date.

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[1] The authors are or have been a consultant on electricity market design, transmission pricing and/or market power for the entities listed in endnote A. The views presented here are not necessarily attributable to any of those entities and any errors are solely the responsibility of the author. This paper has benefitted from a discussion of these issues over the past several years with Dhiman Chatterjee, Navid Nivad, and Ryan Sutton of the Midwest ISO, Paul Gribik (now with PG&E but at the Midwest ISO during the initial development of the ramp capability dispatch concept), Lin Xu and Mark Rothleder of the California ISO, and Dr. Harvey's current and former colleagues on the California ISO Market Surveillance Committee, Ben Hobbs, James Bushnell and Shmuel Oren, as well as participants in a variety of stakeholder and industry meetings. In addition, Zach Campbell played a key role in carrying out the empirical analysis discussed in section VI.

The views expressed in this paper, however, reflect the views of the authors and do not necessarily reflect the views of any of the individuals listed above, nor do they necessarily reflect the views of the Midwest ISO, the California ISO nor the collective views of the California ISO Market Surveillance Committee, nor the views of any of the current or former clients listed in endnote A.

Both CAISO and MISO recognized early-on that increased intermittent resource production would require a sufficient quantity of generation resources capable of ramping up and down to be on-line to accommodate real-time net-load changes in the time frame of the 5 or 10-minute intervals of the real-time dispatch. They would need dispatchable capacity available to respond in the immediately upcoming interval, as well as in subsequent intervals, because difficult-to-predict net-load changes would also occur in future intervals.

Early experiences associated with accommodating increased ramping requirements driven by intermittent resource development led both the CAISO and MISO to introduce ramp capability dispatch (both upward and downward) in 2016. A ramp capability dispatch has a number of key design features: 1) price determination; 2) target quantity; and, 3) penalty price (i.e., the price at which the ramp capability target will not be met) which were included in the initial MISO and California ISO designs. Locational ramp requirements, which were not included in the initial MISO and California ISO designs, appear to be a necessary fourth design feature based on our assessment of the performance of the MISO and California ISO designs. In this paper we explain each of these design choices, and summarize the ramp capability product design choices made by the CAISO and MISO. In particular, we explain how the design choices for the CAISO and MISO depended on their use of a multi-interval (California ISO) or single-interval (MISO) real-time dispatch.

The focus of this paper in Section VI is on the performance of the ramp capability dispatch in the CAISO and MISO markets since implementation in 2016 and the lessons for other system operators assessing alternatives for managing increasing levels of intermittent resource output. A key finding in reviewing the initial performance data is that the price of ramp in the real-time dispatch has almost always been zero -- in over 99% of all dispatch intervals for the California ISO (6/1/2017 – 2/20/2018) and over 93% for the MISO (4/1/2017 – 4/30/2018). The implication of this finding is particularly striking for the California ISO. It indicates that the ramp capability dispatch design had no impact on the amount of ramp capability available in the California ISO real-time dispatch in over 99% of all dispatch intervals. The zero price means that no change in the dispatch occurred to maintain the target quantity of ramp set by the ramp capability design, so that there was no impact from implementing the ramping product. Hence, the design as implemented has contributed almost nothing to better balancing intermittent resource output in real-time. Moreover, our analysis shows that the ramp capability dispatch rarely had any impact on the ramp available in the intervals prior to when power balance violations actually occurred, resulting in upward price spikes in the California ISO real-time dispatch.

These disappointing findings are based on publicly available data. It is a more difficult to use publicly available data to determine why the ramping capability product implementations have been ineffective. In the case of the California ISO, system operator review over the last year of the anomalous relationship between ramping product price and power balance violations in subsequent intervals has identified a number of implementation errors. These errors involved the setting of the ramp target that caused the target to be set at or near zero in hours in which high ramp needs existed, accounting in part for the lack of impact of the flexiramp constraint on the real-time dispatch.

The limited amount of data available since these errors in the calculation of the California ISO ramp target were corrected show some decrease in the frequency of zero ramp prices in the real-time dispatch, but the improvement has not been very substantial and the price of ramp is still often zero in intervals prior to or during power balance violations. We are not aware of any issues with the ramp target in the MISO that would account for the frequency of zero ramp prices in the MISO.

In addition to the flawed implementation of ramp targets in the California ISO, another reason for the zero prices of ramp in the CAISO and MISO, even during periods in which there is not enough ramp capability available to balance load and generation in the real-time dispatch, appears to be the lack of locational ramp targets in the initial designs.

Hence, it appears that transmission constraints are frequently leading to outcomes in which the target level of ramp capability is available at a zero system wide ramp price, but the ramp capability is located on resources at constrained down locations at which the resource cannot be dispatched up to balance load and generation, even when power balance violations occur or spinning reserves must be used to balance load and generation. The implication we draw from this analysis of the early experience is that others seeking to use a ramp capability dispatch to balance variations in intermittent resource output should build some form of locational targets into the designs.

We provide background for this discussion of the ramping capability dispatch implementations in Sections II to V, which discuss the use of economic dispatch to increase the supply of ramp in the context of multiple interval optimization, the use of look-ahead resource commitment designs to increase ramp capability, and explain the ramp capability dispatch concept. These sections provide a foundation for understanding the analysis of the performance of the ramp capability dispatch designs in Section VI and the key design principles that must be addressed when implementing ramp capability dispatch.

In Section VI, in addition to discussing the performance of the initial designs, we summarize the ramp product penalty pricing used by the CAISO and MISO and explain the differences in the two approaches. We conclude this section with a discussion of a few additional ramp capability design issues that do not appear to be the source of California ISO and MISO ramp product performance issues, but that may need to be addressed as these designs evolve. These issues include the possibility that very high cost resources may be relied upon to provide ramp capability under current designs and that the dispatch of these resources could provide very limited production cost savings. Finally, we note that the current ramp product designs only set ramp capability for a five minute interval although it may be the case that ramp capability will be required on a sustained basis for several five minute intervals.

I. Introduction

The key time frame for managing variations in intermittent resource output is the time frame of the real-time economic dispatch, generally based on 5 or 10-minute dispatch instructions. The initial development of economic dispatch was based on single interval optimization in which the value of the objective function of the dispatch depended only on the cost of reliably meeting load in the current dispatch interval. With this single interval structure, the dispatch instructions sometimes do not result in the least overall cost dispatch for meeting both load in the current interval and meeting large predictable changes in net load in subsequent intervals, such as would occur during the morning load pickup or the evening load drop off, or due to large changes in scheduled net interchange.

Given this limitation of conventional single interval economic dispatch, operators have used, and continue to use, a variety of ad hoc mechanisms to manage the availability of ramp capability needed to balance load and generation during periods in which there are large predictable changes in load in future intervals. These mechanisms are discussed in Section II to provide context for the discussion of ramp capability dispatch.

As the limitations of these ad hoc approaches to managing ramp needs were recognized in the early 2000s, particularly by ISOs using markets to balance load and generation, some ISOs began to take another approach to managing such predictable future variations in net load. This approach has been to avoid the need for ad hoc operator actions by factoring expected changes in future load into the economic dispatch, optimizing the dispatch over multiple intervals instead of over a single interval, thereby reducing the need for the operators to manage these variations through ad hoc actions. This use of real-time economic dispatch to manage the supply of ramp available to balance load and generation in future intervals was a first step toward the development of the ramp capability dispatch concept. Section III explains how economic dispatch can be used to create additional ramp up or ramp down capability and discusses the design and features of these multiple interval optimization designs.

Using multiple interval optimization to optimize the dispatch over time to meet expected variations in net load can reduce the likelihood of small unpredictable variations in net load combining with predictable variations to create power balance violations in the real-time dispatch (or large increases in the cost of meeting load). However, this form of multi-interval optimization is likely to be of limited value in balancing variations in the output of intermittent resources because predictable changes in load and generation may be swamped by unpredictable changes in load net of intermittent resource output.

With rising levels of intermittent resource output in several U.S. ISOs after 2009, the difficulties in balancing variations in intermittent resource output led two of the U.S. ISO then most impacted by these rising levels of intermittent resource output to implement changes in their real-time unit commitment practices in an effort to maintain sufficient ramp capabiltiy to balance these variations in intermittent resource output (and other unexpected changes in load and generation in the real-time dispatch). Section IV discusses the impact of rising levels of intermittent resource output on the ability of the California ISO and MISO to balance load and generation in their real-time dispatch and the changes these ISOs introduced in their real-time unit commitment designs in an effort to maintain sufficent ramp capability, headroom constraints in the case of the MISO and the flexiramp constraint in the case of the CAISO. Section IV is focused on discussion of the flexiramp constraint implemented in the California ISO in December 2011, which was explicitly designed to enable better balancing of variations in intermittent resource output and was tested by the rising level of intermittent resource output in the California ISO over the 2011-2016 period. The discussion of the flexiramp constraint also explains why the initial flexiramp constraint design, which accounted for future interval ramp needs in unit commitment decisions but not in the real-time dispatch, limited the improvement in real-time balancing performance realized from this design, while increasing uplift costs.

The limitations of both single and multi-interval dispatch optimization in balancing variations in intermitent resource output and the limited effectiveness of accounting for future ramp needs in real-time commitent decisions but not in the real-time dispatch, led the MISO and California ISO to evaluate alternative dispatch concepts that go beyond conventional multi-interval optimization in order to better manage the reliability challenges posed by high levels of intermittent resource output. This investigation led to the concept of a ramp capability dispatch. The core features of a ramp capability dispatch are described in section V.

Section VI turns to a detailed discussion of some of the implementation challenges associated with key elements of a ramp capability dispatch design, including empirical analysis of the problems encountered by the MISO and CAISO with their initial implementations of a ramp capability dispatch. The analyses focus on issues relating to pricing, setting the ramp capability target, determining the capacity that meets the target and the determination of the value of ramp for use in the dispatch optimization. Section VII provides concluding observations.

II. Ad Hoc Approaches to Maintaining Ramp

Conventional economic dispatch minimizes the cost of meeting load in the current interval, without regard to system conditions in future intervals. This myopic single interval dispatch will not necessarily minimize the overall cost of meeting load when system conditions are changing rapidly and operators have used, and continue to use, a variety of ad hoc mechanisms to manage the availability of ramp capability needed to balance load and generation during periods in which there are large predictable changes in load in future intervals. One method used to increase the available ramp capability is to dispatch slow ramping units up out of merit prior to the beginning of an expected rapid rise in load, moving them to a higher output, and perhaps also dispatching fast ramping units down out of merit in preparation for the upcoming rapid load increase, while letting the remaining units be managed by the economic dispatch. All of these units would be available to be dispatched up when the rapid load pickup occurs.

This ad hoc approach can work reasonably well for managing morning and evening load changes in a cost based dispatch, because the system operator will be able to predict the changes in load and will able be able to observe through trial and error over time which units make good choices for being dispatched out of merit in this manner without creating other problems. This kind of ad hoc approach will work less well in a market based dispatch in which taking units out of merit may have financial impacts and if predictable, such an ad hoc approach may affect the prices at which resources are offered. Such an ad hoc approach will also not work well when the need for ramp capability arises from unpredictable variations in intermittent resource output.

Another method used to maintain additional ramp capability within the limits of conventional single interval economic dispatch is for the operators to adjust[2] the load forecast in the real-time economic dispatch so that on dispatch generation is dispatched to a higher level than needed to meet actual load, with regulating resources backed down to balance load and generation. If the regulating resources are fast moving, capacity constrained resources, such adjustments to the load forecast can create additional regulation capability that can be used to balance load and generation when load begins to rise rapidly. However, if the economic dispatch sets price in a market based electric system, this approach may result in artificially high energy prices when the load forecast is increased to create ramp capability. Moreover, such an adjustment to the load forecast may not provide additional ramp capability if the output of the regulating resources is ramp constrained, rather than capacity constrained.

The limitations of single interval optimization and the ad hoc methods historically used to take account of future conditions in managing ramp availability led some ISOs to develop

[2] This is sometimes referred to as "biasing" the load forecast. See, for example, the disucssion in the Direct Testimony of Joseph Gardner in the MISO filing in FERC Docket ER14-2156 October 31, 2014, pp. 11-12.

more systematic approaches to managing ramp, multi-interval optimization, implemented for the first time in 2004, and ramp capability dispatch, implemented for the first time in 2016. These innovations are not alternatives, their use can be combined (as has been done by the California ISO) or not (as is the case in the MISO with a ramp dispatch but no multiple interval optimization, or the NYISO with multi-interval optimization but no ramp capability dispatch.)

III. Multiple Interval Dispatch Optimization

As the limitations of single interval optimization and the ad hoc methods historically used to take account of future conditions in managing ramp availability were recognized in the early 2000s, particularly by ISOs using markets to balance load and generation, several North American ISOs developed a more systematic approach to managing ramp, multi-interval optimization, implemented for the first time in 2004. Multi-interval optimization in the real-time dispatch seeks to avoid the need for ad hoc operator actions by factoring expected changes in future load into the economic dispatch.

Because these multiple interval optimization dispatch designs minimized the cost of meeting load over the dispatch horizon, rather than over a single interval, the software optimization could, and would, at times dispatch resources out of merit in the current interval in order to have additional ramp available in subsequent intervals when the ramp capability would be needed to meet large changes in load, net scheduled interchange or generator output.

This potential to dispatch system resources so as to increase the supply of ramp capabiltiy that would be available in future intervals exists because the ramp capability available on an electric system at any point in time depends on the ramp rates of on-line units at their current operating point and on the upper or lower operating limits of the resources. Resources that have been dispatched to their upper limit have no upward ramp capability, regardless of their nominal ramp rate. Similarly, resources that have been dispatched down to their lower limit have no available downward ramp capability, regardless of their nominal ramp rate. If the ramp up or down available on the system has been reduced by the dispatch of resources to their upper or lower limits, additional ramp capability can be made available for use in future intervals by dispatching capacity limited resources out of merit either below their upper limit (to maintain up ramp capability) or above their lower limit (to maintain down ramp capability).

If resources are dispatched down out of merit below their upper limit so that they have ramp up capability available for the next dispatch interval that would not be available in a pure economic dispatch, their reduction in output in the current dispatch interval must be replaced with higher output from other higher cost generation whose ramp capability is not capacity constrained.[3] This out of merit dispatch will raise real-time power prices and raise the cost of meeting load in the current interval, because lower cost generation will be replaced with higher cost generation. This substitution of high cost for low cost generation could nevertheless be economic on a production cost basis over an optimization horizon longer than the current interval if the availability of the additional ramp in the next interval would either avoid the need to dispatch generation with very high offer prices, avoid potential power balance violations with high reliability costs (reflected in high penalty prices in the dispatch) or avoid shortages of spinning reserves or regulation with high reliability costs in future intervals.

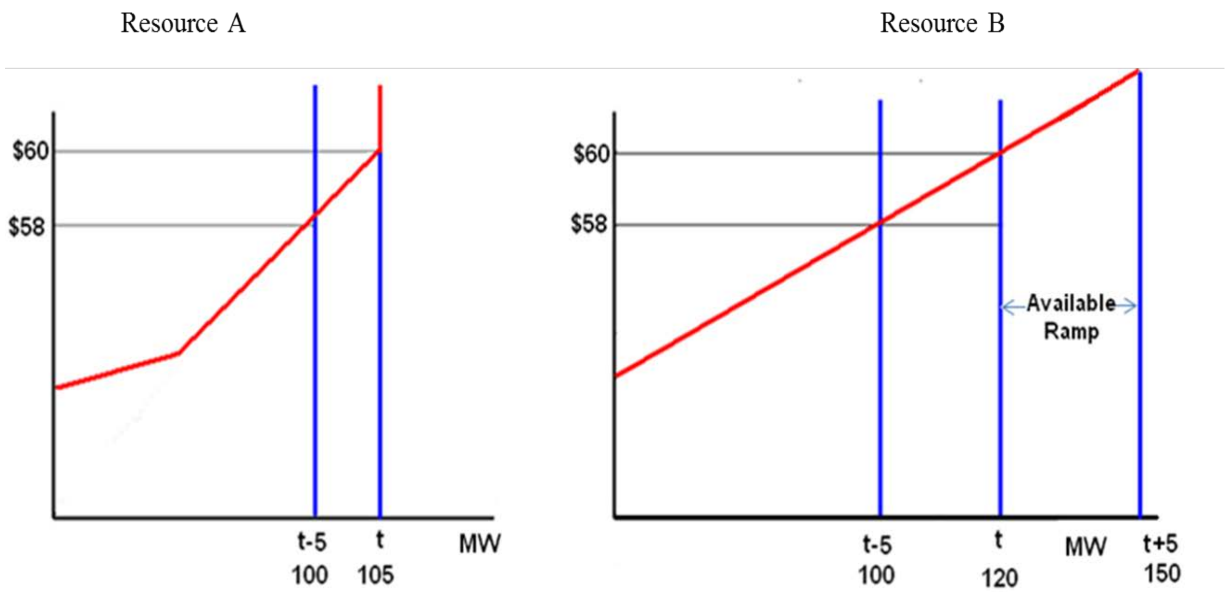
This substitution is illustrated in a very simple two resource context in Figures III-1 and III-2. In Figure III-1 Resource A has a 1 megawatt per minute ramp rate and is dispatched to its upper limit (105 megawatts) in the interval ending at t, with its incremental cost of $60 per megawatt hour equal to the price at its location. Because Resource A is dispatched to its upper limit in the interval ending at t, it has no upward ramp capability available for the next dispatch interval ending at t+5. When Resource A is dispatched to its upper limit, its upward ramp capability is said to be capacity constrained, rather than

[3] These would be generators whose undispatched capacity exceeds their ramp capability.

ramp constrained, because it could not provide additional energy in interval t+5 no matter how high its ramp rate.

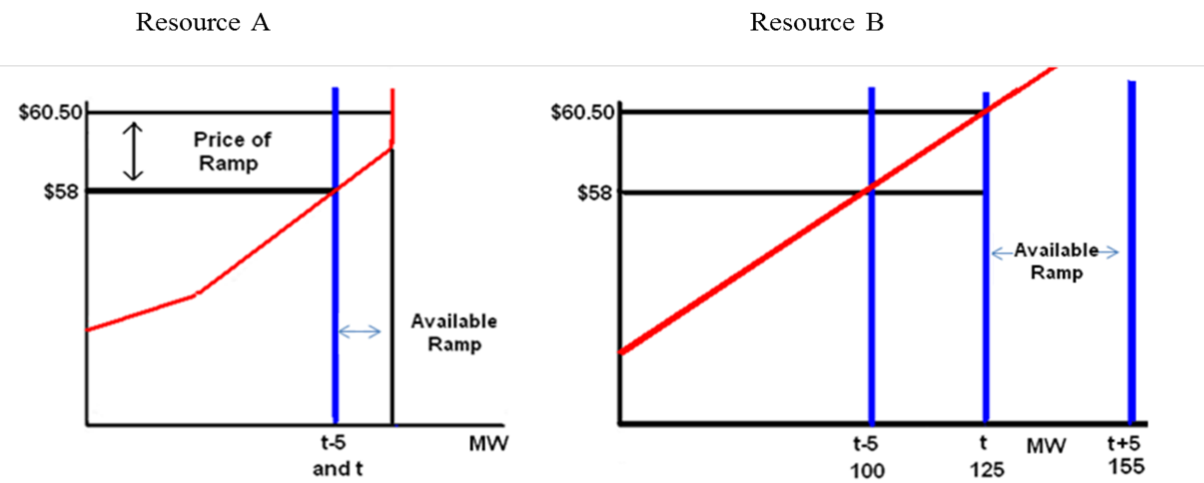
In the example, Resource B has a ramp rate of 6 megawatts per minute and is dispatched up 20 megawatts in the interval ending at t, with its incremental offer of $60, also equal to the price at its location. Because the upper capacity limit of Resource B is 200 megawatts, its ramp capability for the interval ending at t+5 is constrained by its ramp rate (30 megawatts over 5 minutes), not by its upper capacity limit.

Figure III-1
Conventional Dispatch
30 Megawatts Upward Ramp Available t to t +5



If the system needed to have sufficient ramping capability available to meet changes in net load greater than 30 megawatts in the interval starting at t and ending at t+5, real-time dispatch utilizing multiple interval optimization could create additional ramp capability by dispatching Resource B higher on its offer curve (to $60.5 per megawatt hour) in the interval ending at t, instead of dispatching Resource A to its upper limit in this interval as shown in Figure III-2. As a result of dispatching Resource B up in this manner, the cost of meeting load in the current interval would rise, because generation costing $60 or less per megawatt hour would be replaced with generation costing up to $60.5 per megawatt hour. In market based systems such a dispatch would cause the real-time price to rise to $60.5 per megawatt hour because this is the marginal cost of the last increment of supply dispatched to meet load. However, there would be 35 megawatts of upward ramp available for the interval ending at t+5, instead of only 30 megawatts. This out of merit dispatch for the interval ending at t would be efficient overall if the expected value of the additional ramp capability in future dispatch intervals exceeded the cost of the out of merit dispatch required to produce it.

Figure III-2
Ramp Dispatch
35 Megawatts Upward Ramp Available t to t +5



For example, if the projected change in net load for the interval t+5 to t+10 were greater than 30 megawatts and a $1000 per megawatt cost were attached to a power balance violation, a dispatch utilizing multiple interval optimization would find it economic to incur some out of merit dispatch costs in the current interval in order to have enough ramp up capability to balance load and generation in the future interval. In the two unit example above, the ramp capability dispatch only creates 5 megawatts of additional ramp capability, which would have only a small impact on current or future system conditions. However, if a real-time dispatch utilizing multiple interval optimization were applied across a transmission system as broad as that dispatched by the New York ISO, MISO or

California ISO, the multiple interval optimization could potentially dispatch hundreds of megawatts of generation up or down in the current dispatch interval and create hundreds of megawatts of additional ramp capability for use in future dispatch intervals.

Conversely, additional downward ramp capability can be created in a dispatch using multiple interval optimization by dispatching generation that is at its lower operating limit (and that hence could not be dispatched lower in the next interval) up out of merit above its lower limit in the current interval, and dispatching other generation that is lower cost and operating above its lower limit down to balance load and generation. This substitution raises the total cost of meeting load in the current interval, and lowers the real-time energy price in the current period,[4] but provides additional downward ramp capability for use in balancing load and generation in future dispatch intervals.

The potential for the availability of additional downward ramp capability to improve market performance is illustrated in Figures III-3 and III-4. Figure III-3 illustrates a conventional single interval dispatch when load falls by 25 megawatts between t-5 and t. Resources A and B are dispatched down to $24 on their offer curves. Since resource A's incremental offer cost above its minimum load level exceeds $24 per megawatt hour, resource A is dispatched down to its minimum load. This dispatch has the effect that while there would be 30 megawatts of downward ramp available on resource B in the interval t to t+5, no downward ramp would be available on resource A. If load were projected to fall by more than 30 megawatts in the interval t+5 to t +10, the system operator could be required to use its regulating capacity to balance this projected change in load and generation, leaving less regulation available to balance downward variations within the dispatch interval, or might need to dispatch down other resources with extreme negative offer prices.

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[4] The imposition of the ramp capability target causes the price of power to fall because when capacity constrained generation is dispatched up out-of-merit above its minimum load point to provide additional ramping capability, ramp constrained generation is dispatched down to balance load and generation. Hence, incremental load is met with lower cost generation than would be the case absent the ramp constraint.

Figure III-3
Conventional Dispatch
30 Megawatts Downward Ramp Available t to t +5

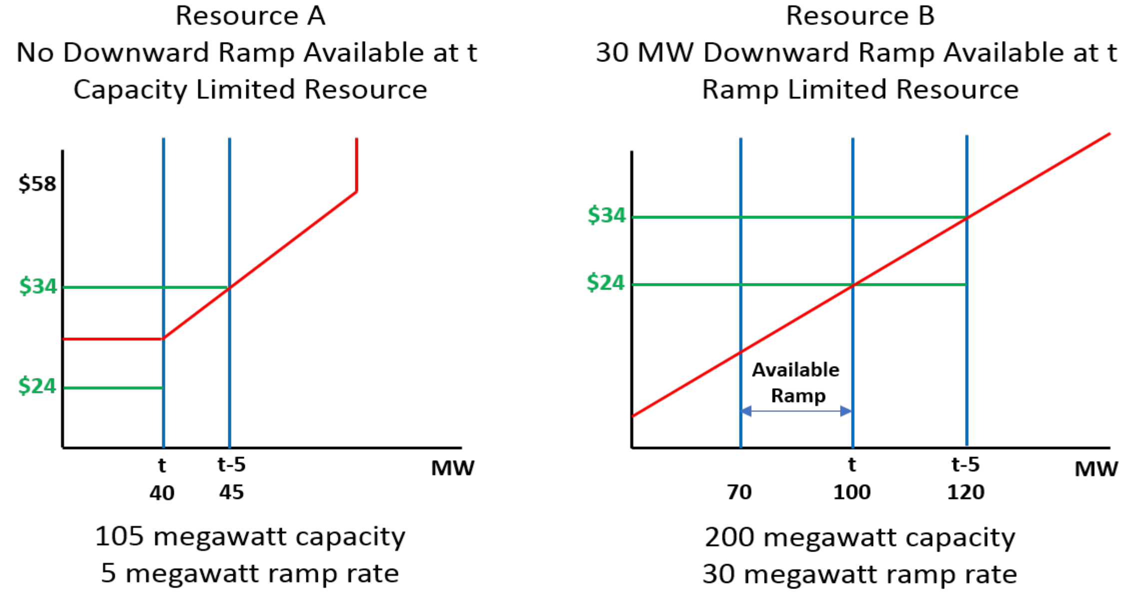
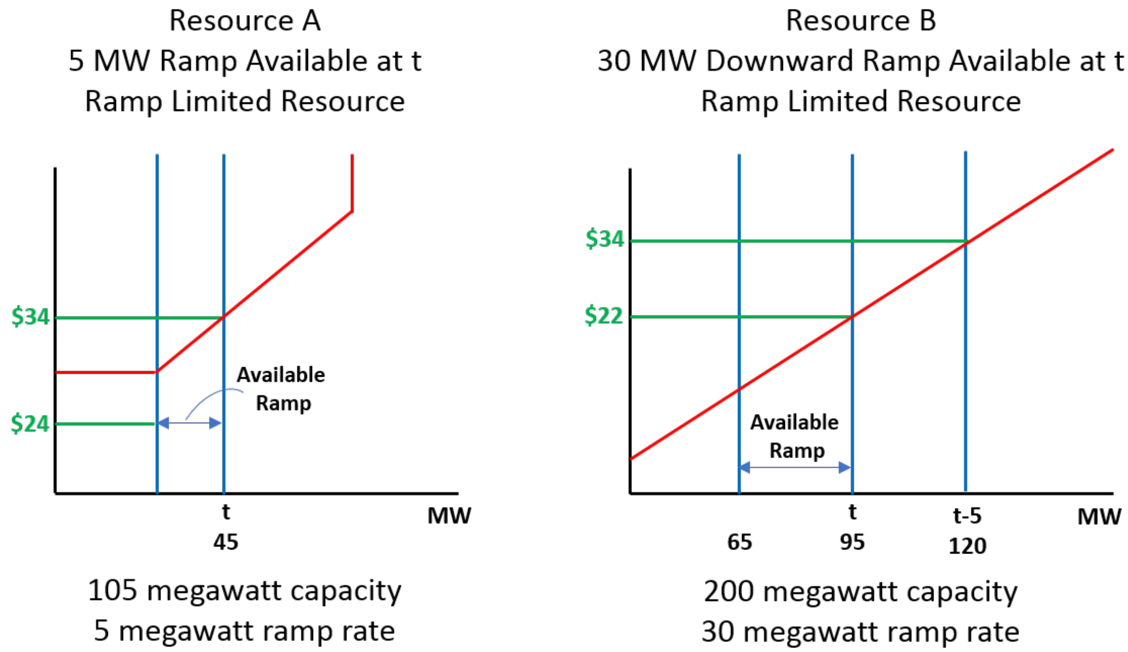


Figure III-4 portrays a multiple interval dispatch to meet a projected need for downward ramp of 35 megawatts in interval t+5 to t+10. Instead of dispatching resource A down to its minimum load, leaving no downward ramp available on resource A at the end of interval t, resource B is dispatched down to 95 megawatts, at an incremental cost of $22 per megawatt hour, and resource A continues to generate 45 megawatts, at a cost of $34 per megawatt hour. This out of merit dispatch at the margin uses output with a cost of $34 per megawatt hour to replace generation with an incremental cost of $22 per megawatt hour. However, this dispatch could be economic if load were projected to fall by 35 megawatts or more in the interval from t+5 to to t + 10 and balancing load and generation in this future interval would otherwise require curtailment of output offered at very negative offer prices.

Figure III-4
Ramp Dispatch
35 Megawatts Downward Ramp Available t to t +5



There can also be a potential to use redispatch to create additional ramp capability on resources that are ramp constrained, if the resources have ramp rates that vary materially based on the output range to which they are dispatched. If the economic dispatch would place such a resource in an operating range in which it has a relatively low ramp rate, dispatching it out of merit to an operating point at which it has a higher ramp rate could raise the total ramp capability available to balance load and generation. This is most commonly the case for resources that have very low upward ramp rates when dispatched down to or near their minimum operating point, but have a higher ramp rate if dispatched to a somewhat higher output. In this circumstance, the units on which the additional ramp is created would be dispatched up out of merit, and other units would be dispatched down, so the real-time price would fall, the total cost of meeting load in that interval would rise, but more upward ramp capability would be available to meet load at lower cost in subsequent intervals.

This potential for out of merit dispatch to create additional upward ramp is illustrated in Figures III-5 and III-6. Figure III-5 shows a conventional economic dispatch in which resource A has been dispatched down to its minimum load because its incremental cost at minimum load ($30 per megawatt hour) exceeds the incremental cost of power on resource B ($24 per megawatt hour). When at minimum load, however, resource A can only ramp up 1 megawatt over 5 minutes, so the total upward ramp available to the system operator is only 31 megawatts.

Figure III-5
Conventional Dispatch
31 Megawatts Upward Ramp Available t to t +5

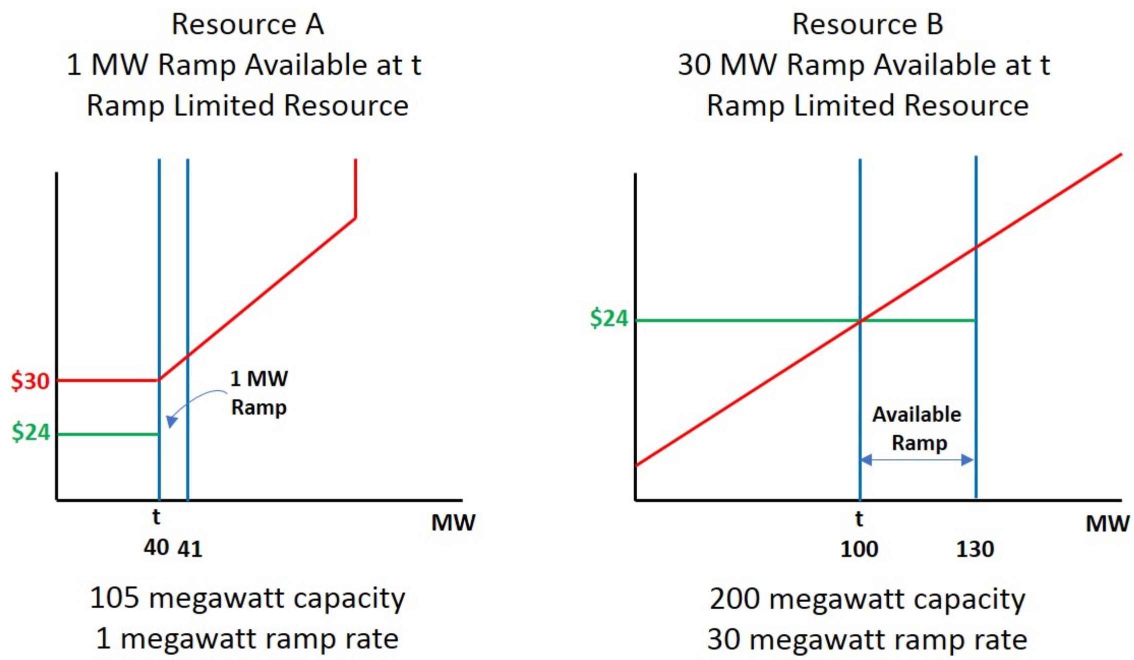
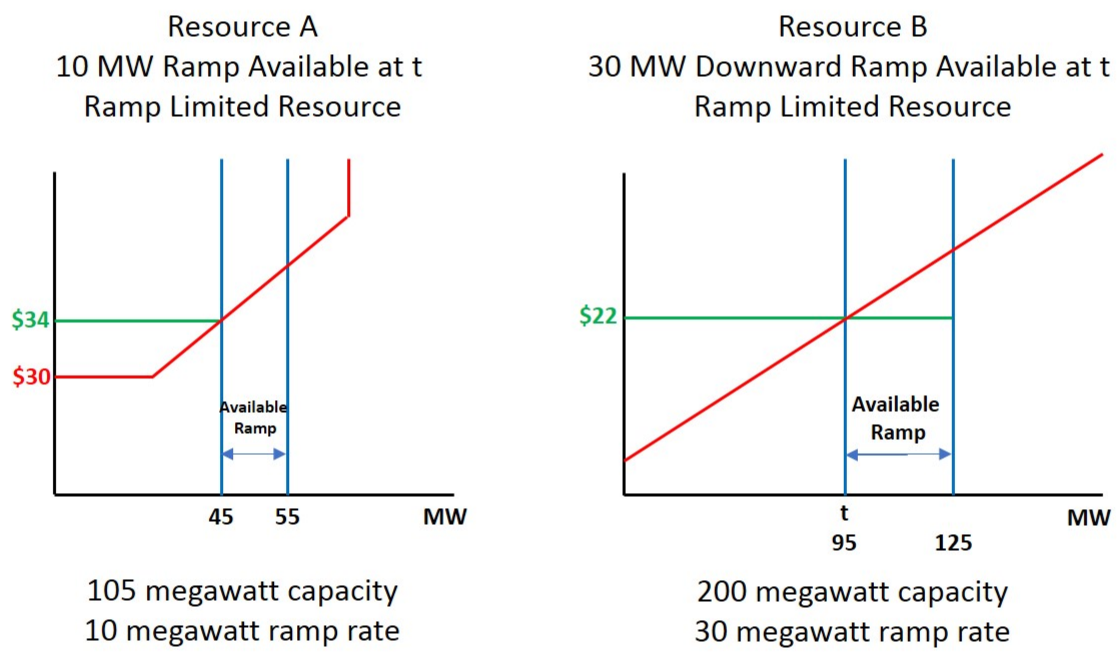


Figure III-6 shows the dispatch based on a multiple interval optimization in which resource A has been dispatched up to 45 megawatts as at that output level its ramp rate is 10 megawatts over 5 minutes, while resource B has been dispatched down to 95 megawatts at an incremental cost of $22 per megawatt hour. At the margin this dispatch is replacing generation with an incremental cost of $22 with generation having an incremental cost of $34, but the available ramp has been increased from 31 megawatts to 40 megawatts. Hence, this dispatch might be optimal from an overall reliability/economic perspective if net load was forecast to rise by more than 31 megawatts in the next dispatch interval.

Figure III-6
Ramp Dispatch
40 Megawatts Upward Ramp Available t to t +5



In 2004, the Ontario IESO was the first ISO to implement a form of multi-interval optimization that could take account of projected future changes in load in its real-time dispatch in 2004. The IESO design optimized the dispatch over the current interval and 4 operator designated periods over the next hour.

The New York ISO was the next to implement multi-interval optimization in its real-time dispatch in 2005. This dispatch looks out 50 to 60 minutes in a combination of 5 minute and 15 minute intervals, with 5 minute intervals for the current quarter hour period (which could include 1, 2 or 3 remaining dispatch intervals), and 15 minute intervals for the remainder of the hour. This design can have from four to six intervals over which the dispatch is optimized. Because the NYISO multiple interval optimization design is looking out over the next 15 to 60 minutes using various combinations of 5 and 15 minute intervals, it has a limited ability to identify and manage ramp constraints due to even predictable variations in net scheduled interchange or net load over a five minute time frame. This multiple interval dispatch design is likely to only identify ramp constraints in future intervals if they would bind over a 15 minute period.

The California ISO introduced the most sophisticated multiple interval optimization in April 2009. The California ISO design looks forward over 12 5 minute intervals. Because it is looking out a full hour in 5 minute increments, it is able to dispatch the system to make additional up or down ramp available to meet predicted variations in net load on a 5 minute basis, but only to the extent that it can foresee the need for adiditional ramp capability.

Other North American ISOs, particularly MISO and ERCOT have considered the implementation of similar dispatch designs but none have implemented such a design since the CAISO in 2009. [5] This is in part because the implementation of ramp capability dispatch may be a better way to manage ramp needs in markets with increasing levels of intermittent resource output.

Multi-interval optimization uses load forecasts for the current and some number of future intervals to calculate the optimal dispatch for the current interval, taking account of the cost of meeting load in future dispatch intervals, as well as the cost of meeting load in the current dispatch interval. This design is similar to the operation of multi-hour optimization in day-ahead markets, except that in the real-time dispatch only the prices and quantities for the first interval of the multi-interval optimization are used for settlements. Because the forecast of system conditions in future intervals is less certain

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[5] The market monitor for the Midwest ISO recommended for several years that the Midwest ISO implement such a multi-interval optimization but this recommendation was dropped in 2013, replaced with a recommendation to develop a ramp capability dispatch design. See Potomac Economics 2013 State of the of the Market Report for the MISO Electricity Markets, June 2014, p.84-85, Potomac Economics 2012 State of the of the Market Report for the MISO Electricity Markets, June 2013, p.79, 2011 State of the Market Report for the MISO Electricity Markets, June 2012, p. 64; 2010 State of the Market Report for the MISO Electricity Markets, June 2011, p. xxvi; 2009 State of the Market Report for the Midwest ISO, p. xxiii.

than the forecast for the current interval, multi-interval optimization may use different weights in the objective function for the cost of meeting load in the current and each future interval. [6]

These forward looking multiple interval dispatch designs can potentially avoid or reduce the frequency and magnitude of power balance violations due to limited ramp capability available to meet rapid changes in non-dispatchable generation (such as changes in the output of intermittent resources) or in load (including variations due to changes in the output of behind the meter generation not predictable by, or perhaps even visible to, the system operator) and reduce the frequency of real-time ramp capability driven price spikes. However, these multi-interval dispatch designs can achieve these goals only to the extent that the rapid changes in load or non-dispatchable generation can be foreseen in the multiple interval optimization. A forward looking multiple interval optimization dispatch design is therefore most useful for managing predictable changes in load (such as the morning ramp up or evening ramp down) or predictable changes in supply (such as pump storage units going on or off line or large changes in scheduled net interchange).

A consideration in evaluating the implementation of multi-interval optimization is that it increases the solution time for the real-time dispatch software, which in turn increases the time lag between the time the dispatch software is initialized based on then current system conditions and when dispatch instructions are sent to resources. Increases in time lag or latency in the data used for the real-time dispatch can contribute to difficulties in balancing load and generation when load or generation are changing unpredictably.

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[6] The New York ISO objective function applies the same weights to all of the dispatch intervals included in the multi-interval optimization, which in effect reduces the weight of the future 15 minute intervals relative to the immediate 5 minute intervals. The IESO has an explicit formula which reduces the weight placed on intervals further in the future while the CAISO uses the same weights for all intervals included in the multi-interval optimization.

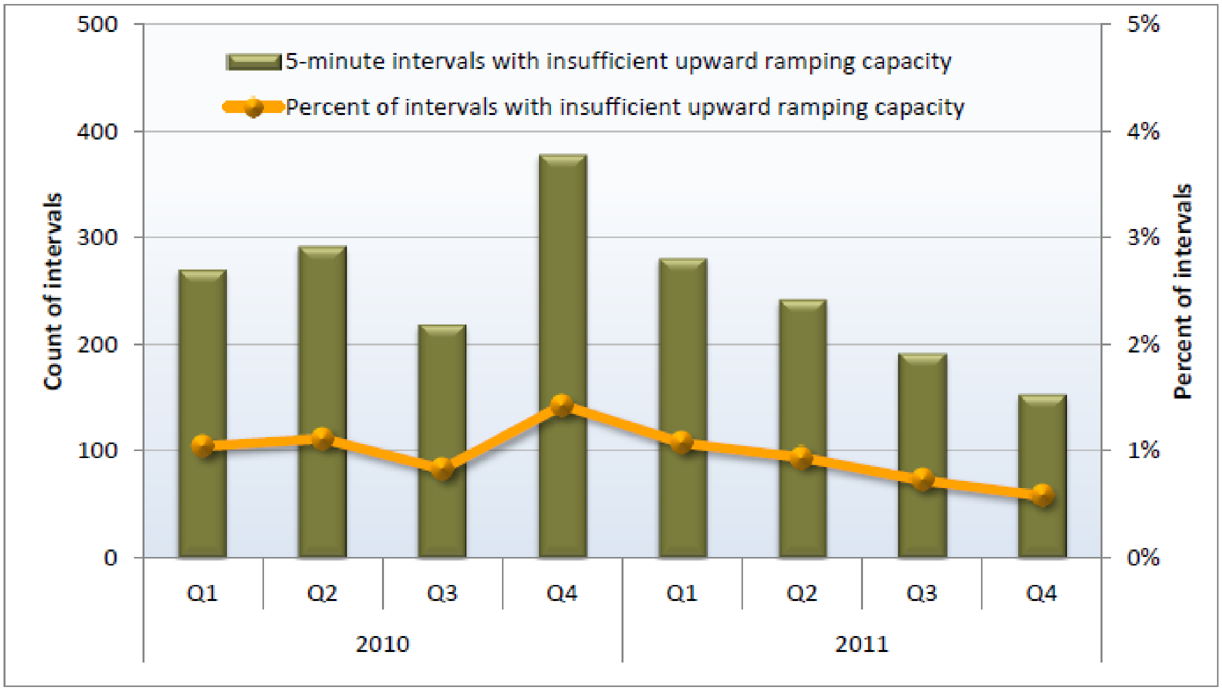
IV. Balancing Intermittent Resource Output and the Need for Ramp Capability

A. Balancing Load and Generation

Rising levels of intermittent resource output in the MISO and California ISO after 2009 created challenges for the system operators in balancing load and generation in real-time, first in the time frame of the five minute interval of the real-time dispatch and second in using regulation to balance load and generation on a 6 second basis. The key problem has generally not been the lack of enough capacity to compensate for real-time decreases in intermittent resource output but rather the inability of the available on dispatch capacity to ramp up or down fast enough to balance variations in net load within the time frame of the 5 minute dispatch. Additional regulating capacity is available to balance changes in net load that cannot be balanced by on dispatch generation within the time frame of the five minute dispatch, but the use of regulating capacity to balance variations that cannot be met within the five minute dispatch leaves less regulating capacity available to balance changes in net load within the dispatch interval and creates an increased potential for significant differences between load and generation at the control area level.

California ISO Department of Market Monitoring calculations indicate that during 2010 and 2011 the California ISO experienced around 200-300 intervals a quarter in which there was insufficient upward ramp available to balance load and generation within the time frame of the 5 minute minute dispatch as shown in Figure IV-1. This amounted to only around 1% of all intervals during the quarter but nevertheless meant that there were essentially 15-20 hours a quarter in the which California ISO could not balance increases in net load within the 5 minute dispatch, leaving the imbalance to be met with regulation.

Figure IV-1
Power Balance Violations in RTD due to Insufficient Upward Ramp Capability
California ISO 2010-2011



Source: 2011 Annual Report on Market Issues & Performance, California ISO, Department of Market Monitoring, April 2012 figure 3.2 page 66.[7]

There was a similar inability to dispatch flexible generation output down fast enough to balance load and generation when intermittent resource output rose rapidly, as portrayed in Figure IV-2.

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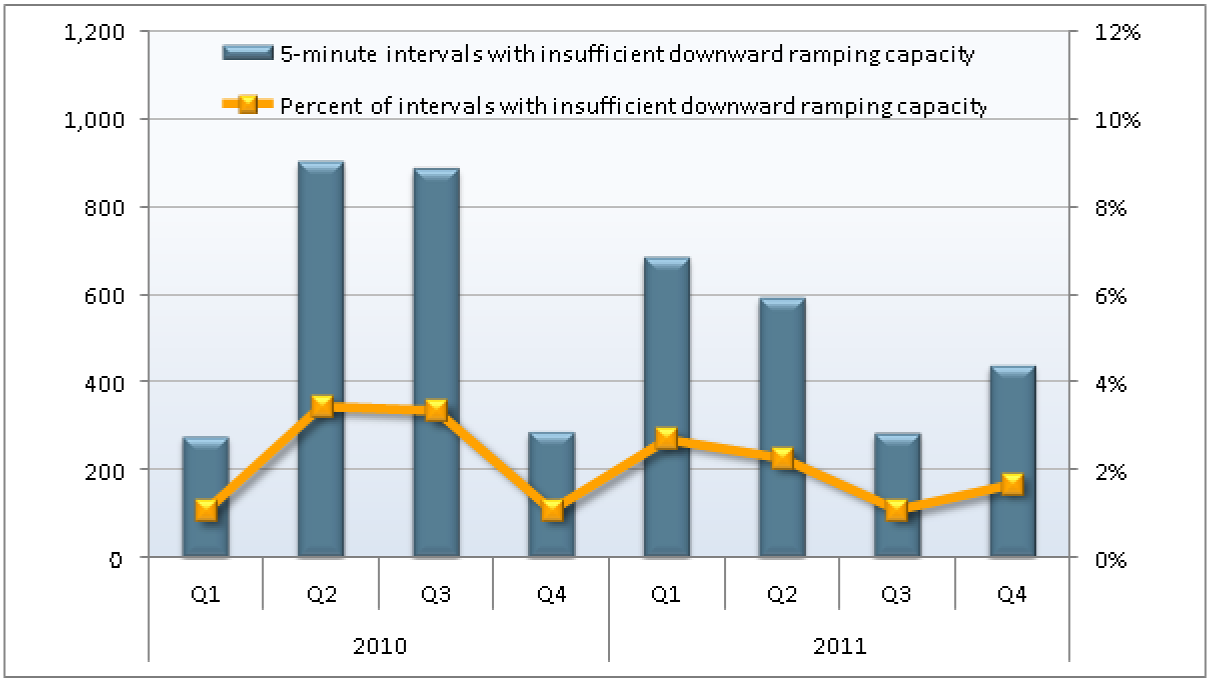
7 The percentages in this figure are not correct. The right axis should be labeled, .4%, .8%, 1.2% etc, rather than 1, 2, and 3%.

Figure IV-2
Power Balance Violations in RTD due to Insufficient Downward Ramp Capability
California ISO 2010-2011



Source: 2011 Annual Report on Market Issues & Performance, California ISO, Department of Market Monitoring, April 2012 figure 3.3 page 66.[8]

Under the California ISO MRTU market design, the price is set to the price cap whenever it is not possible to balance load and generation within the 5 minute dispatch, The price cap was $250 at MRTU start up in April 2009 but then rose $500 later in 2009, to $750 in early 2010 and to $1000 in early 2011 these power balance violations were causing prices to spike to $1000 at California ISO load zones (LAPS), as shown in Figure IV-3.

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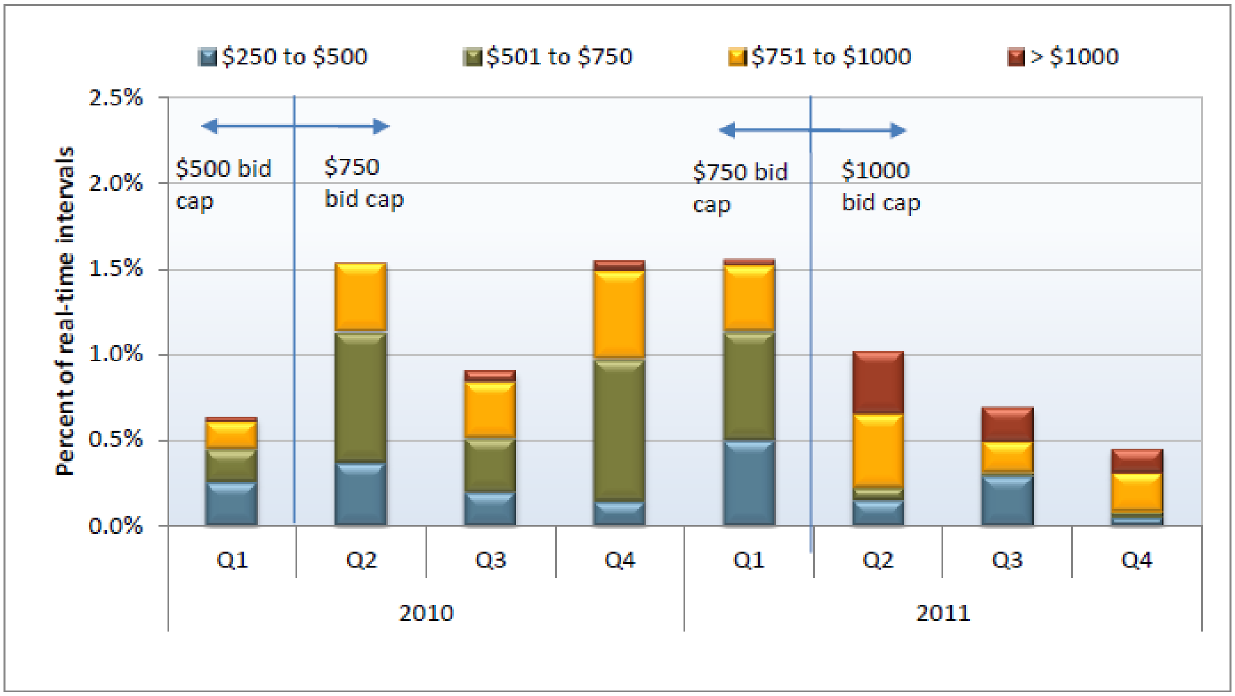
8 The percentages in this figure are not correct. The right axis should be labeled, .8%, .1.6%, 2.4% etc, rather than 1, 2, and 3%.

Figure IV-3
Real-Time Price Spike Frequency by Quarter-
California ISO 2010-2011



Source: 2011 Annual Report on Market Issues & Performance, California ISO, Department of Market Monitoring, April 2012 figure 2.9 page 58.

During this period, ramp constraints in the MISO did not result in power balance violations, instead the MISO relaxed the spinning reserve requirement in its 5 minute dispatch when necessary to balance load and generation. Ramp constraints that prevented balancing load and generation in the 5 minute dispatch therefore showed up as shortages of spinning reserves. The market monitor reported that these spinning reserve shortages were present in a little over 1.1% of all intervals in 2010 and about.77% of all intervals in 2011. [9] The MISO's inability to balance load and generation at this point in time was not primarily due to variations in the output of intermittent resources, instead,

[9] See Potomac Economics, 2010 State of the Market Report for the MISO Electricity Markets, June 2011 Figure 34 p. 55; 2011 State of the Market Report for the MISO Electricity Markets, June 2012, Figure A36 p. A-53.

large unpredictable changes in net scheduled interchange and in non-conforming industrial load played a larger role. [10]

The California ISO and MISO took a number of steps to improve their ability to balance load and generation in real-time over this period. For example, the MISO introduced wind dispatch on June 1, 2011,[11] both ISOs attempted to remove potential incentives for flexible resources to self-schedule or limit their dispatch range, and the MISO improved real-time price formation with the introduction of the demand curve for spinning reserves on May 1, 2012.[12]

The California ISO and MISO also began to evaluate the potential for changes in the economic dispatch in order to provide more ramping capability.[13] The first step in implementing changes in the economic dispatch was the implementation of a constraint in the California ISO's real-time unit commitment process, which came to be referred to in California ISO Stakeholder documents and FERC filings as the Flexiramp Constraint.[14]

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[10] See Potomac Economics, 2010 State of the Market Report for the MISO Electricity Markets, June 2011 pp. 44-50; 2011 State of the Market Report for the MISO Electricity Markets, June 2012, Figure pp. A-46-A48.

[11] See MISO November 1, 2010 Filing in Docket ER11-1991 and Potomac Economics, 2011 State of the Market Report for the MISO Electricity Markets, June 2012 p. 36.

[12] See MISO March 1, 2012 filing in Docket ER12-1185, Potomac Economics, 2012 State of the Market Report for the MISO Electricity Markets, June 2013 p. 31.

[13] See California ISO, Department of Market Monitoring, "Draft White Paper on Over-Supply and Shortage of Downward Ramping Supply in Off Peak Hours, January 14, 2011; California ISO, "Flexible Ramping Constraint," Technical Bulletin, April 19, 2011; California ISO, "Opportunity Cost of Flexible Ramping Constraint, Issue Paper & Straw Proposal," June 24, 2011; Nivad Navid, Gary Rosenwald and Dhiman Chatterhee, MISO, "Ramp Capability for Load Following in the MISO Markets, " July 15, 2011 Version 1.0; Midwest ISO, "Load Following Conceptual Design," Market Subcommittee, June 1, 2010.

[14] The ramp constraint in the real-time dispatch is referred to as the flexiramp product.

B. Committing Capacity to Maintain Ramp

A first step towards the implementation of a ramp capability dispatch was the implementation of a “flexiramp constraint” in the California ISO’s look-ahead unit commitment program, RTPD. This design was implemented in December 2011.[15]

RTPD is a forward looking program (sometimes called RTUC) very similar to the New York ISO’s RTC, that looks forward in 15 minute increments and is used by the California ISO to commit quick start units and schedule interchange. The intent of the flexiramp constraint design was that by including an upward ramp capability target in the RTPD forward evaluations, RTPD would commit additional generation to provide more ramp capability when this ramp capability was likely to be needed.[16] The flexiramp constraint only evaluated the future need for upward ramp capability.

The flexiramp constraint design had two key parameters that governed the incremental commitment of generation and scheduling of interchange. These were the target level of ramp capability for future intervals and the penalty price for an inability to meet this target. The ramp targets used for the initial implementation of the flexible ramping constraint over the period from December 2011 thrugh March 2015 were static values set for each hour based on an off-line analysis of historical data, but subject to real-time adjustment by California ISO operators. The ramp targets were changed seasonally or when system conditions appeared to change.[17] For example, during 2013, the flexible ramping constraint target was set by California ISO operators in real-time with a

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[15] See California ISO October 7, 2011 filing in Docket ER12-50.

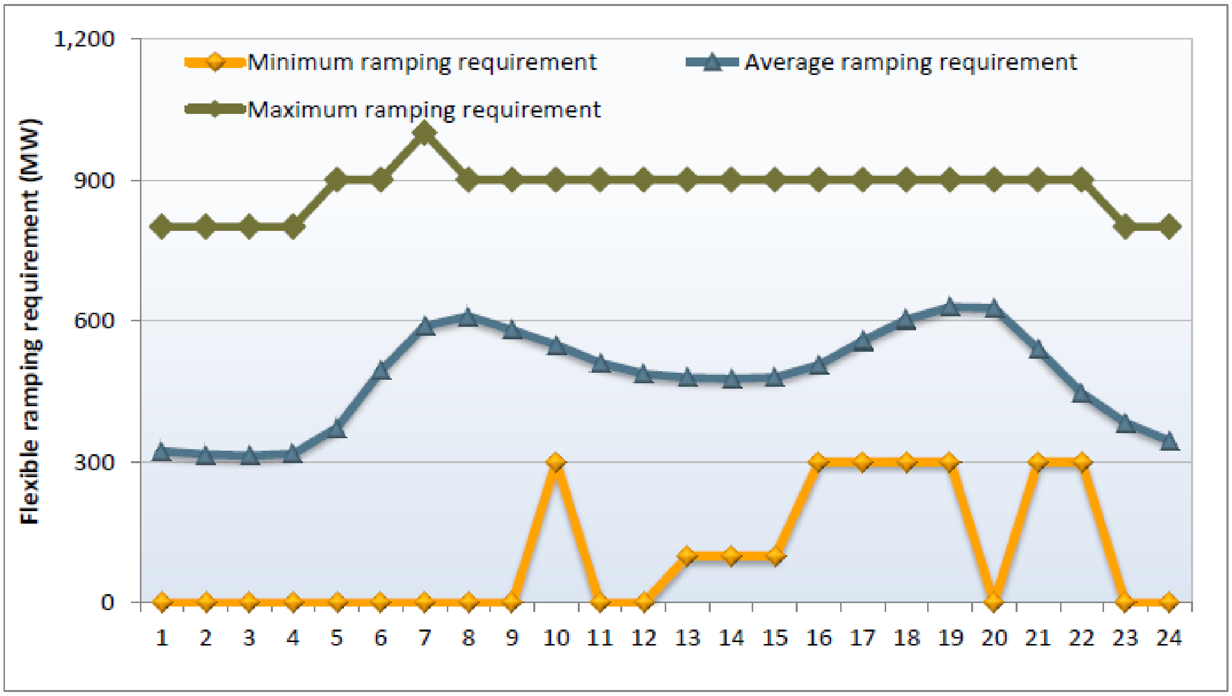
[16] See California ISO Filing letter in Docket ER12-50, California ISO Filing letter in Docket ER15-50, October 6, 2014 pp 3-5, and California ISO, “Opportunity Cost of Flexible Ramping Constraint, Draft Final Proposal” July 20, 2011.

[17] See, California ISO Filing letter in Docket ER12-50 p. 5, Warren Katzenstein, California ISO, “Flexible ramping constraint discussion,” Market Surveillance Committee Meeting, February 11, 2016.

maximum level of 900 megawatts [18] and a default target of 300 megawatts. [19] In practice, the upward ramp target was sometimes set to zero in the early morning hours.

Figure IV-4 below shows the California ISO's Department of Market Monitoring's portrayal of the range of target values used for the flexiramp constraint during 2013.

Figure IV-4
Flexible Ramping Constraint Procurement Targets
2013



Source 2013 Annual Report on Market Issues and Performance, California ISO, Department of Market Monitoring, April 2014 Figure 3.8, p. 94

The other key parameter of the flexiramp constraint implementation was the penalty price. The penalty price for the flexiramp constraint was set at $247 per megawatt through 2014. As part of the analysis of 15 minute market the CAISO determined that a

[18] Except for 1 hour on December 6, 2013 when the target was set to 1000 megawatts. See California ISO, Department of Market Monitoring, 2013 Annual Report on Market Issues and Performance, April 2014 p. 94.

[19] See California ISO, Department of Market Monitoring, 2014 Annual Report on Market Issues and Performance, June 2015 p. 87, 91.

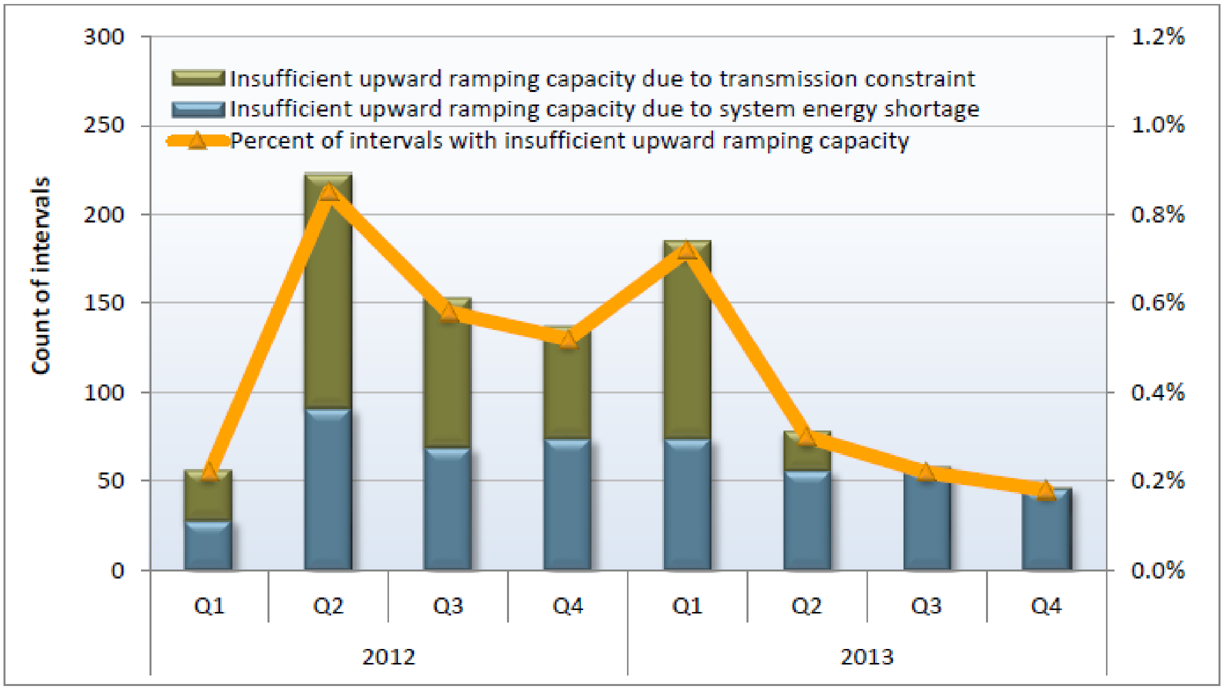
lower value was appropriate and filed to reduce the penalty price to $60 in FERC Docket No. ER15-50. The penalty price was lowered to $60 effective January 15, 2015.[20]

The implementation of the flexiramp constraint in RTPD likely led to somewhat more efficient scheduling of interchange transactions and to some incremental commitment of generation to provide additional ramp capability.[21] The implementation of the flexiramp constraint had relatively little apparent impact, however, on the frequency of power balance violations in the California ISO's real-time dispatch. Figure IV-5 portrays California ISO Department of Market Monitoring data on upward load balance violations due to insufficient ramp in 2012 and 2013. These data show that except for 1st Quarter 2012, the level of upward power balance violations during 2012 was very similar to that in 2011, although many of the power balance violations in the period 2Q 2012 through 1Q 2013 were due to transmission constraints within the California ISO that resulted in localized power balance violations.

[20] See California ISO, Filing Letter in Docetk ER15-50, October 6, 2014, California ISO, Department of Market Monitoring, 2014 Annual Report on Market Issues and Performance, June 2015 p. 87-88.

[21] The flexiramp constraint price was related to the opportunity cost of ramp in the RTPD dispatch solution and was also impacted by ad hoc adjustments arrived at in a settlement. We will not discuss these adjustments in this paper because the ad hoc pricing design reflected in part the anomalous design of the flexiramp constraint which was enforced in RTPD but not in the real-time dispatch as discussed below.

Figure IV-5
Power Balance Violations in RTD due to Insufficient Upward Ramp Capability
California ISO 2012-2013

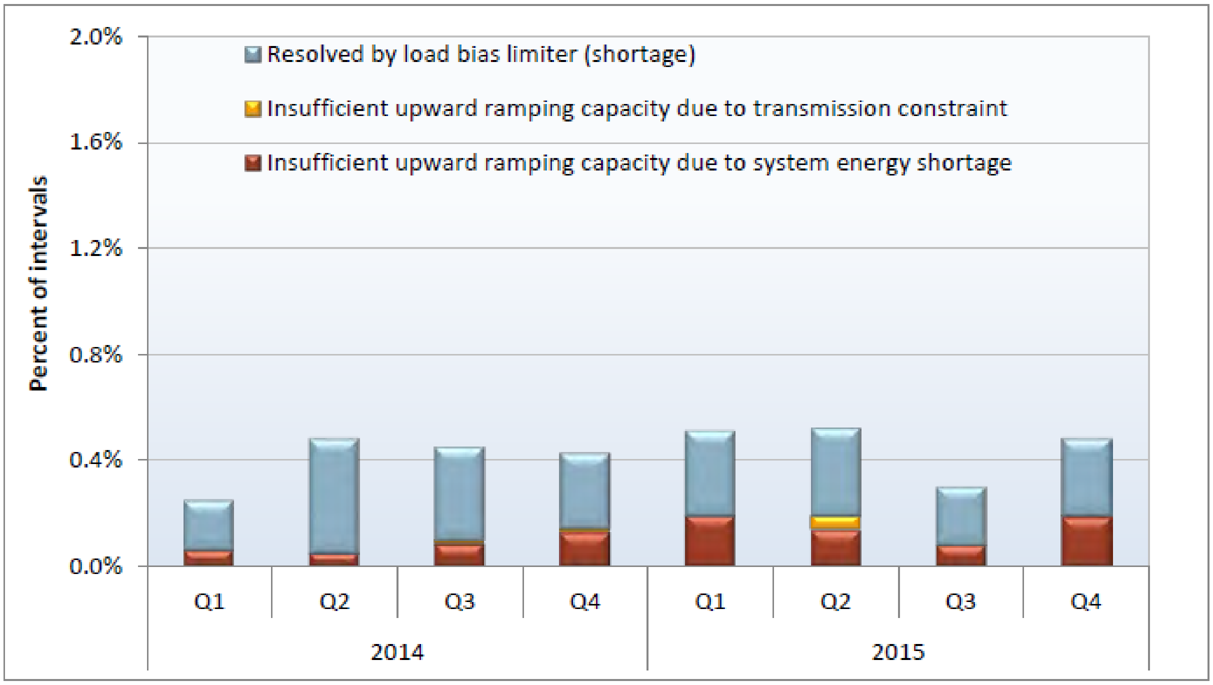


Source: 2013 Annual Report on Market Issues & Performance, California ISO, Department of Market Monitoring, April 2014, Figure 3.1, p.86.

California ISO Department of Market Monitoring data indicates that the general level of upward power balance violations fell to around .4% over all intervals in the period 2013-2014. Figure IV-6 portrays the level of upward power balance violations in 2014 and 2015 as reported by the California ISO Department of Market Monitoring, which remained around .4% of all intervals.[22]

[22] The characterization in Figure IV-6 of power balance violations whose impact was resolved by the "load bias limiter" refers to power balance violations in the real-time dispatch whose impact was not reflected in in prices because the operators load forecast adjustment was reduced in order to avoid the real-time price being set by the power balance penalty price.

Figure IV-6
Power Balance Violations in RTD due to Insufficient Upward Ramp Capability
California ISO 2014-2015



Source 2015 Annual Report on Market Issues and Performance, California ISO, Department of Market Monitoring, May 2016 Figure 3.8 p. 81

While the implementation of the flexiramp constraint likely had some beneficial impact on the upward ramp available in the California ISO real-time dispatch, the benefits of this market design innovation appear to have been materially reduced by differences between the ramp capability counted as available in RTPD and the amount of ramp capability that was actually available in the real-time dispatch (RTD). RTPD notionally dispatches generating resources on a 15 minute basis in its dispatch solution, so it is nominally able to create "ramp" by dispatching resources down out-of-merit below their upper limit. However, these notional generation dispatch schedules in RTPD do not have any physical significance because the resources are physically dispatched on a five minute basis in RTD that is completely independent of the 15 minute RTD energy schedules for the resource. RTPD would count ramp as available based on an out of merit dispatch in RTPD to create ramp in the RTPD dispatch step, but this out of merit dispatch would not occur in the actual real-time dispatch, because the real-time dispatch did not include the same ramp constraint. This discrepancy had the effect that less ramp would be available in real-time than calculated in RTPD.

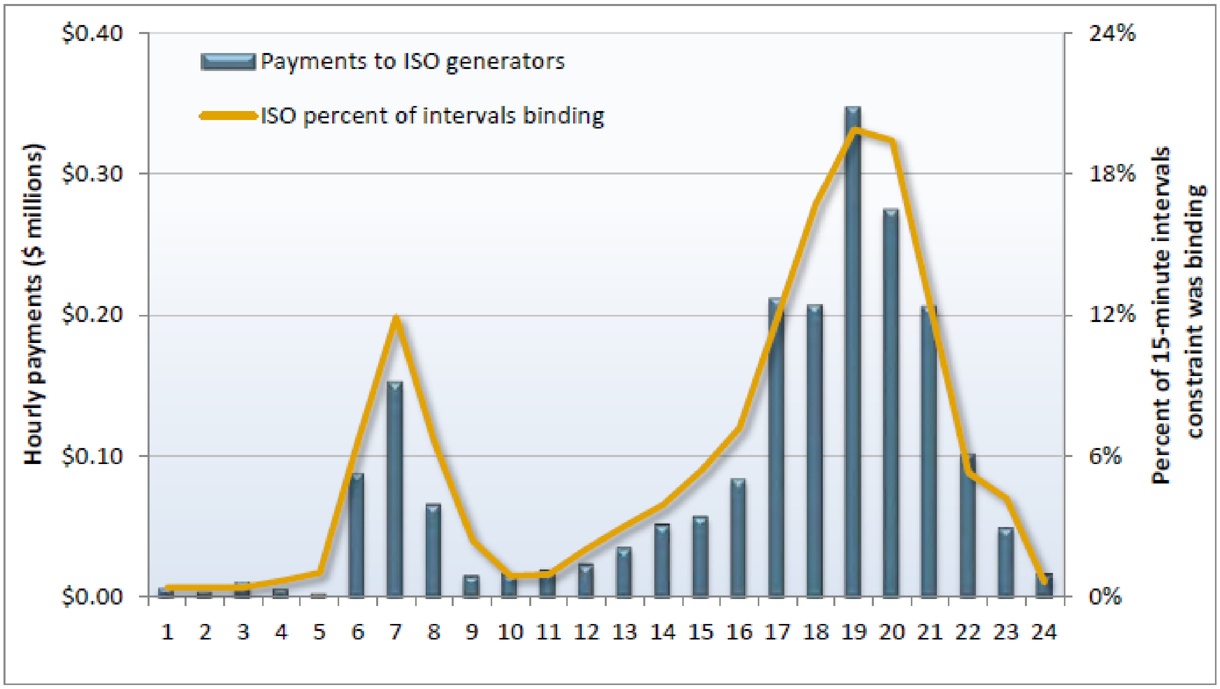
The disconnect between the RTPD dispatch and the actual physical dispatch in RTD was the core limitation of the flexible ramp constraint as implemented by the CAISO. Much of the additional "upward ramp" the flexible ramping constraint creates in the RTPD solution is created by dispatching resources down out of merit in RTPD. This "phantom" ramp was not available in the five minute dispatch, however, because there was no ramp constraint in the real-time dispatch in the flexiramp constraint design. This feature of the design had the consequence that the resources dispatched down to create ramp in RTPD were not dispatched down out of merit to create this ramp in the five minute dispatch.

This inconsistency between RTPD and RTD was potentially a significant problem in the flexiramp constraint implementation. Any time the shadow price of ramp in RTPD was non-zero, this implies that less than the target amount of upward ramp capability was available in real-time. A non-zero shadow price in RTPD means either that some of the ramp capability calculated in RTPD was on resources dispatched out of merit in RTPD (giving rise to a non-zero shadow price) that would not be dispatched that way in RTD or that the shadow price was being set by the penalty price for scheduling less than the target amount of ramp in RTPD.

This has the implication that since the flexible ramp constraint often bound during the morning and afternoon ramp as shown by California ISO Department of Market Monitoring calculations in Figure IV-7 below (indicating a need to dispatch resource out of merit in order to create more upward ramp than would otherwise be available). As Figure IV-7 shows, the CAISO was short of the target amount of ramp much more often than intended in those hours because the ramp procured in RTPD was not actually available in real-time. Figure IV-7 shows California ISO Department of Market

Monitoring calculations of the frequency with which the flexiramp constraint was binding in RTPD in 2015 by hour of the day.

Figure IV-7
Flexible Ramping Constraint Binding Intervals by Hour
2015



Source: 2015 Annual Report on Market Issues and Performance, California ISO, Department of Market Monitoring, May 2016, Figure 3.14 p. 9.0

The magnitude of this effect is difficult to analyze directly but various data compiled by the California ISO lead us to infer that RTPD was likely committing units to provide additional ramp only once every few days,[23] and that there was a material amount of phantom ramp in the RTPD ramp calculation because of the out of merit dispatch in RTPD that did not occur in the real-time dispatch.[24]

The California ISO's implementation of 15 minute scheduling of interchange in spring 2014 offered the potential for larger benefits from the flexible ramping constraint because of the ability to use adjustments to near-term interchange schedules to create additional ramp up or down. This benefit did not materialize, however, at least not to a material degree. We believe this was in part because there was initially not much participation by suppliers in adjacent balancing areas in 15 minute scheduling on the California ISO interties. In fact, offer based scheduling of real-time interchange fell materailly with the implementation of the California ISO's Order 764 15 minute scheduling design on May 1, 2014.[25]

Another change implemented in connection with Order 764 Compliance on May 1, 2014 that impacted the flexiramp constraint design was that the California ISO began clearing a fifteen minute energy market (FMM), in addition to the real-time dispatch (the five minute market). With the implementation of the fifteen minute market on May 1, 2014

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[23] See "Abhishek Hundiwale, Don Tretheway and Lin Xu "Order 764 Implementation – Flexible ramping constraint performance," March 11, 2014 Slide 5 shows real-time commitments in the time frame of the ramp commitment over the period January 1- February 17. There were one or more units committed in RTPD on 19 days, more than 1 unit on 5 days. The exact cause of these commitments would be complex to determine and it has not been verified that all of these units were committed due to the flexiramp constraint, but they could have been. Hence, these figures are a ceiling on the number of units committed as a result of the flexiramp constraint over this period.

[24] See "California ISO, Abhishek Hundiwale, Don Tretheway and Lin Xu "Order 764 Implementation – Flexible ramping constraint performance," Market Surveillance Committee Meeting, March 11, 2014 Slide 6 portrays estimates of the phantom ramp in RTPD; perhaps on average 30-40% of the total ramp counted in RTPD. An earlier initial effort to assess the level of phantom ramp is reported in California ISO, Lin Xu and Don Tretheway, "Flexible Ramping Product," Market Surveillance Committee Meeting, October 19, 2012 pp 9-12

[25] See California ISO, Department of Market Monitoring, 2014 Annual Report on Market Issues & Performance, pp. 75-77. California ISO, Market Performance and Planning Forum, July 29, 2014 pp. 8-10; September 9, 2014 pp. 8-10.

the California ISO began settling the 15 minute market based on the prices calculated in the RTPD dispatch in which flexible resources that were on the margin could be dispatched up to allow other flexible resources to be dispatched down below their upper limit in order to create upward ramp.

This additional market settlement likely lead to some increase in energy market costs because the resources that were dispatched down in the fifteen minute market to create ramp would typically not have been dispatched down in the five minute dispatch because the ramp constraint was not enforced. Hence, they would be paid for providing upward ramp under the 15 minute market design, but would not actually have been dispatched down in RTD. Moreover, since the flexiramp constraint was not enforced in RTD there was no deviation between the amount of flexiramp for which the resources were paid in the 15 minute market and the amount of ramp these resources provided in the real-time dispatch that these resources had to settle in the 5 minute market. Conversely, resources that were dispatched up above their day-ahead market schedule in the 15 minute market to replace the output of the resources dispatched down to provide upward ramp, would sell this output in the 15 minute market at the 15 minute market price, then settle the deviation in their energy schedule between the 15 minute market and RTD at the lower RTD price when there was no flexiramp constraint in RTD and they were dispatched down in real-time.[26]

In fall 2014 the Energy Imbalance Market (EIM) dispatch was implemented between the California ISO and thePacifiCorp balancing areas on a 15 and 5 minute basis. This provided the CAISO with more ability to adjust interchange to create ramp in RTPD, but the availablility of this ramp was constrained by the limited transmission between PacifiCorp and the CAISO. With Nevada joining the EIM at the end of 2015 and Arizona Public Service joining in the Fall 2016, there is substantially more transfer capability in and out of the CAISO that can be scheduled on a 15 minute basis to make

[26] See California ISO, "FERC Order 764 Compliance 15-Minute Scheduling and Settlement, Addendum to Draft Final Proposal," April 24, 2013 pp.18-22.

use of flexible resources located elsewhere in the Western EIM as of the Spring of 2018. In addition, fleixble generating resources offered in the EIM market in these external balancing areas could be dispatched to balance California ISO generation on a 5 minute basis in real-time so not only could the ramp available on resources within the CAISO be used to balance variations in intermittent resource output, but additional ramp was available on units within the Nevada and Arizona Public Service balancing areas.

Another way of looking at the benefits from the explicit modeling of net load uncertainty in forward commitment processes such as the day-ahead market and particularly in intra-day unit commitment and interchange scheduling processes is that it effectively causes these processes to treat the load forecast as uncertain. In a standard look-ahead process the optimization treats the load forecast and intermittent resource output forecasts as certain, and will at times choose a solution that is optimal if the forecasts are exactly right but will result in infeasibilities and power balance violations if the forecast is off by even a little. The net load forecast used in forward unit commitment and interchange scheduling processes is only an estimate of the actual value for net load that will ultimately be used in the real-time dispatch. Recognizing that the load forecast used in forward commitment process is only an estimate can enable more efficient commitment and interchange scheduling decisions.

V. Ramp Capability Dispatch

A. Introduction

To address the limitations of the flexiramp constraint design in making additional ramp capability available to balance net load in real-time the California ISO developed the flexiramp product (a ramp capability dispatch) which was implemented in December 2016. The key changes in the initial flexiramp constraint design that were to be implemented in December 2016 with the implementation of the flexiramp product was first that a ramp target for the next interval was to be incorporated in the CAISO's real-time dispatch, as well as in RTPD. It was intended that with the implementation of the ramp constraint in the 5 minute dispatch the problem of phantom ramp counted upon and paid for in RTPD, but then not available in RTD, would be resolved. The goal was to achieve a material improvement in the California ISO's ability to balance load and generation in RTD, as reflected in fewer power balance violations. In addition, a second change was that the CAISO proposed to implement a better method for determining the ramp capability target and a more graduated penalty price for making ramp available for use in the dispatch. Finally, a third change was that the flexiramp product implemented a downward ramp target in addition to an upward target.

While using multiple interval optimization to optimize the dispatch over time to meet expected variations in net load (load less intermittent resource output) can reduce the likelihood of small unpredictable variations in net load (load less intermittent resource output) combining with predictable variations to create power balance violations or large increases in the cost of meeting load, this form of multi-interval optimization is likely to be of limited value in balancing variations in the output of intermittent resources because predictable changes in net load may be swamped by unpredictable changes. This limitation of multi-interval optimization has led some ISOs with substantial, and growing, intermittent resource output to not only develop processes for committing additional generation to provide ramp capability such as those discussed in section IV, but to also evaluate alternative dispatch concepts that go beyond conventional multi-interval optimization, in order to better manage the reliability challenges posed by high levels of intermittent resource output.

With the increased importance of intermittent generation since 2009 the California ISO and MISO have developed a new dispatch concept that is intended to better position generation resources to respond to unpredictable changes in net load (load net of intermittent resource output) in future intervals. In particular, the Midwest ISO and California ISO have developed a concept that we refer to as ramp capability based dispatch. This ramp capability design is not a change in the pricing system but is a change in the objective function used for the real-time dispatch. Like multiple interval optimization, ramp capability dispatch seeks to not just minimize the cost of meeting load in the current dispatch interval, but also attempts to dispatch generation (and potentially load resources) so as to reduce the cost of meeting uncertain variations in net load in future intervals.

The California ISO ramp dispatch design is combined with multiple interval optimization in the real-time dispatch but unlike conventional multiple interval optimization, the California ISO ramp capability dispatch design attempts to not only reduce the cost of meeting predictable variations in load or net load but to also reduce the cost of balancing unpredictable future variations in net load by dispatching generation to maintain incremental ramp capability for use in responding to unexpected changes in net load in subsequent dispatch intervals.[27] The MISO ramp capability dispatch, on the other hand, is implemented in a single interval dispatch design that minimizes the cost of meeting load in the current interval while reducing the expected cost of meeting load in the next interval by maintaining a target level of ramp capability to meet load in the next interval.[28]

B. Core Concept

The basic concept underlying ramp capability dispatch is to slightly modify the objective function in the real-time dispatch to include an objective of maintaining target levels of ramp capability that would be available to meet variations in next load in future intervals, subject to the cost of this additional ramp capability not being too high. The purpose in implementing such a ramp capability dispatch is to reduce the frequency with which ramp constraints in the real-time dispatch require the ISO to use very high cost on

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[27] Lin Xu and Donald Tretheway, California ISO, “Flexible Ramping Products, Revised Draft Final Proposal,” August 9, 2012.

[28] Midwest ISO, Ramp Capability in MISO Markets, Stakeholder 5th Technical Workshop, April 14, 2012.

dispatch generation, reserves or regulation to balance generation with projected net load. The short-run benefit from such a ramp capability dispatch is the additional ramp capability that would be available in real-time for use in balancing variations in intermittent resource output.

As the examples in Section III show, the real-time dispatch can be used to create additional ramp for the next interval, at a cost. This additional ramp capability would then available for use in the next interval to meet expected or unexpected variations in net load. This higher cost dispatch solution for the current interval in order to create additional ramp capability that would be available in future intervals can be cost effective on a production cost basis if the expected reduction in the cost of meeting load in future intervals is greater than the increase in the cost of meeting load in the current interval. Since load will sometimes be higher than expected in future intervals and sometimes lower, this higher cost dispatch to create additional ramp capability for use in future intervals will only be economic when there is a potential for a lack of ramp capability to lead to a much higher cost dispatch in future intervals and when the cost of creating the extra ramp capability in the current interval is not very high.

This dispatch design for upward ramp capability up is no different than the way generation is sometimes dispatched to create incremental spinning reserves. Lower cost generation is dispatched down to create the spinning reserves that can be activated to balance load and generation following a contingency, and the output of the generation dispatched down to provide spinning reserves is replaced with the output of other higher cost generating resources. In essence the upward ramp created by the ramp capability dispatch is just a category of spinning reserves that are available for dispatch to balance load and generation at a lower penalty price than conventional spinning reserves. Unlike spinning reserves, though, the amount of ramp capability scheduled in each period is based on the projected need for additional ramp capability in future periods, rather than the size of generation or transmission contingencies. Additionally, unlike a spinning reserve requirement, a ramp capability dispatch design can anticipate the need for generation to be able to ramp down in future intervals, enabling the system operators to accommodate rapid increases in intermittent resource output at lower cost.

C. Key Design Features

While the core concept underlying ramp capability dispatch is simple, turning the concept for a ramp capability dispatch into a cost effective operating design that improves reliability and reduces the cost of meeting load requires addressing a number of key design features.

These features are:

- How does the ramp capability dispatch impact the determination of prices in a market based dispatch?
- How much ramp capability should the dispatch attempt to create in each interval for potential use in future intervals and at what cost?
- When should ramp capability be used to reduce the cost of meeting load in the current interval rather than maintained to potentially reduce costs in future intervals?
- Which undispatched capacity should be counted towards the ramp capability target?[29]

1. Pricing

We will break the discussion of pricing down into a discussion of pricing in real-time, when gas supply costs are sunk, and in the day-ahead market when gas scheduling costs would be a variable cost.

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[29] These features are discussed in Section VI with respect to location and energy offer prices.

a. Real-Time Pricing

The discussion of ramp pricing in this section focuses on the pricing of ramp capability in real-time, when any gas scheduling costs would be sunk costs. The pricing of ramp capability in real-time has two dimensions. First, when a generator is dispatched down out of merit in the current interval in order to provide additional ramp up capability in future intervals, the generator does not receive any economic benefit from this out-of-merit dispatch and forgoes the margin (the difference between the market price and its incremental cost) it would have earned had it operated at its upper limit. Similarly, a generator dispatched up out of merit in order to provide additional downward ramp capability in a future interval would be paid an LMP price that would be less than the cost of its incremental output, incurring a loss at the margin. Some payment for the supply of ramp capability from resources dispatched out of merit to create ramp capability is needed in a market based system to compensate these resources for the opportunity cost of being dispatched down to create upward ramp, or the cost of being dispatched above the market price at their location to create downward ramp capability.

There are four general approaches that could be taken to providing compensation to resources providing ramp capability. The first approach would be to pay a bid production cost guarantee to the resources dispatched up out of merit to provide downward ramp capability and to pay resources dispatched down out-of-merit the opportunity cost of their forgone output based on their offers and the energy price at their location. This approach would make resources whole for being dispatched out of merit to provide additional ramp capability. However, since resources that are ramp rate constrained in the amount of ramp they provide would receive no compensation for the ramp capability they provide under this design, this pricing system would not provide any incentive for ramp constrained resources to incur costs to take actions that would increase their ramp rate and hence increase available ramp capability when they are not capacity constrained.

High cost providers of additional ramp capability would be made whole for their cost of providing ramp under such a pricing design, but these resources would have no incentive to make investments or changes in operating practices that would allow them to provide the same or increased ramp capability at a lower cost. In addition, such a design would lead to pricing inconsistencies in markets in which real-time reserve prices are set by opportunity costs, as infra-marginal capacity scheduled to provide spinning reserves would receive higher compensation than similar capacity scheduled to provide ramp capability.

A second approach would be to pay all resources providing ramp capability the market price of ramp capability, with the market price determined by either the opportunity cost of the marginal resource (if constrained down), the out of merit cost of the marginal resource (if constrained up), or the ramp capability penalty value if less than the target amount of ramp capability is available. Like the first approach, this approach would make all resources whole for the costs they incur when they are dispatched out-of-merit to provide ramp capability.

This second pricing design would provide compensation equal to the marginal value of ramp capability to resources that provide ramp capability but do not incur any out of merit costs. By providing compensation to resources that are constrained in the amount of ramp they provide by their ramp rate, this design provides incentives for these resources to incur costs in order to improve their ramp rates in the longer term or to choose a different trade-off between higher maintenance costs and offering a higher ramp rate for use in the economic dispatch.[30]

This pricing design is exactly the same design the New York ISO and ISO New England use to price spinning reserves in real-time, the market price of spin is equal to the

[30] The increase in ramp rates could be a result of both changes in physical capability or a change in the economic tradeoff between higher maintenance costs and the profits from offering a higher ramp rate for use in the economic dispatch. This pricing design is also consistent with the reserve pricing formulation in Mike Cadwalader. Scott Harvey, William Hogan and Susan Pope, Reliability, Scheduling Markets and Electricity Pricing May 1998.

opportunity cost of the capacity dispatched down out of merit to provide incremental spinning reserves.

This second pricing system has the property that if there is generally enough ramp capability without dispatching resources out of merit, the cost of ramp and payments for ramp capability will be low. If, on the other hand, the system is frequently short of ramp capability unless resources are dispatched out-of-merit, then the payments for ramp capability will be higher.

A third potential approach to pricing ramp capability would be to employ a market based pricing system as under the second approach but to also allow suppliers to submit capacity bids for supplying ramp capability. Like the second approach, this pricing system would ensure that suppliers of ramp capability would be made whole if they were dispatched out of merit to provide ramp and would provide incentives for resources to incur costs to improve their ramp capability. This pricing system is essentially the same as the design the MISO and CAISO use to price spinning reserves in real time and the New York ISO, California ISO and MISO use to pricing spinning reserves in their day-ahead markets.

Extensive discussion of this third pricing approach in the California ISO stakeholder process failed to identify any incremental costs of ramping capacity that would be reflected in such a real-time capacity bid. Resources would in practice be dispatched up or down making use of their ramp capability to balance load and generation without regard to whether they were paid a capacity price for providing ramp capability, just as they are today. The only apparent impact of including capacity bids in the determination of prices for ramp capability would be to inflate the price of ramp capability by potentially causing resources that actually would provide ramp capability in real time to not be counted against the ramp capability target if their capacity offer price exceeded the "clearing" price. Under such a design, the "clearing price" for ramp would not actually be the clearing price, because additional ramp capability would in fact be available for use in the dispatch at a lower price than the clearing price used for ramp settlements.[31]

A fourth approach to pricing ramp capability would be to provide compensation for ramp capability in the resource adequacy design, rather than in the energy market. This approach is very popular with some stakeholders in the California ISO that argue in many contexts that the costs incurred by resources with resource adequacy contracts is included in the payment for general resource adequacy capacity or for flexible capacity. There are, however, several fundamental limitations of an approach based on compensation soley through the resource adequacy system, whether a capacity market or some other resource adequacy mechanism. First, the system operator does not need all resources to have ramping capability, it just needs some of them to be able to provide ramp capability. Hence, a broad requirement that all resource adequacy resources provide ramp capability is not necessary, would unnecessarily restrict the set of resources able to supply capacity, and would needlessly raise the cost of incremental capacity needed to meet peak load.

Second, the cost of using particular resources to provide ramp capability depends not only on their ramp rate but also on their economics relative to the market price and whether they are economic to commit. It is unclear how the California ISO or CPUC could accurately evaluate these resource bidding economics in a forward capacity market or resource adequacy procurement process. The difficulties the California ISO and CPUC have encountered in defining attributes for flexible capacity and establishing appropriate "counting rules" provide a good illustration of how complex such an approach would have to be, if it could be developed.[32] Third, it is difficult to require

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[31] See, Scott Harvey, "Flexible Ramping Product Bidding Rules," July 15, 2015. However, for markets such as the MISO and CAISO which include capacity bids in the determination of real-time spinning reserve prices, such a bid for ramp would be consistent with the current CAISO and MISO pricing of spinning reserves.

[32] See, for example, California ISO, "Flexible Resource Adequacy Criteria and Must Offer Obligation – Phase 2, Second Revised Flexible Capacity Framework, April 27, 2018 section 5.4.3 and Appendix A pp 39-40; California ISO, "Flexible Resource Adequacy Criteria and Most Offer Obligation Working Group Meeting, September 26, 2017, California ISO, "Fracmoo2 Working Group," August 2, 2017, and California ISO, "Flexible Resource Adequacy Criteria and Must Offer Obligation – Phase 2 Supplemental Issue Paper: Expanding the Scope of the Initiative, November 8, 2016 .

capacity resources to provide flexible ramping capability in real-time as it depends on the price at which supply is offered as well as the physical characteristics and non-price offer parameters of the resource. Hence, an alternative view of resource adequacy obligations is that performance incentives for flexible capacity are better provided in the energy market, with the result that resources that provide the ISO with the flexibility needed to balance net load have larger margins in the energy and ancillary service markets and hence would be a lower cost supply of capacity for load serving entities in meeting resource adeauacy or capacity market obligations. Hence, load serving entities procure capacity from resources that were actually able to efficiently provide flexibility needed by the ISO to balance net load in real-time would incur lower resource adequacy or capacity market costs.

Both the California ISO and the MISO have taken the second approach to pricing ramp capability. Hence, the price of ramp capability is non-zero only when generation is dispatched out of merit to provide incremental ramp for future intervals.

b. Day-Ahead Market

A second ramp pricing design choice is how to integrate real-time ramp pricing designs with a day-ahead market. The level of ramp capability available in real-time can be impacted by the characteristics of the resources committed in the day-ahead market. Resources with a lower minimum load in proportion to their upper limit and faster ramp rates, or resources with short start times that could be committed as needed during the operating day would provide more flexibility in real-time and could be favored in clearing the day-ahead market.

Another choice variable that could impact the amount of ramp capability that is available in real-time is the level of interchange scheduled in the day-ahead market. Hourly interchange schedules provide less flexibility in balancing variations in intermittent resource output within the hour relative to committing generation resources that can be dispatched up or down to balance load and generation during the hour. Hence, there could be a trade off in clearing the day-ahead market between scheduling internal dispatchable resources and imports for meeting load in the off-peak hours, with the dispatchable range of the dispatchable resources providing more ability for the system operator to accommodate higher than expected levels of intermittent resource output. However, keeping these resources on line and dispatching them above minimum load in order to provide downward ramp could be expensive relative to simply curtailing intermittent resource output.

Conversely, there will also be a need to ensure that there is enough rampable capacity on-line to meet load if real-time intermittent resource output is lower than expected day-ahead. This need for upward ramp could favor scheduling more imports in high load hours in order to back down internal resources that would be available to provide more upward ramp capability.

The MISO ramp capability design implemented in spring 2016 included both day-ahead market and real-time ramp schedules, while the California ISO design only implemented the ramp capability target and pricing in the California ISO 15 minute and 5 minute real-time markets.

The MISO's day-ahead market ramp capability design uses estimates of real-time intra-hour operating conditions as a basis for setting an hourly ramp capability target value for clearing the day-ahead market.[33] Using these hourly ramp capability targets the MISO's day-ahead market engine reserves both hour-to-hour and intra-hour ramping capability for the following day. The MISO's day-ahead market prices ramp capability up and down whenever there is a positive shadow price associated with the ramp capability

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[33] MISO, Energy and Operating Reserve Markets Business Practices Manual, BPM-002-r15, Effective Date: MAR-17-2016, at 3.30-31.

targets. Deviations between day-ahead and real-time resource ramping awards are settled based on real-time ramp capability up and down clearing prices.

Approaches to integrating a real-time ramp capability dispatch into the day-ahead market have been discussed by the California ISO but the implementation is still in the future. The California ISO considered implementation of a flexiramp constraint in the California ISO day-ahead market (Integrated Forward Market or IFM) in conjunction with the implementation of the flexiramp product but implementation of a day-ahead market flexiramp design was deferred and is now being developed in conjunction with other substantial changes being considered for the structure of the California ISO day-ahead market.[34]

2. Ramp Capability Target

The ramp capability target is the amount of ramp capability that the dispatch software will seek to have available to meet load in the next period (i.e. the next hour in the day-ahead market, the next 15 minute interval in RTPD or the next 5 minute real-time dispatch interval). The discussion here will focus on the ramp target in the 5 minute dispatch. The concept of maintaining ramp for use in a future dispatch interval is not a new concept. As explained in Section III above, current multi-interval optimization designs for the real-time dispatch take account of the impact of ramp capability on the cost of meeting load in future intervals in their objective function, which includes the cost of meeting load in future intervals. The new element introduced by ramp capability dispatch is to set this target for ramp capability in future dispatch intervals in a manner that accounts not only for expected ramp needs, but also for the ramp needed to balance unexpected variations in the level of net load, and hence the uncertain value of additional ramp capability in future dispatch intervals.

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34 See California ISO, “Day Ahead Market Enhancements,” April 11, 2018; George Angelidis, California ISO, “Integrated Day-Ahead Market,” September 28, 2012; Lin Xu and Donald Tretheway, California ISO, Second Revised Draft Final Proposal, October 24, 2012, section 2.5; Lin Xu and Donald Tretheway, California ISO, “Flexible Ramping Products, Revised Draft Final Proposal,” August 9, 2012, section 2.5.

The selection of the ramp capability target is extremely important both from the standpoint of achieving the intended benefits of a ramp capability dispatch and of keeping the cost of achieving these benefits low. If the ramp capability target is set too low, there will be many intervals when additional ramp capability is needed to meet increases in net load and could have been created at low cost but was not created, leading to high real-time prices when the ISO does not have enough ramp capability to balance load and generation in the next interval, resulting in power balance violations. Scheduling too little ramp thus risks forgoing potential benefits from reducing production costs when the system becomes ramp constrained in a subsequent interval.

Conversely, scheduling too much ramp capability, or at too high cost relative to the likely value of the ramp in future intervals, would increase in the cost of meeting load when it turns out that the incremental ramp capability is not needed in future intervals to compensate for variations in net load or other changes in system conditions. These increases in the cost of meeting load in the current dispatch interval in order to maintain additional ramp capability for future intervals would offset some or all of the reductions in the cost of meeting load in future intervals from the additional ramp capability, thereby reducing or eliminating the potential net benefits from a ramp capability dispatch design.

Optimizing the scheduling of ramp capability is not straightforward because the value of increased ramp capability for the next interval is uncertain at the time the dispatch is solved. It is essential for system operators that implement a ramp capability dispatch design to carefully analyze patterns in the value of ramp capability over the day, and over the year, and, potentially also take into account other factors such as the current level of intermittent resource output in setting the ramp capability target for each interval so that the system operator can choose cost effective ramp targets.[35]

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[35] A high level of upward ramp capability is more likely to be valuable when the level of intermittent output is high (and hence could fall a lot), than when it is low (and hence could only fall a little).

The setting of the ramp capability dispatch target has at least two elements. The first is a megawatt quantity defining the target amount of ramp capability. The second element is a shortage price capping the additional costs that would be incurred in the current-interval dispatch in order to create additional ramp.

The simplest implementation of a ramp capability dispatch would be a megawatt target with a cost cap. A more complex approach would be a target defined as a demand curve with more ramp scheduled when the cost of ramp is lower.

While there is limited practical experience with ramp capability dispatch designs, it appears likely to us that selection of the ramp capability target is central to achieving the intended reductions in the cost of meeting load, but is also complex. In order to achieve the potential benefits the ramp target needs to account for differences in the expected value of incremental ramp over the day, by time of year, by load levels and by the level of intermittent output.[36] The complexity of these ramp capability targets can be reduced somewhat in a multi-interval optimization which accounts for the expected load in the next interval.

The second component of the target, the selection of the shortage price, is the same as the question of when ramp capability should be released and scheduled as energy or reserves in the current interval, which is the question we now turn to.

3. Reserving or Using Ramp Capability

While the questions of what cost cap should be applied to the target for maintaining ramp capacity and when ramp capability should be released to reduce price spikes may at first appear to be distinct, they are describing the same trade-off between holding capability as

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[36] If intermittent output is currently high, large increases in intermittent output are less likely in the next interval and large decreases more likely, so more ramp up capability is needed than ramp down capability and the converse applies if intermittent resource output is low in the current interval.

ramp for use in a future period or using it as energy or reserve in the current period. Thus, the question: when is the value of ramp so high in the current dispatch interval that the ISO should not attempt to create additional ramp capability for future intervals is actually the same as the question: When is the value of ramp capability so high in the current period that some or all of the available ramp should be used to minimize the cost of meeting load in the current period, rather than reserved for use in a future interval?

There is more than one way to resolve this tradeoff between using available ramp in the current dispatch interval or maintaining it for use in future intervals. It is suggested here that in principle the best way to resolve this trade off would be to set an appropriate penalty price for the expected value of ramp capability in future intervals and let the optimization solve for the amount of ramp capability that is maintained in the current interval, given the cost of scheduling incremental ramp in the dispatch. This is the approach the MISO and California ISO have implemented, after considering several alternatives.[37] A high shadow price of ramp capability in the current interval signifies that it would be expensive on a production cost basis to maintain additional ramp capability for use in future intervals. This occurs because the system is ramp constrained in the current interval and it would be expensive to dispatch low cost capacity down and replace it with higher cost generation to create additional ramp up capability.

The shortage or penalty value for ramp capability does not have to be a single value. Although the early ramp capability dispatch designs analyzed by the MISO and the California ISO's implementation of the flexiramp constraint in RTPD were both based on a single penalty value, this is not an inherent feature of a ramp capability dispatch design. The MISO's initial implementation of a ramp capability dispatch design utilizes a ramp target with a single penalty price, while the CAISO's initial design is based on a demand curve for ramp capability. The details of how the CAISO determines this demand curve are discussed in section VI.

[37] See Midwest ISO, Ramp Capability in MISO Markets, Stakeholder 5th Technical Workshop, April 14, 2012.

There are alternatives to a penalty price based approach to determining the quantity of ramp capability scheduled in the dispatch including a scenario based approach, a surprise based approach, and a full stochastic optimization design. These alternatives are discussed briefly below.

Scenario Based Approach

Some ISOs and RTOs currently run multiple cases of their real-time dispatch or look-ahead commitment programs, and the operators choose which case to use for the actual unit commitment and dispatch. One can envision an alternative approach to managing ramp capability that would run multiple dispatch cases with differing levels of intermittent resource output at various locations in future intervals. The operators could then choose which commitment or dispatch case to use for operations.

Some of the potential limitations of this approach are 1) the implementation burden of setting up the multiple cases in the time frame of the real-time dispatch in a way that provides useful information for the operators, and without adding materially to dispatch latency; 2) the operational burden on the operators to review the scenario solutions and select the appropriate dispatch case for use in real-time, again without adding materially to dispatch latency; and, 3) would enable the operators to select a dispatch that would be optimal for a particular scenario, but this dispatch might not be the best option over a range of scenarios.

This kind of approach might be useful in providing a check on whether particular dispatch solutions would be able to manage the remaining requirements of particular scenarios in future intervals.

Surprise Based Ramp Release Rules

Another approach that was considered at length by the California ISO would be to release ramp capability in real-time in response to surprises, i.e. when the real-time net load differs from that projected in the look-ahead scheduling process (RTPD in the case of the California ISO).[38]

This approach has two limitations. First, defining what constitutes a "surprise" would be complex and introduces the likelihood of unintended consequences. While defining a surprise may seem straight forward if viewed as a difference between the net load that was projected in the forward evaluation and that seen in the real-time dispatch, these differences will arise both because of "surprises" occurring in the current interval, and those that occurred prior to the current interval. Depending on the timing employed by a particular ISO or RTO the forward evaluation may have been initialized between 20 and 45 minutes prior to the current dispatch interval. Differences between the net load in the two solutions arises both from surprises in the current interval and surprises that occurred in prior intervals after the forward evaluation initialized. It would not be necessary or cost effective to release ramp capability to deal with surprises that have already occurred and which been met in the economic dispatch of prior intervals. Defining a "surprise" and the megawatt amount of the surprise is therefore potentially very complex.

Second, even if a current period "surprise" could be readily defined, not all surprises have an equal cost impact and it would not be optimal to release scarce ramp to deal with a "surprise" that has only a minor impact on the cost of balancing load and generation. The penalty price approach provides a better outcome, releasing ramp capability when it has a high value in the current interval and maintaining it when it has a low cost, independent of whether the "surprise" relative to some baseline is big or small.

Stochastic Optimization

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[38] See Lin Xu and Donald Tretheway, Flexible Ramping Products, Draft Final Proposal, April 9, 2012; Lin Xu and Donald Tretheway, Flexible Ramping Products, Third Revised Straw Proposal, March 6, 2011.

It is also possible to imagine optimizing the dispatch to account for ramp capability using stochastic optimization methods,[39] rather than the targets, penalty factors and eligibility rules of the approach described in Section V.C. Beibei Wang and Benjamin Hobbs compare the performance of the two approaches and show the potential for stochastic optimization to achieve a more optimal solution if it includes a better representation of the relevant outcomes.[40] Research examining the application of stochastic optimization in conjunction with the deployment of flexible ramping products continues to evolve.[41] Most of these studies, however, are based on extremely small numbers of resources and either completely ignore transmission constraints or are applied to very small networks.[42] A core problem in applying these methods to actual systems any time in the foreseeable future is that absent breakthroughs, the required solution time would increase dispatch latency far beyond what would be workable in systems with high levels of intermittent resource output.

Another way of looking at the "deterministic" and stochastic optimization approaches is in terms of a tradeoff between detailed forward analysis of generic probabilities embodied in targets, penalty factors and ramp rules, which will generally not be fully optimal because the choices will not be optimized for the exact real-time state of the system, and real-time stochastic optimization based on the current real-time state of the system, which will also generally not be fully optimal because it will be optimized only

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[39] Or robust optimization, or one of the variations on these concepts that is being explored.

[40] Beibei Wang and Benjamin Hobbs, "Flexiramp Market Design for Real-Time Operations: Can it Approach the Stochastic Optimization Ideal?" IEEE Summer PES meeting, April 14, 2013. See also, Beibei Wang and Benjamin Hobbs, Real-Time Markets for Flexiramp: A Stochastic Unit Commitment-Based Analysis, IEEE Transactions on Power Systems, Vol. 31, No. 2, March 2016.

[41] See, for example, James Mc Calley and Guangyuan Zhang, Stochastic Look-Ahead Economic Dispatch with Flexible Ramping Product, IEEE, 2015.

[42] See for example , Houman Heidarabadi, Seyed Hamid Hosseini and Hossein Ranjbar, "A Robust Approach to Schedule Flexible Ramp in Real-Time Electricity Market Considering Demand Respouse," 2017 25th Iranian Conference on Electrical Engineering; Beibei Wang, Benjamin Hobbs, "Real-time Markets for Flexiramp: A Stochastic Unit Commitment-Based Analysis," IEEE Transactions On Power Systems, March 2016; Zhiwen Wang, Chen Shen, Feng Liu, Jianhui Wang, and Xiangyu Wu, "An Adjustable Chance-Constrained Approach for Flexible Ramping Capacity Allocation," DOI 10.1109/TSTE.2018.2815651, IEEE Transactions on Sustainable Energy.

over the cases analyzed, which will be limited by performance considerations in real-time.

To the extent that the number of possible future states of the system that can be probabilistically evaluated in real-time is limited, there will likely be a trade off between not analyzing particular outcomes at all in a stochastic optimization framework or analyzing them in advance and applying the kind of generic dispatch rules described in section V.C, with key states that can be evaluated in detail within the relevant solution time frame solved using a stochastic optimization framework.

D. Empirical Illustration

Empirical examination of the application of the ramp capability dispatch concept to historical Midwest ISO dispatch data and price spike events showed that the application of this dispatch concept could be cost effective in reducing the cost of meeting load on a production cost basis given current price spike frequencies and current Midwest ISO penalty values for spinning reserves shortages.[43] This examination also showed that the benefits of such a ramp capability based dispatch are sensitive to the penalty value used to value incremental ramp capability, the criteria used to set the target level of ramp capability,[44] as well as the frequency with which the ISO is unable to meet the load balance constraint with its real-time dispatch, and the value assigned to being able to avoid these situations.[45]

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[43] See Midwest ISO, Ramp Capability in MISO Markets, Stakeholder 5th Technical Workshop, April 14, 2012. pp. 54-61.

[44] See Midwest ISO, Ramp Capability in MISO Markets, Stakeholder 5th Technical Workshop, April 14, 2012. pp. 54-61

[45] The California ISO, for example, assigns a $1000 value to being able to avoid violating the load balance constraint, which increases the benefits to implementing such a dispatch methodology.

The Midwest ISO's initial analysis of a ramp capability dispatch design was restricted to Midwest ISO wide price spikes with no congestion, which is a small proportion of all price spikes.

The application of the ramp capability dispatch concept is illustrated in Table V-1, drawn from a simulation of the operation of a ramp capability based dispatch in the Midwest ISO footprint. Table V-1 portrays the operation of a ramp capability based dispatch with a $10 penalty value and no cap on the ramp target other than the penalty price.

In this simulation, the production cost of additional ramp capability exceeded the $10 penalty value in the first interval, so no additional ramp was created by out of merit dispatch and there was no change in production cost. Then in the interval beginning 1:05 it was economic to redispatch the system to create 4.1 megawatts of additional ramp at a total production cost of $6.63 per hour. The generation dispatched down out of merit to create the additional ramp was replaced with slightly more expensive generation, raising LMP prices by $.22 per megawatt hour at the location at which generation was dispatched up.[46]

In the dispatch for the interval beginning 1:10 it was economic to create an additional 18.3 megawatts of ramp at a total production cost of $64 per hour, raising the LMP price by $1.83 per megawatt hour. In the following dispatch interval a total of 48.4 megawatts of additional ramp were created at a total production cost of $142.39 per megawatt hour and raising the LMP price by $3.76 at the location at which generation was dispatched up to replace the output of the generation dispatched down to create additional ramp.

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[46] Because the cost of marginal losses varies by location, the change in prices would have varied slightly around this $.22 per megawatt hour figure from location to location.

Table V-1
Spike on January 26, 2011
$10 Cap, No Ramp Capacity Cap

[A] Interval	[B] LMP	[C] Change in LMP[1]	[D] Change in Production Cost[2]	[E] Spin Shortage	[F] Change in Available Spin	[G] Change in Spin Shortage Costs[3]	[H] Up Ramp Left in Original Dispatch	[I] Up Ramp Used in Original Dispatch	[J] Original Total Up Ramp [H] + [I] - [E]	[K] Additional Ramp in New Strategy	[L] Total Up Ramp in New Strategy [J] + [K]
1:00	44.2	0.00	0.00	0	0	0	80	221.1	301.1		301.1
1:05	41.42	0.22	6.63	0	0	0	132.7	134.5	267.2		267.2
1:10	36.6	1.83	64.09	0	0	0	150.6	107.6	258.2	4.1	262.3
1:15	35.68	3.76	142.39	0	0	0	237.9	90.6	328.5	18.3	346.8
1:20	47.28	1.61	3.12	0	0	0	39.9	334.7	374.6	48.4	423
1:25	191.75	-10.75	-2145.01	156.9	13.5	-1105.2	2.7	403.8	249.6	13.1	262.7

Total Production Cost	**-1928.78**
Total Production Cost and Shortage	**-3033.98**
Production Cost Benefit in Spike Interval	**2145.01**
Total Production Cost Benefit in Spike Interval Including Shortage	**3250.21**
Average Production Cost in Non-Spike Intervals	**43.25**
Ratio without Shortage Benefits	**49.60**
Ratio with Shortage Benefits	**75.15**

Notes:
1. Calculated as the highest percent increase in marginal cost for units ramped up multiplied by [B]. Uses the recalculated LMP for the final interval, 1:25.
2. Sum of the new marginal cost of units ramped up (weighted by MW shifted from actual dispatch) minus the new marginal cost of units ramped down (weighted by MW shifted from actual dispatch.
3. $98 per MW to decrease the spin shortage to 150, and $65 per MW thereafter.

Source: Midwest ISO, Ramp Capability in MISO Markets, Stakeholder 5th Technical Workshop, April 14, 2012, P. 56.

In the interval beginning at 1:20 the LMP price rose by more than $10 in the original dispatch, meaning that all of the resources dispatched down in the prior interval would have an opportunity cost in excess of $10 per megawatt in this interval. The amount of additional ramp created in the dispatch was only 13.1 megawatts, at total production cost of only $3.12 per megawatt hour and raising the LMP price by $1.61.

The additional 13.1 megawatts of ramp capability maintained in the interval beginning at 1:20 was used in the interval beginning at 1:25 when the price originally rose by almost $150 to $191.75 per megawatt hour. With the 13.1 megawatts of additional ramp capability available, the price rose to $181 ($191.75- 10.75) per megawatt hour in the simulation. In addition to reducing prices, the availability of the additional ramp would have reduced production costs in that interval by $2145 per hour. The additional ramp capability also would have permitted a reduction of 13.5 megawatts in the shortage of spinning reserves. At current MISO shortage values for spinning reserve, this reduction would have been valued at $1105.2 per hour, so the total production and shortage costs savings would have been $3250 at an hourly rate.[47]

Table V-2 shows a redispatch of the same time period using a penalty value of $20 per megawatt of ramp. It is noteworthy that although there is a larger reduction in both production costs and shortage costs during the price spike interval, there is a net increase in production costs over the period modeled and a much small net reduction in the sum of production costs and shortage costs than with the lower penalty value. This example illustrates the importance of carefully choosing the ramp capability shortage value and the potential for a shortage value that is too high to diminish the efficiency benefits from implementing such a design in the real-time dispatch.

Table V-2
Spike on January 26, 2011
$20 Cap, No Ramp Capacity Cap

[A] Interval	[B] LMP	[C] Change in LMP[1]	[D] Change in Production Cost[2]	[E] Spin Shortage	[F] Change in Available Spin	[G] Change in Spin Shortage Costs[3]	[H] Up Ramp Left in Original Dispatch	[I] Up Ramp Used in Original Dispatch	[J] Original Total Up Ramp [H] + [I] - [E]	[K] Additional Ramp in New Strategy	[L] Total Up Ramp in New Strategy [J] + [K]
1:00	44.2	0.77	139.11	0	0	0	80	221.1	301.1		301.1
1:05	41.42	0.22	560.50	0	0	0	132.7	134.5	267.2	26	293.2
1:10	36.6	1.83	735.61	0	0	0	150.6	107.6	258.2	74.4	332.6
1:15	35.68	3.76	1182.17	0	0	0	237.9	90.6	328.5	86.7	415.2
1:20	47.28	1.61	54.46	0	0	0	39.9	334.7	374.6	129	503.6
1:25	191.75	-128.04	-2282.29	156.9	16.9	-1326.2	2.7	403.8	249.6	20.1	269.7

Total Production Cost	**389.56**
Total Production Cost and Shortage	**-936.64**
Production Cost Benefit in Spike Interval	**2282.29**
Total Production Cost Benefit in Spike Interval Including Shortage	**3608.49**
Average Production Cost in Non-Spike Intervals	**534.37**
Ratio without Shortage Benefits	**4.27**
Ratio with Shortage Benefits	**6.75**

Notes:
1. Calculated as the highest percent increase in marginal cost for units ramped up multiplied by [B]. Uses the recalculated LMP for the final interval, 1:25.
2. Sum of the new marginal cost of units ramped up (weighted by MW shifted from actual dispatch) minus the new marginal cost of units ramped down (weighted by MW shifted from actual dispatch.
3. $98 per MW to decrease the spin shortage to 150, and $65 per MW thereafter.

Source: See Midwest ISO, Ramp Capability in MISO Markets, Stakeholder 5th Technical Workshop, April 14, 2012. p. 57.

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[47] The period analyzed in the simulation was prior to the time that the MISO implemented shortage pricing for spinning reserves in its real-time dispatch so the reserve shortage was not reflected in energy prices in the original dispatch.

VI. Ramp Dispatch Implementation Complexities

Section V provided a conceptual discussion of ramp capability dispatch and an explanation of its key design components: price determination, the ramp capability target, and the ramp capability target price. This section discusses these design coomponents in more depth assessing how they have performed in the initial implementations, and describing additonal issues that will need to be addressed in future ramp capability dispatch designs.

With the implementation of ramp capability dispatch by MISO in May 2016, and by CAISO on December 1, 2016, it was anticipated that the industry would gain some insight into the practical effectiveness of these designs with respect to the impact of the additional ramp capability on the frequency of price spikes and power balance violations or reserve shortages. We discuss below what is known about the performance of these designs with respect to pricing, the setting of the ramp capability target, locational requirements, and the penalty price for shortages of ramp capability.

A. Pricing

1. Pricing Design

Both the California ISO and MISO implemented designs in which the price paid to capacity providing ramp (the shadow price of ramp) is determined by the cost of the out of merit dispatch required to provide the target amount of ramp capability, with this cost capped by a penalty price (or demand curve) at which less than the target amount of ramp would be scheduled. In the MISO design, ramp is scheduled in the day-ahead market and then is either used to meet load or retained as ramp capability for use in future intervals in the real-time dispatch. If the shadow price of ramp equals the penalty price, then some of the available ramp that could have been reserved for use in future intervals is used to meet load and paid the energy or rserve price in the current interval. When this happens the supplier scheduled to provide ramp would be dispatched for energy and would settle the deviation against its day-ahead market ramp schedule (or 15 minute market ramp schedule in the case of the California ISO) at the real-time price of ramp.

It is important to understand that there is no deviation against forward schedules in the case of a flexible resource that is ramp rate constrained, rather than capacity constrained, in the amount of ramp it provide. This is because the ramp rate constrained resource will be able to provide the full amount of the ramp scheduled in the forward market when it is dispatched up for energy until the resource is dispatched into a range in which it has a lower ramp rate, becomes capacity constrained in the amount of ramp it can provide, or the ramp it can provide is limited by an energy constraint.[48]

When less than the target amount of ramp is available and the price of ramp is set by the penalty price in real-time, the penalty price would be reflected in the price of energy as well as in the price of ramp, because a resource dispatched at the margin to provide energy could also provide ramp. Therefore, resources scheduled to provide ramp in the day-ahead market that were dispatched for energy in real-time would either break even or earn incremental profits from being dispatched for energy, rather than providing ramp capability, in real-time.

The long-run impact of such a ramp dispatch on resource returns is complex. Resources providing ramp will be paid the market price of ramp when ramp capability has an opportunity cost, which will raise returns to dispatchable resources. However, the overall impact of implementing a ramp capability dispatch is to increase the supply of ramp when it is needed in real-time, reducing the frequency and/or magnitude of real-time upward and downward price spikes. Thus, resources providing ramp could realize lower energy market returns from upward price spikes following implementation of a ramp product. Non-dispatchable resources such as nuclear plants would not receive ramp

[48] An energy limit would be most likely to limit the ramp provided by storage resources.

payments and a reduction in upward price spikes would reduce the real-time revenues of such non-dispatchable resources. However, the overall net impact of a ramp capability dispatch on the revenues of these resources is still ambiguous because these non-dispatchable resources would likely benefit from fewer extremely negative prices in real-time.

Those entitled to the economic value of the contracts of variable generation resources are also likely to benefit from the implementation of a ramp capability dispatch because real-time prices will not fall as low when intermittent resource output rises, and will not rise as high when intermittent resources output falls.

2. Initial Implementations

An important feature of LMP based electricity markets is that the pricing design for ramp capability in both the MISO and CAISO allows us to examine the supply and use of ramp capability by examining the market price of ramp. California ISO pricing data reveals that the target amount of ramp capability has virtually always been available at zero cost in the real-time dispatch (RTD), so the implementation of flexiramp on November 1, 2016 had essentially no effect on the ramp capability available in the real-time dispatch.[49] This conclusion is consistent with the observed lack of dramatic change in the frequency of power balance violations following flexiramp implementation in the CAISO in November 2016.[50] This section will focus on the pricing data that demonstrates the lack of impact of the ramp capability dispatch in the CAISO. Sections B and C will discuss our understanding of why the price of ramp has been zero, yet there have continued to be many power balance violations in the California ISO markets.

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[49] A zero shadow price of ramp capability implies that no out of merit dispatch was required to meet the ramp target, so the supply of ramp is not changed by the ramp capability design.

[50] See, for example, California ISO, Department of Market Monitoring, Q1 2017 Report on Market Issues and Performance July 10, 2017, Figure 1.4 p13; Q2 2017 Report on Market Issues and Performance September 25, 2017 Figure 1.10 p. 21 (the lack of impact was not noted by the Department of Market Monitoring in the report but is evident in the data portrayed in these figures for the frequency of price spikes in RTD).

MISO pricing data also shows that the target amount of ramp capability has often been available at zero price, but not nearly to the extent that has been the case in the California ISO.

California ISO

The California ISO data on ramp up shadow prices in RTD, the 5 minute dispatch, are fairly stunning. These data show that over the period June 1, 2017 to February 21, 2018 the shadow price of ramp was zero or negative in 99.5% of all 5 minute market intervals. Moreover, this statistic has not changed following software changes that corrected errors in the calculation of the ramp target that were implemented on February 21, 2018. The shadow price of ramp was zero in RTD in 99.6% of all intervals over the period February 22 to April 30, 2018. This statistic means that the ramp dispatch design in the CAISO real-time dispatch (RTD) almost never had any impact on the CAISO dispatch, or on the amount of ramp capability available, despite a penalty price for ramp that ranges up to $247 and despite the continued high frequency of power balance violations in the CAISO real-time dispatch that indicates continuing shortages of ramp capability.

Moreover, the price of ramp up was generally zero even in the intervals in which RTD energy prices were very high, despite the high energy generally being due to a lack of ramp in RTD. Figure VI-1 show the relationship between the flexiramp product price (Ramp-Up Shadow Price) and the average load aggregation area price in RTD over the period April 1, 2017 through October 31, 2017. It is striking that the price of flexiramp is zero in the vast majority of the intervals in which the RTD price exceeds $200. Since the high price in virtually all of these intervals reflects the impact of ramp constraints on the cost of meeting load, the surplus of ramp up in the flexiramp evaluation in RTD at the same time there is a shortage of ramp in the real-time dispatch reveals a fundamental disconnect in the flexiramp implementation.

Figure VI-1
Average LAP LMP and FlexiRamp up Shadow Price in Same Intervals
All RTD Intervals
April 1, 2017 – October 31, 2017

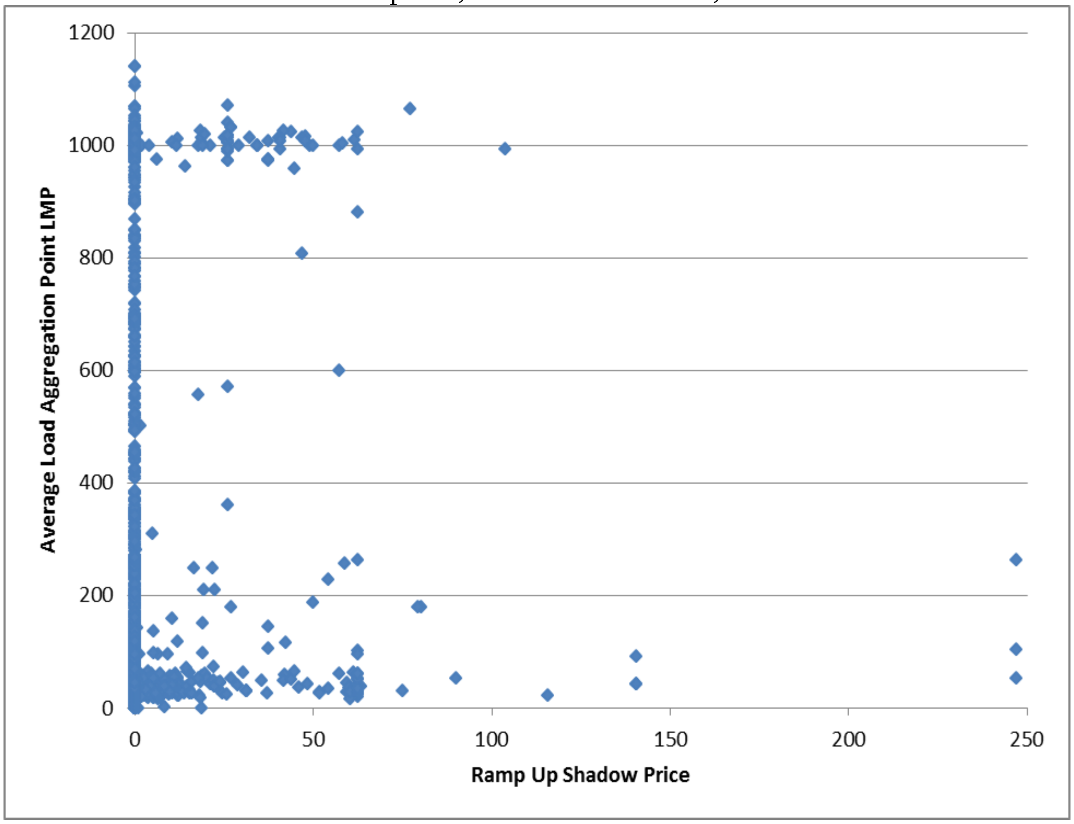
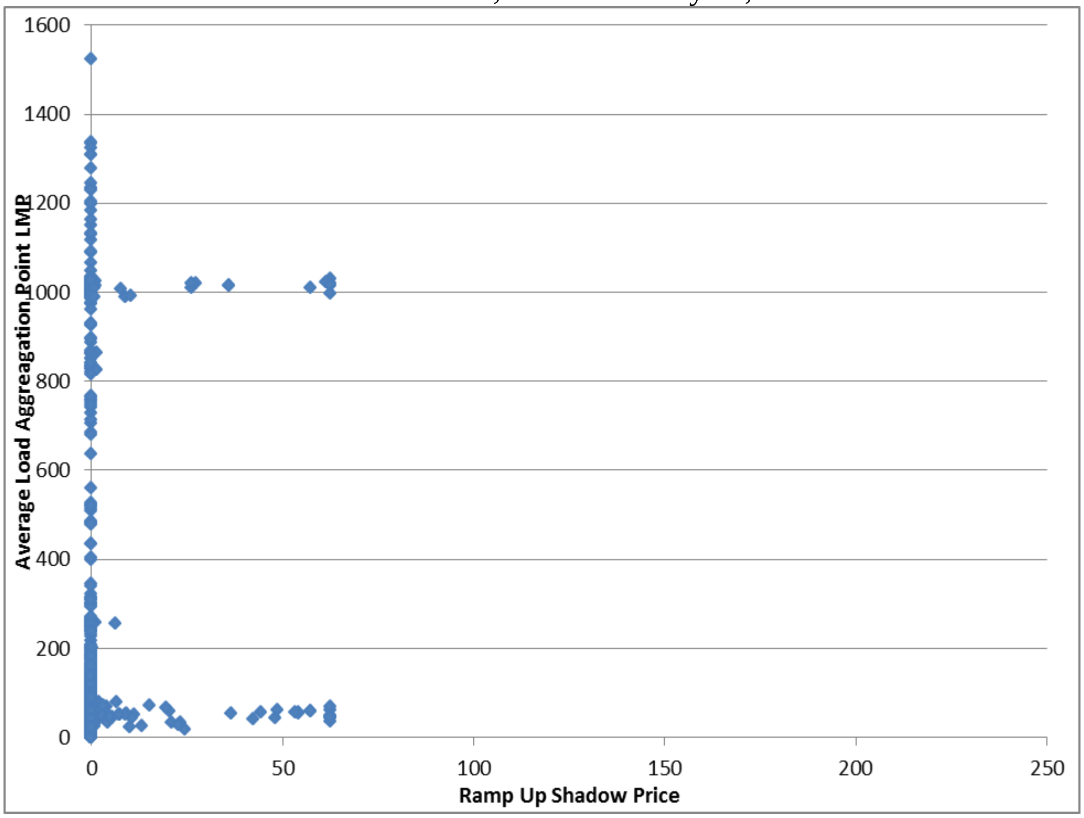


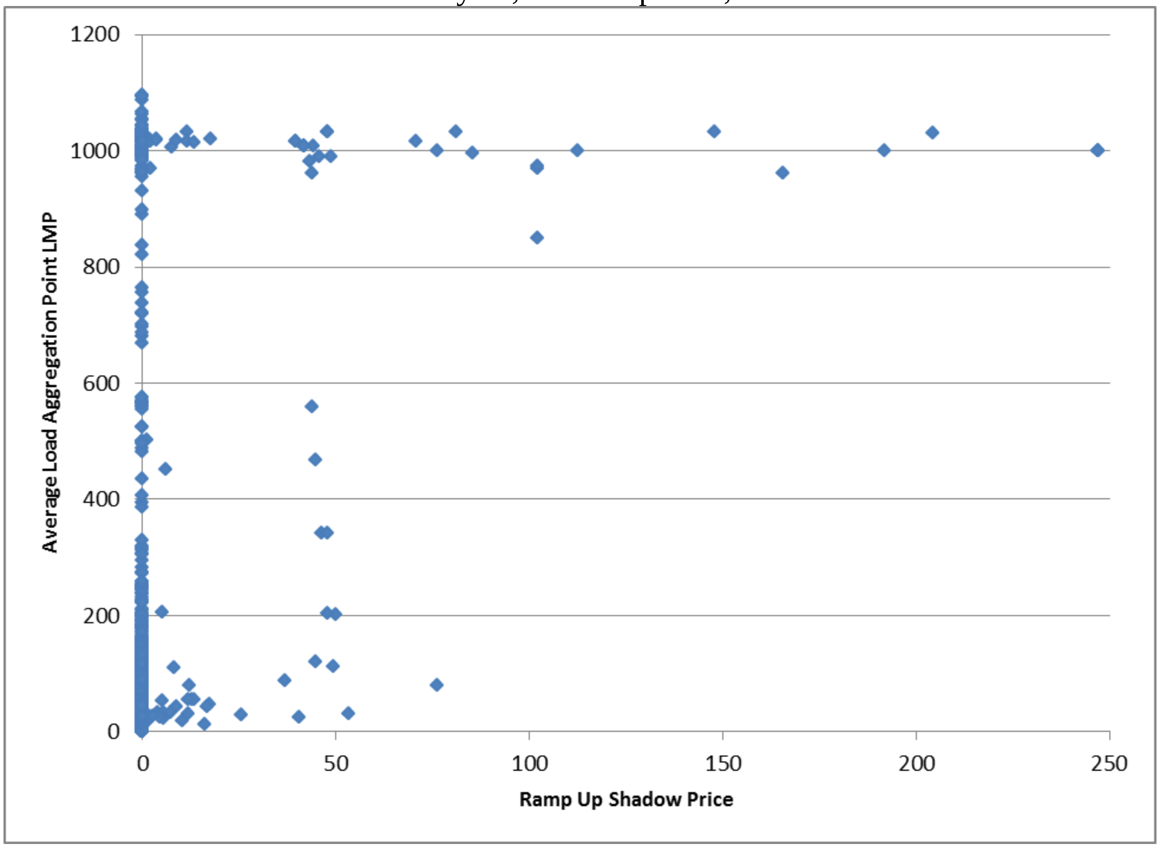
Figure VI-2 shows the relationship between the flexiramp product price and average load area price in RTD over the subsequent period, November 1 2017- February 20, 2018. There is no apparent change in the relationship from the prior period.

Figure VI-2
Shadow Price of Ramp and Average LAP Prices in Same Intervals
All RTD Intervals
November 1, 2017–February 20, 2018



Finally, Figure VI-3 shows the relationship between the flexiramp product price and average load area price in RTD since February 20, 2018 when the California ISO corrected a major flaw in the calculation of the ramp target. There is an increase in the proportion of high energy price intervals having non-zero ramp prices in this period, but the price of ramp is still zero in more than two thirds of the high priced intervals.

Figure VI-3
Shadow Price of Ramp Up and Average LAP Price in Same Interval
All RTD Intervals
February 21, 2018 –April 30, 2018



Figures VI-4 through VI-6 show the relationship between the flexiramp product price in interval t and the average load aggregation area price in RTD in the next RTD interval over the same time periods portrayed in Figures VI-1-3. It is again striking that the price of flexiramp up is zero in RTD in the vast majority of the intervals in which the RTD price exceeded $200 in the following interval. Hence, more ramp could have been procured at zero cost in these intervals, yet the price spiked in the next interval.

Figure VI-4
Shadow Price of Ramp Up and Average LAP Price in Following Interval
All RTD Intervals
April 1, 2017- October 31, 2017

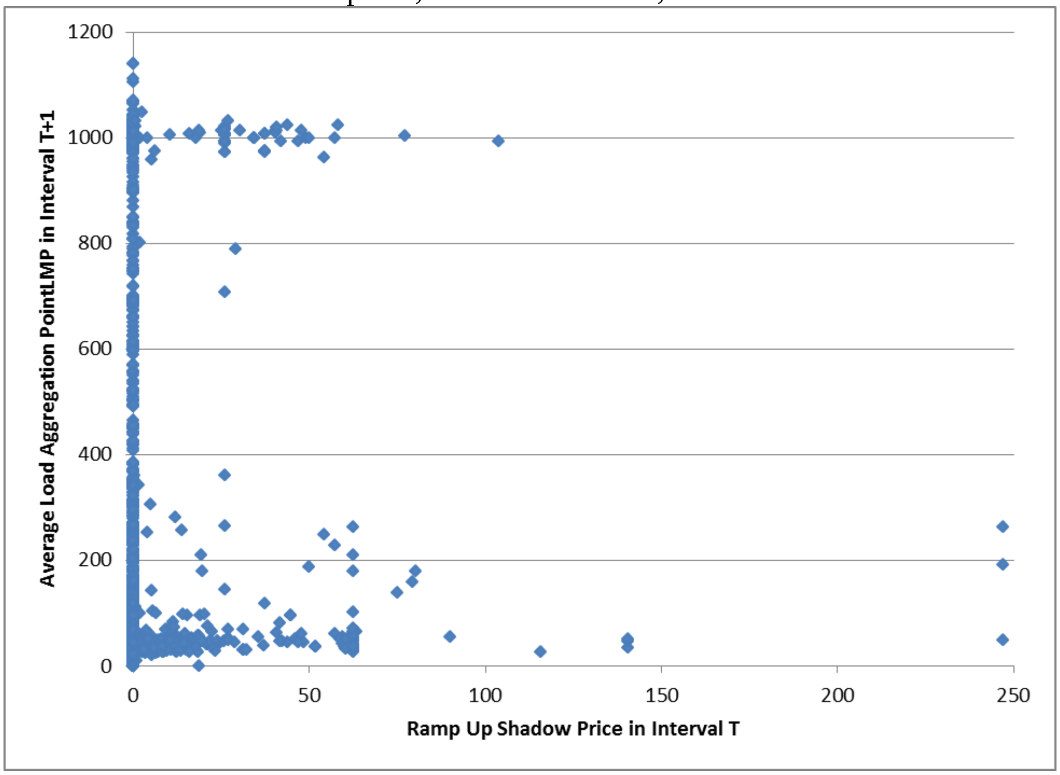
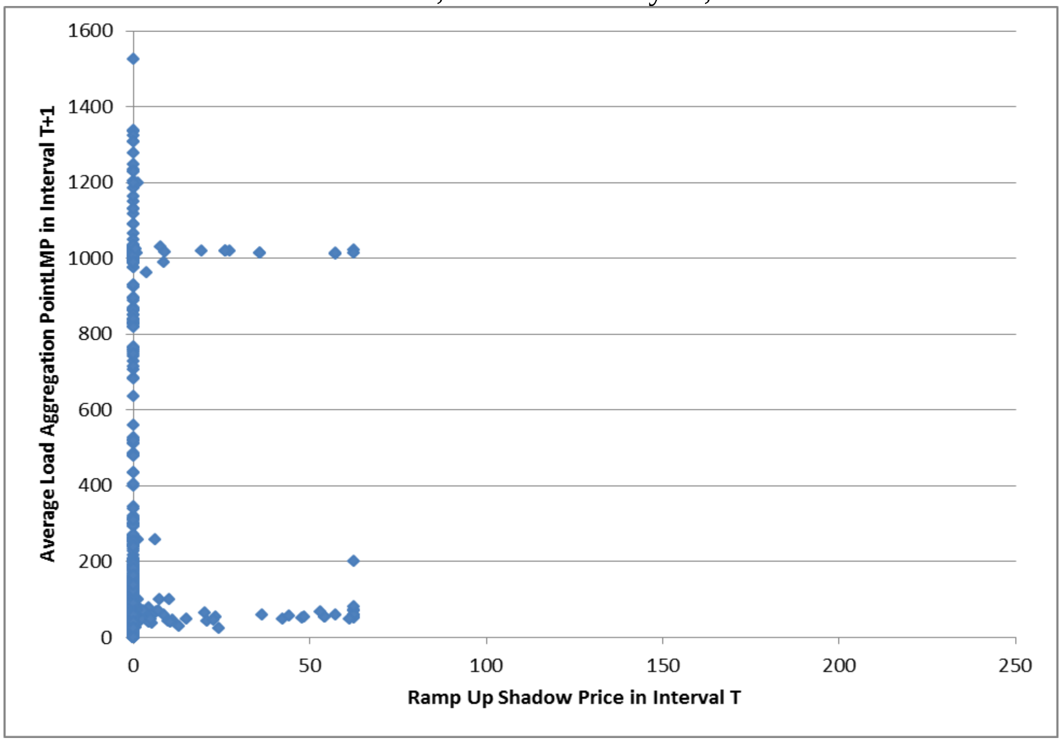
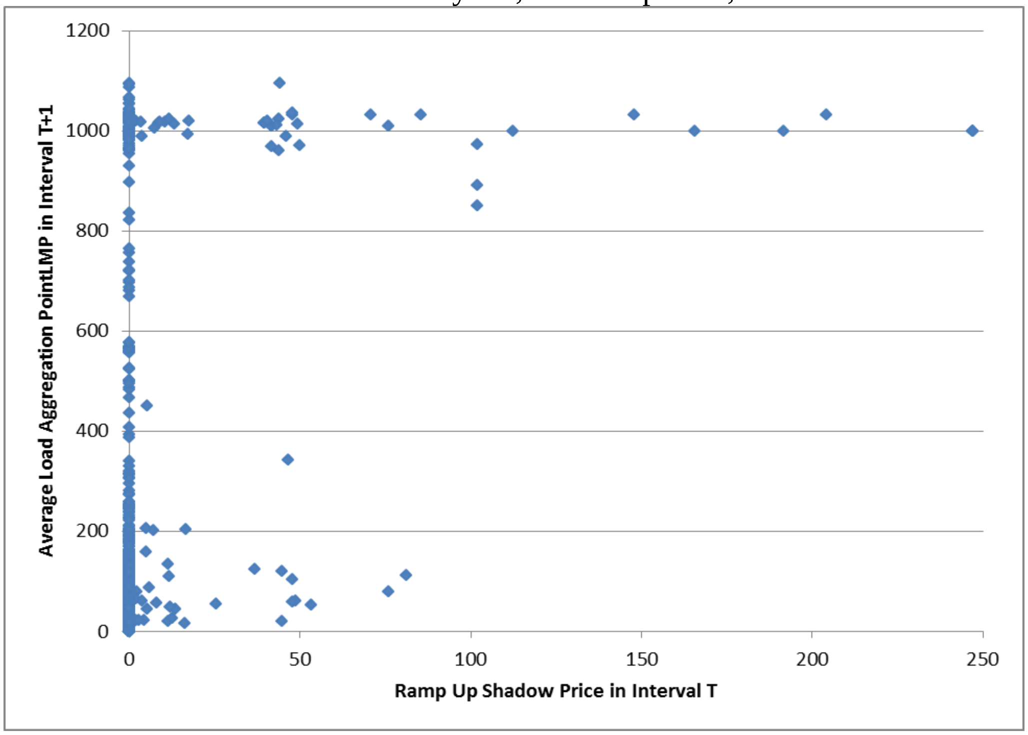


Figure VI-5
Shadow Price of Ramp Up and Average LAP Price in Following Intervals
All RTD Intervals
November 1, 2017 – February 20, 2018



There is a greater frequency of non-zero ramp prices in the intervals prior to high energy prices since the changes in the calculation of the ramp target were implemented on Feb. 21, but the price of ramp is still zero in more than two thirds of the prior intervals.

Figure VI-6
Shadow Price of Ramp Up and Average LAP Price in Following Intervals
All RTD Intervals
February 21 , 2018 –April 30, 2018



CAISO data on ramp up shadow prices in the 15 minute market over the April 2017-April 2018 period is somewhat less anomalous, showing that the shadow price of ramp up is zero in just under 84% of all 15 minute market intervals. The shadow price of ramp is between 0 and $5 in 6.4% of all 15 minute intervals and between $0 and $10 in 10.2% of all intervals. In the 15 minute market the incremental cost of ramp exceeded $100 per megawatt hour in only 7 out of almost 38,000 15 minute intervals. Taken at face value, these data indicate that additional ramp was available at a cost of $5 or less in over 90% of all intervals and at a cost of $10 or less in over 94% of all intervals.

The question highlighted by both the RTD and 15 minute price data is why the target amount of ramp is often available at zero cost, even when the system is short of ramp in the current interval or in the next interval. This outcome was at least in part, and likely largely due to flaws in the CAISO implementation that will be discussed in Sections VI.B and VI.C. It is noteworthy that the performance problem with the California ISO flexiramp implementation can readily be identified in publicly posted price data.

MISO

The MISO implemented its ramp capability dispatch about six months earlier than the CAISO, on May 1, 2016. The MISO has also seen low prices for ramp up capability, with the average real-time hourly price of ramp up ranging from $.10 to $.35 per megawatt hour over the period September 2016 through March 2018.[51] Data on ramp product performance reported through September 2016 showed that the real-time price was zero 87.3% of the time, between 0 and $5 12.6% of the time, and at the $5 penalty price .1% of the time.[52] These data indicate that most of the time, the target level of ramp up was available at zero cost in real-time, and that there were a significant number of additional hours in which the target amount of ramp could be procured at a relatively low cost ($5 or less). What is somewhat surprising in these data is that the value of ramp up has reached or exceeded $5, and hence the target amount was not been procured in the real-time dispatch, in only .1% of all hours.

One limitation of this data which may make these statistics a little misleading is that the real-time data were compiled by the MISO by hour rather than by dispatch interval. We have compiled the shadow price of MISO ramp on an interval basis over the period April 2017 through April 2018 (see Figure VI-7). The shadow price of the ramp constraint was zero in 93.0% of all dispatch intervals, and at least some ramp was released at the $5 penalty price in just over 4.3% (4,922/113,839) of all dispatch intervals. In the remaining roughly 2.7% of all intervals the target level of ramp was procured at a dispatch cost of less than $5. The interval data shows that ramp capability was used in the current

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[51] See MISO Informational Forum, October 2017, p. 16; April 2018 p. 16.

[52] MISO Ramp Capability Product Performance Update, Market Subcommittee, November 29, 2016, p. 24 available at: https://cdn.misoenergy.org/20161129%20MSC%20Item%2005f%20Ramp%20Capability%20Post%20Implementation%20Analysis74816.pdf

interval (i.e. less than the target quantity of ramp procured as indicated by the shadow price of ramp reaching the $5 penalty price) much more frequently than suggested by the hourly data.

Table VI-7
MISO Ramp Up Shadow Prices
April 1, 2017 – April 30, 2018

	Count of 5 Minute Intervals				% of Nonzero	Total
Month	**p = 0**	**0 < p ≤ 1**	**1 < p < 5**	**p = 5**	**Prices**	
April 2017	7897	104	153	486	8.60%	8640
May 2017	8100	116	194	518	9.27%	8928
June 2017	8309	63	68	200	3.83%	8640
July 2017	8157	94	152	525	8.64%	8928
August 2017	8259	138	161	370	7.49%	8928
September 2017	7988	128	166	358	7.55%	8640
October 2017	8079	171	189	489	9.51%	8928
November 2017	7949	115	154	422	8.00%	8640
December 2017	8723	31	52	123	2.31%	8929
January 2018	8444	84	57	343	5.42%	8928
February 2018	7722	68	86	266	5.16%	8142
March 2018	8377	72	129	350	6.17%	8928
April 2018	7902	95	171	472	8.54%	8640
Total	105906	1279	1732	4922	6.97%	113839

Source: MISO Historical Real-Time ExPost Ramp 5-Min Market Clearing Prices, available at: https://www.misoenergy.org/markets-and-operations/market-reports/#nt=%2FMarketReportType%3AHistorical%20MCP&t=10&p=0&s=MarketReportPublished&sd=desc

We have also examined in detail the shadow price of ramp in the intervals during which the MISO system reference price was $100 or greater (See Table VI-8). We used the $100 per megawatt hour threshold because the MISO releases spinning reserve at a shadow price of $65 per megwatt hour which would tend to produce an energy price around $100 per megawatt hour. Of the 1374 dispatch intervals in which the MISO reference price was $100 or greater over the period April 1, 2017 through April 31, 2018, the shadow price of ramp was 0 in 807 of the prior dispatch intervals, meaning no incremental ramp was created in the dispatch because the target ramp quantity was available without out of merit dispatch. The shadow price of ramp was $5 in 541 of the intervals in which the MISO reference price exceeded $100, meaning less than the target amount of ramp was procured because its cost exceeded the $5 penalty price, and in only 26 intervals was the full amount of ramp procured at a non-zero price.

The apparent zero cost of incremental ramp in almost 60% of the intervals with price spikes in real-time[53] could be a result of setting too low a ramp target in these intervals, reflecting the difficulty in predicting when additional ramp capability will be valuable. However, the frequency of price spikes when the target amount of ramp was procured could also be a result of transmission constraints that prevented some of the available ramp capability from being used to meet load, with the result that the ramp that was actually available for use in the real-time dispatch was less than the target quantity.

The MISO system reference price exceeded $200 in 240 intervals over the period April 1, 2017 to April 31, 2018, and less than the target amount of ramp was procured in 109 of these intervals, with 33 of these intervals having a reference price at or greater than $300. Thus, many of the intervals with relatively high reference price levels were also intervals in which the target amount of ramp was not procured.

Table VI-8
MISO Ramp Up Shadow Prices
April 1, 2017 – April 30, 2018

Reference Bus	Ramp Up Shadow Price ($/MWh)			
LMP ($/MWh)	**Equal to 0**	**Between 0 and 5**	**Equal to 5**	**Total**
100 to 200	680	22	432	1134
200 to 300	87	1	76	164
300 to 400	18	1	18	37
400 to 500	5	0	4	9
500 to 600	2	0	2	4
600 to 700	2	1	3	6
700 to 800	4	1	0	5
800 to 900	1	0	0	1
900 to 1000	0	0	0	0
1000 to 1100	0	0	0	0
1100 to 1200	1	0	0	1
1200 to 1300	3	0	1	4
1300 to 1400	4	0	4	8
1400 to 1500	0	0	1	1
1500 to 1600	0	0	0	0
Total	807	26	541	1374

[53] 807/1374 = 58.7%

3. Two Settlement Design

Real-Time ramp schedules are settled as deviations from forward schedules (fifteen minute market schedules in the CAISO and day ahead schedules in the MISO). This two settlement design requires that resources scheduled to provide ramp capability in forward markets that is dispatched for energy and therefore not available to provide ramp in real-time, settle the deviation between their forward and real-time ramp schedules at the real-time price of ramp. This settlement system should make it profitable for resources scheduled to provide ramp to be dispatched for energy in real-time as the resources should only be dispatched for energy when the energy market margin is greater than or equal to the price of ramp. This is consistent with the way the New York ISO, MISO and ISO New England settle deviations between day-ahead market and real-time energy and reserve schedules for resources reoptimized to provide energy rather than reserves in real-time.

The California ISO ramp capability design is only implemented in the CAISO 15 minute market (FMM) and the real-time dispatch. There are in consequence no deviations between day-ahead market schedules and 15 minute market schedules for ramp. Ramp can be scheduled in the California ISO fifteen minute market on capacity segments that did not receive a day-ahead market schedule or on capacity segments that received a day-ahead market schedule for energy but are dispatched down below their day-ahead market schedule in the fifteen minute market, either because net load is lower than scheduled day-ahead or because the resource's day-ahead market schedule has been replaced with incremental imports or by the output of other resources, including resoures comitted in RTPD or Short Term Unit Commitment (STUC).

The MISO ramp capability design is implemented in both the day-ahead and real-time markets. The MISO calculates day-ahead market clearing prices for ramp up and ramp down that are equal to the the up and down ramp capability constraint shadow prices.[54] The MISO similarly calculates real-time ramp up and ramp down capability prices that are equal to the up and down ramp capability constraint shadow prices.[55] The MISO settles deviations between day-ahead and real-time ramp schedules based on the product of the difference between the day-ahead hourly ramp schedule and the real-time cleared ramp up and ramp down schedules and the hourly real-time market clearing price of ramp, summed over all intervals of the hour.[56]

B. Ramp Capability Target

The cost effective implementation of ramp dispatch requires that the ISO be able to identify when more ramp is likely to have a high value so that the ISO can target the scheduling of more ramp capability to these periods, and avoid incurring out of merit dispatch costs to create additional ramp capability that has little or no value. As explained in section IV, ramp capability can be maintained by incurring a higher production cost of meeting load in the current interval. This higher cost dispatch will only be cost effective if this cost is incurred to provide additional ramp capability when that additional ramp capability has a high enough expected value in future intervals to offset the higher cost in the current interval. Hence, the more accurately the ISO is able to predict when having more ramp capability will provide large cost savings or reliability benefits, the more cost effective the ramp capability dispatch will be.

The challenges in predicting ramp needs are somewhat different for the MISO and the CAISO. The CAISO real-time dispatch uses multi-interval optimization, which takes account of the ramp needed to meet the expected change in netload over the dispatch horizon. Hence, the change introduced by the CAISO's flexiramp design is the

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[54] MISO FERC Electric Tariff, 39.2.9, Day-Ahead Energy and Operating Reserve Market Process.

[55] MISO FERC Electric Tariff, 40.2.17, Calculation of Real-Time Ex Post LMPs and Ex Post MCPs.

[56] MISO FERC Electric Tariff, 40.3.3, Real-Time Energy and Operating Reserve Market Settlement Cal.

scheduling of ramp to meet unpredictable variations in net load that are not accounted for in the multi-interval optimization.

The MISO on the other hand, uses a single interval optimization which does not take account of the need for ramp to meet expected or unexpected changes in net load in future intervals. Hence, the MISO flexiramp target needs to account for the ramp needed to meet both expected and unexpected changes in net load.

Accurately estimating the value of ramp that would be used to meet unpredictable variations in net load requires assessing whether there are particular times of day, times of the year, or system conditions during which large errors in the net load forecast are more likely. The more accurate this assessment is in setting the ramp target, the more cost effective the performance of the ramp dispatch design will be.

The historical error in net load forecasts can be analyzed and used to set targets for the ramp needed to meet unpredictable variations in net load. Some of the challenges using historical data for this purpose are:

- Rising levels of behind the meter generation (such as rooftop solar) can limit the value of data on load forecast error from the same time of year in prior years;
- With high levels of behind the meter solar generation, changes in the distribution of forecast error by hour over the day and by time of year due to changes in the time of sunset and sunrise reduce the value of data available from a different time earlier in the current year;
- More data is needed to accurately estimate the tails of distributions than the mean;
- The size of the net load forecast error may be related to system conditions, such as high or low intermittent output at the time, as well as simply time of day or year;

With this background, we turn to a discussion of lessons from the CAISO and MISO efforts to forecast ramp needs.

California ISO

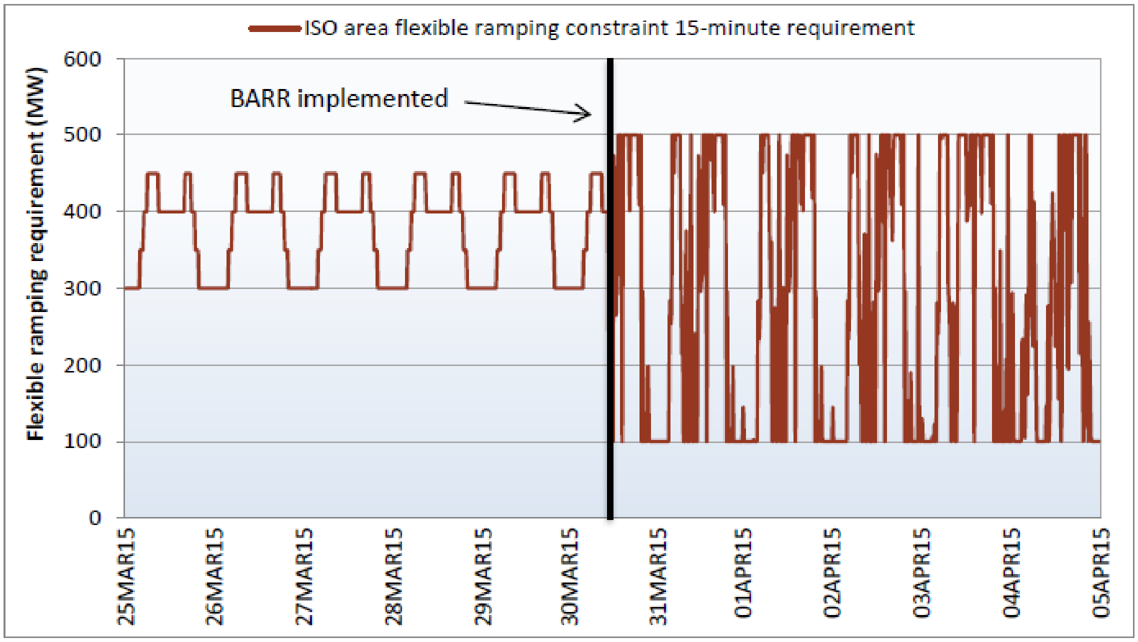
The CAISO has found it difficult to develop a workable method for estimating ramp needs. Part of the design problem is that a large number of data points are needed to estimate the tail of statistical distribution. Another problem for the California ISO is the high and increasing level of behind the meter solar generation.

As described in section IV, the ramp targets used for the flexible ramping constraint over the period from December 2011 through March 2015 were values set for each hour based on an off-line analysis of historical data, combined with ad hoc operator adjustments in real-time.

In an effort to reduce the impact of ad hoc operator adjustments, beginning in March 2015 the California ISO began estimating ramp targets on a real-time basis using what it referred to as the "BARR tool." This tool attempted to estimate the distribution of differences between the net load forecast in the 15 minute market (the RTPD run that initializes 37.5 minutes before real-time) and the net load forecast in RTD (initializing 7.5 minutes prior to the beginning of the dispatch interval). This tool attempted to calculate the 95th percentile of the difference in net load forecasts, and procure enough ramp to cover such a change in the net load forecast.

Figure VI-9 shows the California ISO's Department of Market Monitoring's portrayal of large swings in CAISO flexiramp procurement target from one 15 minute period to the next in 2015 following implementation of this design. The core problem illustrated by the erratic forecasts produced by this approach is that estimating the tail of a distribution using a small number of data points will often result in estimates of ramp needs that reflect random variations in the outcomes from one historical sampe to the next rather than reflecting changes in the underlying probability of large forecast errors.[57]

Figure VI-9
CAISO Flexiramp Requirements 2015



Source: California ISO, Department of Market Monitoring, Q2 2015 Report on market Issues and Performance, August 17, 2015, Figure 2.4 p. 44.

A feature of the CAISO implementation that contributed to the variability of the estimated ramp needs is that the net load forecast error was estimated for each 15 minute interval of each hour, looking back over the variability in that interval of the hour on prior week days or weekend days. While it might appear desirable to use data for the same 15 minute interval on each day to estimate the variability of the net load forecast, this approach results in very small sample sizes which contributes to poor estimates of net load variability.

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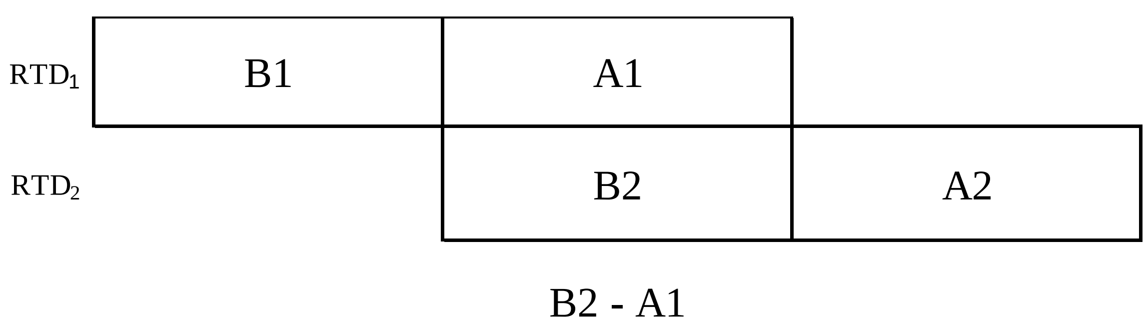
57 See also the dicussion in California ISO, Department of Market Monitoring, 2016 Annual Report on Market Issues and Performance, May 2017, pp. 110-111.

In discussions of this approach the CAISO was encouraged to pool the historical data over all intervals of the hour and to also pool the historical data over similar hours in order to develop more robust estimates of net load variability. This problem was discussed in CAISO stakeholder and Market Surveillance Committee meetings in the development of the flexiramp product design and the ramp target was to be based on a larger number of intervals. In August 2015 the CAISO implemented slight changes in the way the BARR tool calculated ramp needs. [58]

The California ISOs draft final technical appendix for the flexiramp product described the process for using historical data to estimate the probability distribution of net load forecast errors in RTD. These estimates would be based on a comparison of the net load forecast in successful RTD runs, comparing the net load forecast in the 1st advisory interval of the RTD run at t, to the net load forecast in the binding interval of the next run at t+5 as illustrated in Figure VI-10, drawn from one of the many California ISO documents explaining the methodology.[59]

Figure VI-10
Proposed Design for Histogram Construction



Source: California ISO, Flexible Ramping Product, Draft Final Technical Appendix, January 25, 2016, Figure 8, p. 11

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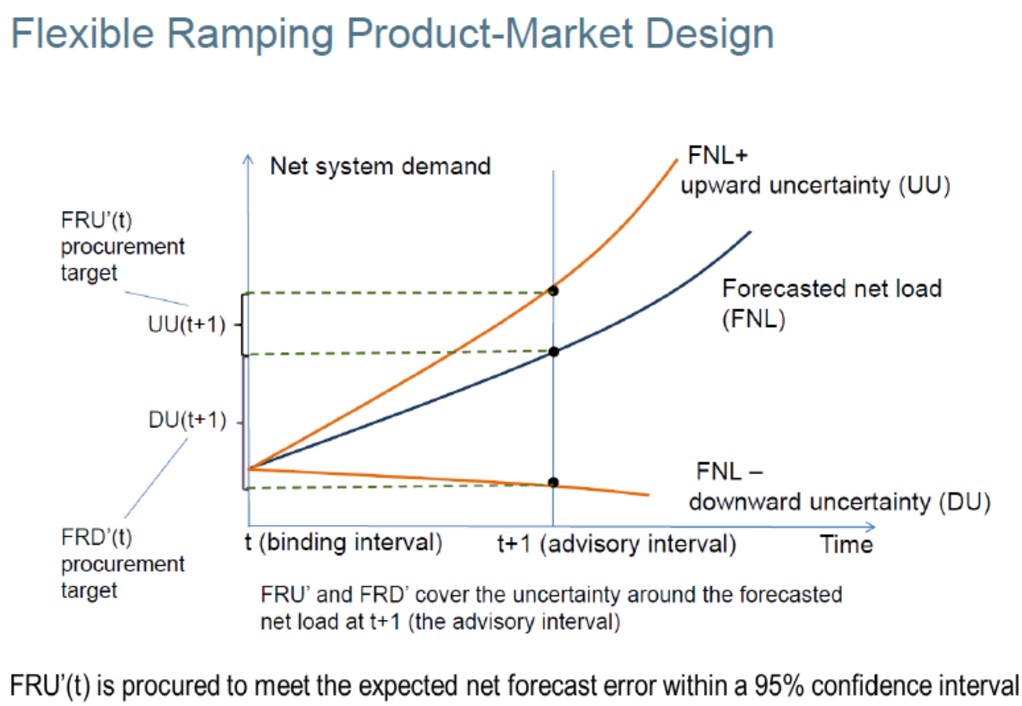
[58] See, Warren Katzenstein, California ISO, "Flexible ramping constraint discussion," Market Surveillance Committee Meeting, February 11, 2016.

[59] California ISO, Flexible Ramping Product, Draft Final Technical Appendix, January 25, 2016 p. 11. The same diagram appears in many California ISO documents portraying the ramp targets.

This probability distribution of net load forecast errors was then to be turned into a demand curve for ramp procurement in RTD by calculating the probability that a given level of ramp would be insufficient to cover the net load forecast error and result in a power balance violation so that enough ramp would be available to balance load and generation between the upper and lower bounds portrayed in Figure VI-11.[60]

Figure VI-11



Source: California ISO, "Flexible ramping product performance discussion." Market Surveillance Committee Meeting," Feb 2, 2018 p. 3.

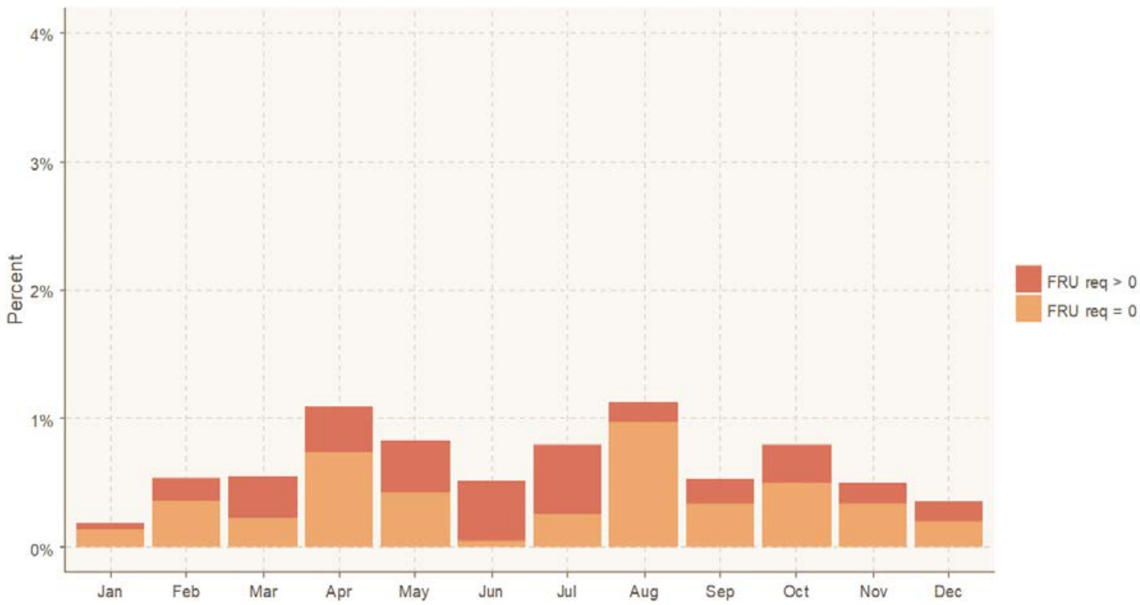
[60] California ISO, Flexible Ramping Product, Draft Final Technical Appendix, January 25, 2016 pp14-17.

The methodology for determining the ramp target for the flexible ramping product was discussed during the lengthy flexiramp product development process.[61]

When the anomalously low flexiramp RTD shadow prices were observed, an initial question was whether these prices were low because ramp capability was rarely needed. However, as discussed in subsection A above, it was found that the flexiramp price was almost always zero even during intervals with power balance violations and in the interval before a power balance violation. The next step was a California ISO analysis of the level of the flexiramp procurement target during intervals with power balance violations. This analysis revealed that in practice the flexiramp target was often set to zero during intervals with price spikes due to power balance violations. Figure VI-12 is a graph the California ISO prepared to portray the observed levels of ramp targets during dispatch intervals with power balance violations.

[61] See Roger Avalos, California ISO Department of Market Monitoring, Brliefing on flexible ramping product, Market Surveillance Committee Meeting, July 15, 2015; California ISO Department of Market Monitoring, Comments on Demand Curves in the Flexible Ramping Product Draft Technical Appendix, June 15, 2015.

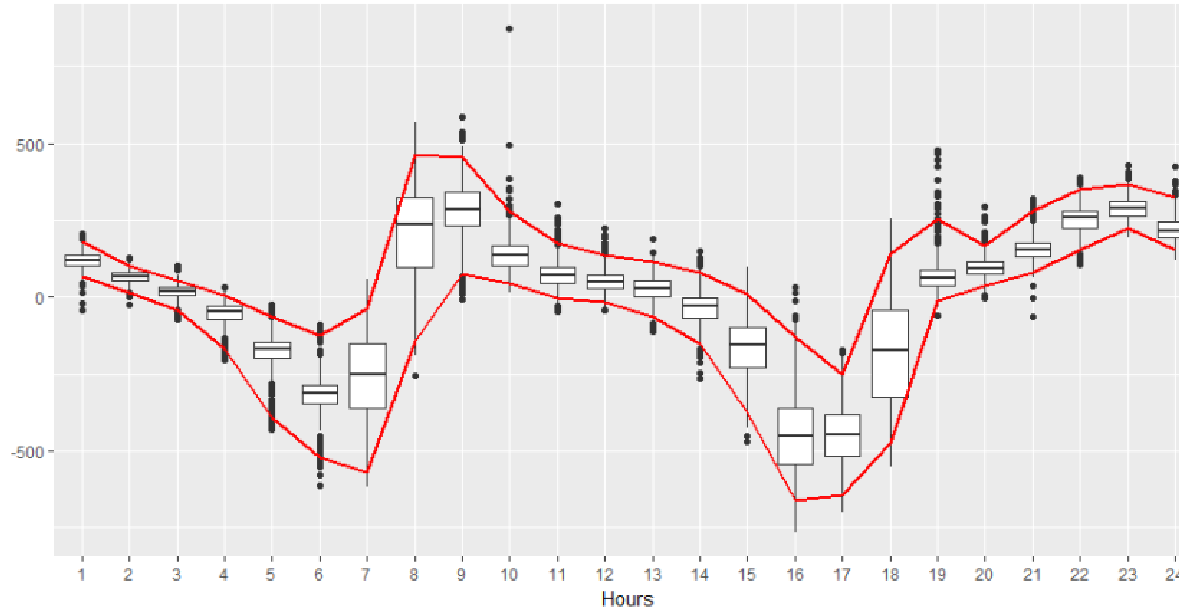
Figure VI-12
Percentage of 5 Minute Dispatch Intervals
System Reference Price Greater than $500



Source: California ISO, "Flexible ramping product performance discussion." Market Surveillance Committee Meeting," Feb 2, 2018 p. 4.

Figure VI-13 shows an illustrative California ISO histogram portraying the estimated flexible ramping requirement needs that produced the zero target for flexiramp up capacity from a recent California ISO planning forum. It is noteworthy that this diagram shows a negative need for ramp for hours 5, 6 and 7 and 16 and 17. It is hard to believe that such a relationship could exist, which suggests that there is something wrong with the data used to compile this histogram.

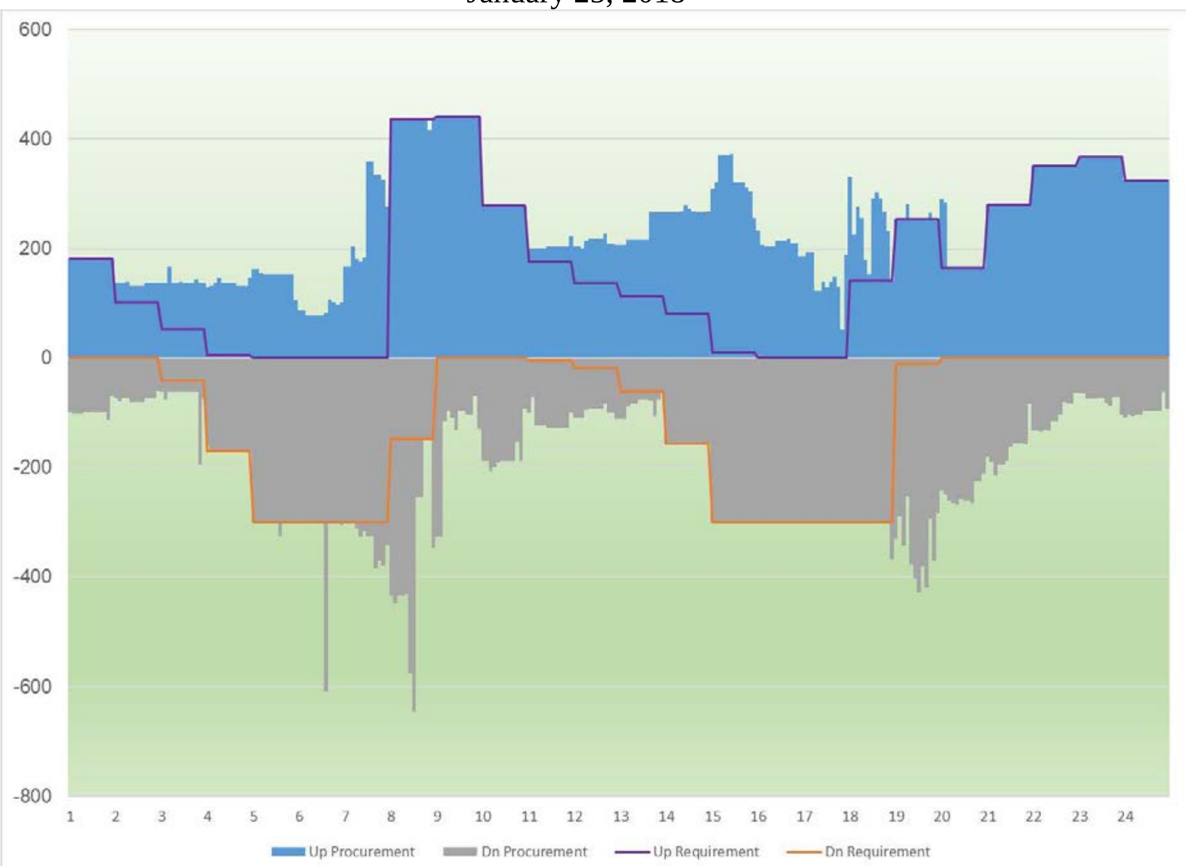
Figure VI-13
Histogram Used By CAISO to Determine Flexible Ramp Requirement



Source: California ISO, Market Performance and Planning Forum, February 20, 2018 p. 24

This histogram for ramp needs translated into a 0 ramp requirement for hours 5 ,6, 7, 15 and 16 and very low requirements for several other hours. Hence, even very low levels of available ramp would satisfy the ramp target set by this histogram, which are consistent with zero shadow prices for the ramp constraint described above. Figure VI-14 was prepared by the California ISO to portray the ramp target and procurement for a representative day in early 2018. While the zero target did not result in no ramp at all being available during these hours, it meant that the ramp target would not cause any out of merit dispatch to create ramp so the economic dispatch and cost of meeting load was the same as it would have been if the ramp product had never been implemented.

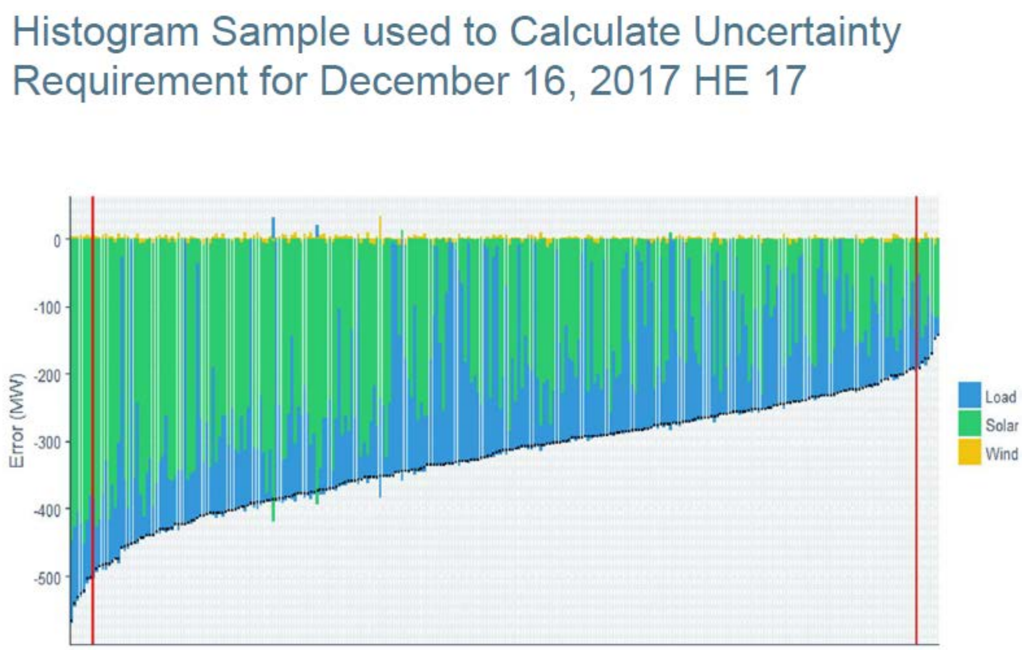
Figure VI-14
RTD Average Flexible Ramp Requirement for EIM Area
January 25, 2018



Source: California ISO, Market Performance and Planning Forum, February 20, 2018 p. 25.

The historical data used to calculate the ramp target (net-load forecast uncertainty) was examined by the California ISO in greater detail in early 2018 to understand the reasons for the low ramp targets. Figure VI-15 shows the data used to derive the ramp target for a December 2017 interval. Figure VI-15 shows a remarkable pattern in which load was always lower, and solar and wind output always higher, than forecasted, consistent with the negative ramp need portrayed in Figure VI-13 for similar hours.

Figure VI-15



Source: California ISO, “Flexible ramping product performance discussion.” Market Surveillance Committee Meeting,” Feb 2, 2018 p. 14.

It was of course very hard to believe that this pattern reflected actual load and generation forecast errors and it turned out that it did not.

With further investigation following the February 2, 2018 Market Surveillance Committee meeting, the California ISO determined that the historical ramp data had not been compiled correctly and these histograms were not correct. The California ISO Department of Market Monitoring reported that it had identfied several errors in how the California ISO had been calculating flexiramp target. First, instead of calculating load uncertainty as the change in load forecast between the advisory and binding dispatch for the same interval in successive RTD runs, this was calculated as the difference between the advisory and binding intervals in the same RTD run. The measure used in the dispatch software was therefore the negative of the projected change in load.[62] When this error was identified, the California ISO modified the calculation of the ramp need to compare the advisory load forecast from one RTD run to the binding interval load forecast used in the next interval. This comparison generally showed no change in the load forecast because California ISO system operators apparently had a practice of not allowing the updated load forecast for the binding interval to flow into RTD, so instead the binding interval load forecast was the same as the advisory interval forecast. Hence there was almost never any change in the load forecast.[63] The California ISO Department of Market Monitoring identified a number of other flaws in the implementation of the flexiramp target calculation which they concluded were less consequential.[64]

The California ISO subsequently reported that the correct histogram for January 25, 2018 should have been as shown in Figure VI-16.

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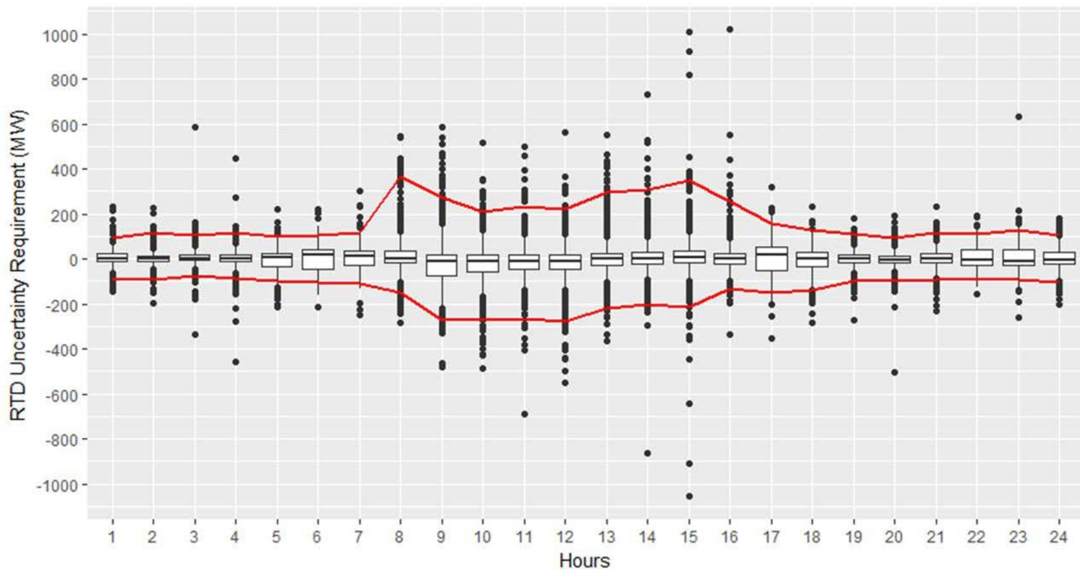
[62] See California ISO, Department of Market Monitoring, "Flexible Ramping Product Uncertainty Calculation and Implementation Issues, April 18, 2018 p. 7, pp. 9-12; California ISO, Market Performance and Planning Forum, February 20, 2018; Amber Motley, California ISO, "Flexible ramping product requirements and load forecast discussion," Market Surveillance Committee Meeting, pp. 4-8, June 7, 2018.

[63] See California ISO, Department of Market Monitoring, "Flexible Ramping Product Uncertainty Calculation and Implementation Issues," April 18, 2018 p. 18 and Amber Motley, California ISO, "Flexible ramping product requirements and load forecast discussion," Market Surveillance Committee Meeting, pp. 23-30, June 7, 2018.

[64] See California ISO, Department of Market Monitoring, "Flexible Ramping Product Uncertainty Calculation and Implementation Issues, April 18, 2018 p. 7, pp. 12-17.

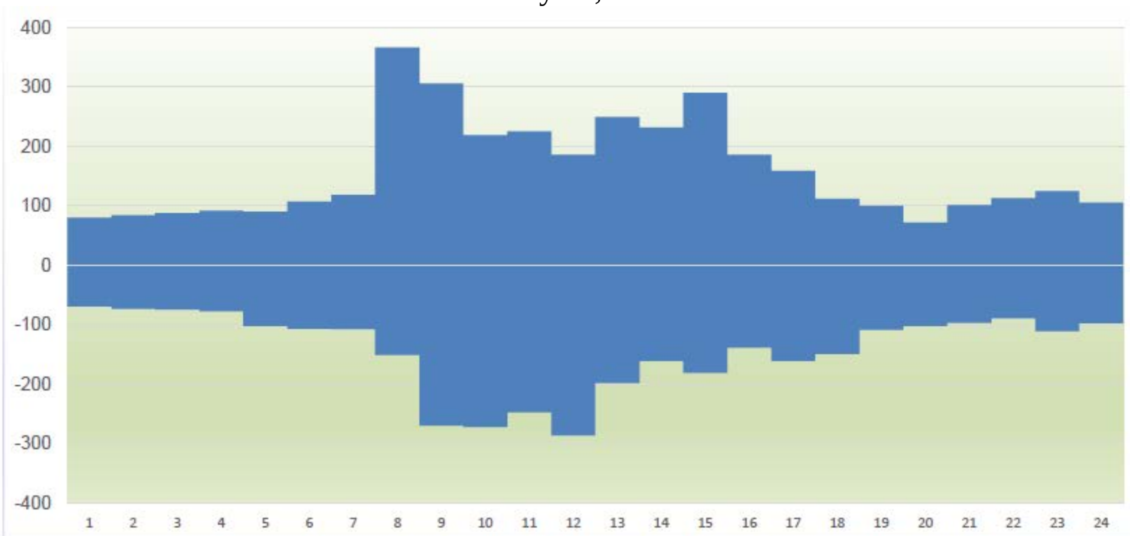
Figure VI-16
Histogram That Should Have Been Used to Determine Uncertainty Requirement
EIM Area
January 25, 2018



Source: California ISO, Market Performance and Planning Forum, February 20, 2018 p. 26

The California ISO then showed that the correct histogram would have produced a rather different set of flexiramp procurement targets for this representative day.

Figure VI-17
Intended RTD Average Flexible Ramping Product Requirement
EIM Area
January 25, 2018



Source: California ISO, Market Performance and Planning Forum, February 20, 2018 p. 27

Unfortunately, fixing the various calculation errors impacting the California ISO's estimate of ramp needs does not ensure that the California ISO's current method for estimating the ramp capability target will produce economically useful estimates of ramp needs. Once calculation errors impatcing the ramp target have been corrected, stakeholders will be able to observe how well the intended design performs in practice and assess its performance.

We highlighted above the difficulty in accurately estimating ramp needs due to the small sample sizes available if only recent data is used for the estimates. The impact of the small amount of recent data is aggravated in forecasting load and solar output by the fact that the time of sunrise and sunset are changing over the year and that there will be times of the year when looking back over 4 to 8 weeks will be associated with very different times for the sunset at the beginning of the look back period than at the end of the look back period. These temporal relationships have the potential to result in large errors if the historical data used to develop the estimate of load forecast error is tied to the same clock hour over the look back period. This suggests the need for forecasters to develop look back periods that are tied to the time relative to sunset or sunrise rather than to the clock hour. Methods of this type, such as solar contour forecasting, are already used by the California ISO in forecasting utility solar output and could be applied to forecasting ramp needs.[65] However, these alternative time calibration approaches would not reflect the impact of clock hour on gross load, which determines when people leave work and arrive at home. If gross load and solar output were separately metered these issues could be better addressed, but in the case of rooftop solar, the data used by the ISO combines the two effects, making it very difficult for the California ISO to disentangle the two effects in developing forecasts.

In addition to using larger sample sizes to estimate potential errors in the net load forecast, it is possible that cost effective implementation of ramp capability dispatch will need to go further than just basing the ramp target on the time of day but will need to factor in whether intermittent output is high (hence more likely to go down a lot) or low (and hence not likely to require a lot of ramp up). The CAISO is not taking these conditions into account in setting its ramp target and neither is the MISO.

MISO

In contrast to the CAISO, the MISO has published limited information about the ramp capability targets used in its day-ahead market and real-time dispatch. Thus, in our anlaysis we are limited to reviewing data on ramp product performance reported by MISO for the May – September 2016 time period. The determination of theMISO ramp capability target may be less impacted by the problems that the CAISO has encountered because the MISO load forecast is much less impacted by the output of behind the meter solar generation resources.

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[65] See Amber Motley, California ISO, “Flexible ramping product requirements and load forecast discussion,” Market Surveillance Committee Meeting, pp. 15-20, June 7, 2018

The MISO includes its ramping product in both the day-ahead and real-time markets. The determination of ramp capability targets for the day-ahead time frame are different than for real-time. The MISO sets its real-time ramp capability target based upon the expected change in net-load plus a measure of forecast uncertainty over the next two dispatch intervals (i.e., ten minutes).[66] The MISO sets its day-ahead ramp capability target similarly, but the expected net-load variability and forecast uncertainty are scaled to an hourly basis.[67] The objective in both the day-ahead and real-time market is to have available ramp up and ramp down capability to accommodate variations due to expected changes in net-load and forecast uncertainty.

Net-Load Change

The MISO analyzes the expected change in load, intermittent generation output, and net-scheduled interchange (NSI)[68] using historical data to estimate variations in in net-load. When MISO developed its ramp capability product it calculated net-load changes for different hourly time periods during the day for each month of the year.[69] MISO calculated forecast net-load change and variations in the actual net load change for four separate periods during the day: 1) on-peak period; 2) off-peak period; 3) morning ramp up period, and, 4) afternoon/evening ramp up period. MISO observed differences in the range of net-load changes month-to-month and its ramp up and ramp down requirements in each of these periods. The net-load changes within and across the hours assocoiated with these different daily time periods reflect the underlying variation in load, wind generation and NSI.

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[66] Navid N., and Rosenwald, G., Ramp Capability Product Design for MISO Markets, Market Development and Analysis, 12/22/2013.

[67] MISO, Energy and Operating Reserve Markets Business Practices Manual, BPM-002-r15, Effective Date: MAR-17-2016, at 3.30-31.

[68] MISO is a subtanial net-importer of eletricity and 2016 average day-aehad and real-time import quantities were 2,400 MW and 5,600 MW, respectively (Potomac Economics, MISO 2016 State of the Market report at 63).

[69] Navid N., and Rosenwald, G., Ramp Capability Product Design for MISO Markets, Market Development and Analysis, 12/22/2013.

Net-Load Uncertainty

The second component of the MISO ramp capability target requirement is derived from the forecast errors for load and generation, and dispatchable resource deviations from set-points.[70] MISO analyses during the development of the ramp product provided illustrative estimates of these values based on statistical analysis of the load and wind generation forecast errors, and dispatchable resource deviations.[71] Combining statistical analyses of forecast error and dispatch deviations yielded an illustrative estimate of net-load uncertainty of ±625 megawatts at a confidence level of 99%.[72] However, an uncertainty level of ±575 megawatts was recently reported as currently being used for the MISO's ramp capability product.[73]

Real-Time and Day-Ahead Ramp Capability Targets

The MISO calculates values for the net-load uncertainty ramp capability targets in the up and down direction for all intervals in the day-ahead and real-time markets.[74] The net-load change is calculated for a time interval of 10-minutes in the real-time market and scaled up in the day-ahead market and other forward processes to a time interval of an hour. While the actual MISO ramp capability targets used day-to-day are not published,[75] Figure VI-18 is the MISO's portrayal of reported average hourly ramp up and down capability requirements (covering both expected and unexpected variations in

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[70] There is no NSI forecast error as interchange schedules are fixed 20 minutes prior to real-time.

[71] Nivad Navid, Gary Rosenwald, "Ramp Capability Product Design for MISO Markets," 12/22/2013 at 10-11.

[72] Id.

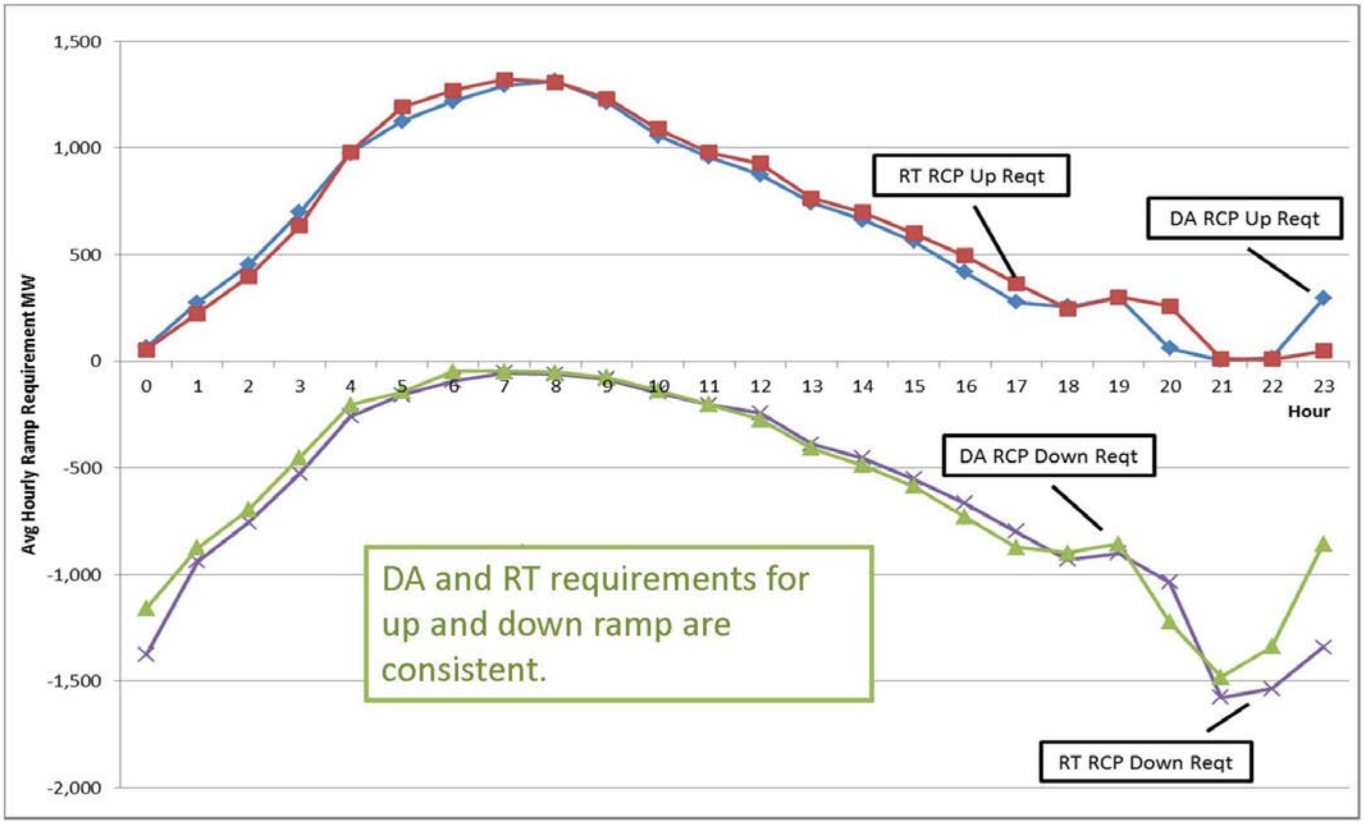
[73] Avallone, E.D., Market Design Concepts to Prepare for Significant Renewable Generation, Flexible Ramping Product, NYISO, March 7, 2018, at 12, available at: http://www.nyiso.com/public/webdocs/markets_operations/committees/bic_icapwg/meeting_materials/2018-03-07/Market%20Assessment%20Design%20Concepts%20-%20Flexible%20Ramping%20Product%203%207%202018.pdf.

[74] MISO Energy and Operating Reserves BPM Section 3.4.2.

[75] Communication with MISO Client Relations, May 3, 2018.

net load) in the May-September 2016 time frame ranging from nearly zero to roughly ±1,300 megawatts.[76]

Figure VI-18
MISO Hourly Average Ramp Capability Product (RCP) Requirements
May 1, 2016 – September 30, 2016



MISO, Market Subcommittee, "Ramp Capability Product Performance Update", November 29, 2016, available at: https://cdn.misoenergy.org/20161129%20MSC%20Item%2005f%20Ramp%20Capability%20Post%20Implementation%20Analysis74816.pdf

The MISO's depiction of the application of the ramp capability targets for ramp up and down is shown in Figure VI-19. The vertical blue bars represent the equal amounts of ramp up and down that are procured above and below the forecasted load (solid black line). The amount that is procured is fixed for ten-minutes and provides the amount of

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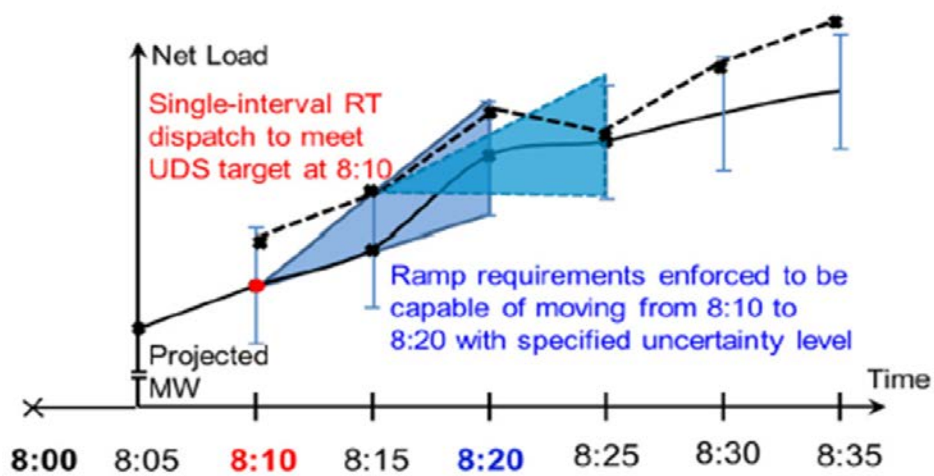
[76] MISO, Market Subcommittee, "Ramp Capability Product Performance Update", November 29, 2016, at 10, available at: https://cdn.misoenergy.org/20161129%20MSC%20Item%2005f%20Ramp%20Capability%20Post%20Implementation%20Analysis74816.pdf

ramp capability that is needed to meet the forecast change in net load over the next ten minutes and provide a margin to cover net load forecast uncertainty above and below projected net load. As load changes (shown as a dashed line), the dispatch attempts to maintain sufficient ramp capability to meet projected changes in netload. After ten minutes elapse a new ten-minute requirement is applied for the next ten minute interval.

Figure VI-19
MISO Ramp Capability Target Example



MISO, Market Subcommittee, "Ramp Capability Product Performance Update", November 29, 2016, available at: https://cdn.misoenergy.org/20161129%20MSC%20Item%2005f%20Ramp%20Capability%20Post%20Implementation%20Analysis74816.pdf

Figure VI-19 portrays how the real-time ramp capability target is applied for the single interval dispatch. In the day-ahead market the MISO uses hourly values, which vary throughout the day based on net-load variability, for its ramp capability targets.

The MISO has employed a much simpler ramp capability target for net load uncertainty than the California ISO, using a single ramp target for net load uncertainty over all hours of the day and year. This choice in part reflects the different sources of unexpected changes in ramp needs in the MISO, which is less impacted by variations in utility and behind the meter solar generation output than the California ISO, and much more industrial load than the California ISO. Nevertheless, evolving the MISO ramp target to set a higher target in periods of the day in which the incremental ramp is more likely to have a high value would be a potential source of long run improvements in the MISO design. A more pressing issue in the MISO, however, is the setting of locational ramp targets which is discussed next.

C. Locational Requirements

The initial flexiramp implementations in CAISO and MISO did not impose restrictions on the location of resources providing ramp capability to meet the California ISO or MISO ramp target. These non-locational procurement designs create the potential for ramp capability to be procured in a location where it cannot be dispatched to balance load and generation in real-time because of transmission constraints. The potential need for locational constraints on the procurement of ramp capability was recognized by both the California ISO and the MISO in the development of their designs. Moreover, the need for locational ramp targets was suggested by issues the California ISO experienced with the use of a single system wide target for ramp capability in its flexiramp constraint design in RTPD over the period since December 2011. The flexiramp constraint target in RTPD was California wide and at times was met with undispatched capacity in PG&E's service territory in Northern California, which had a low opportunity cost precisely because transmission constraints prevented it from being dispatched to meet load in southern California, and also meant that it could not be dispatched up to meet variations in net load in southern California.[77] This pattern of constrained down resources being designated to provide ramp capability in RTPD appeared to change in 2014 and very few power balance violations were subsequently identified as related to transmission congestion.[78]

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[77] California ISO, Department of Market Monitoring, Q3 2012 Report on Market Issues and Performance, November 13, 2012 pp. 44-45; 2012 Annual Report on Market Issues and Performance, April 2013 pp. 88-89

[78] See California ISO, Department of Market Monitoring, 2014 Annual Report on Market Issues and Performance, June 2015 p. 84- Figure 3.8

In part because the congestion during ramp constrained intervals that was present in 2012 appeared to disappear in 2014 and later years, and in part due to the complexity of analyzing possible congestion patterns and differences in the locational value of ramp prior to implementation of the California ISO ramp dispatch, it was decided that the initial California ISO ramp dispatch implementation would be based on a California ISO balancing area wide target.

The scope of the Western EIM was expanding, however, at the same time the California ISO ramp dispatch was being implemented and the design that was actually implemented allowed the California ISO balancing area ramp capability target to be met with ramp capabilility on resources located in other EIM balancing areas. This design has proved problematic because a material amount of ramp capability has been scheduled in balancing areas within the Western EIM which are export constrained, so the ramp capabilility scheduled to meet the target has not been available for use when other balancing areas within the Western EIM, including the California ISO, are ramp constrained.

The MISO also analyzed the congestion patterns associated with ramp constraint driven price spikes prior to implementation and made a similar decision to initially implement a MISO wide ramp target.[79]

As a result of these decisions, neither the MISO nor California ISO ramp dispatch implementation has locational requirements within the MISO or California ISO balancing areas. This was a recognized limitation of the initial designs, and it was recognized that this design choice would need to be reexamined after the designs were implemented to assess whether changes were needed. It appears to us that one of the lessons from these initial implementations is that at least some degree of locational target setting needs to be implemented within dispatch regions as large as the MISO and the Western EIM.

[79] See Direct Testimony of Joseph Gardner, MISO filing in Docket ER14-2156, October 31, 2014 p. 15. MISO Tariff Section 39.2.8A and Schedule 28, Sections VI and VII.

California ISO and Western EIM

The flexiramp design implemented by the California ISO includes ramp capability targets for each balalncing area within the western EIM. These locational restrictions, if binding, would tend to spread ramp capability across the footprint. However, the design implemented in December 2016 allows the balancing area ramp requirement to be met with ramp capability elsewhere in the EIM, as long as the balancing area has sufficient import capability.

The flaw in this implementation design is that it does not test whether the balancing area providing the ramp capability has sufficient export capability to deliver the power from the resource providing the ramp capability to the balancing area needing the ramp capability. Import and export capability are essentially the same if there are only two balancing areas involved, but when there are many balancing areas with intervening balancing areas between the source and sink balancing areas for the ramp, and multiple potential contract paths, testing whether a balancing area has enough import capability in aggregate does not ensure that resources in a particular other balancing area could be used to meet load.

This design has had the consequence that the California ISO flexiramp implementation can count ramp on resources in EIM Balancing Areas outside the California ISO as meeting the California ISO balancing area ramp requirement, despite binding transmission congestion between those other balancing areas and the California ISO. As a result, it has often been possible to meet the California ISO ramp target at 0 cost in RTD, at the same time that the California ISO has had insufficient ramp to balance load and generation as discussed in section VI.A, because the ramp capabability scheduled is on resources that are constrained down in remote balancing areas and cannot be used to balance load and generation within the California ISO due to congestion between those balancing areas and the California ISO.

As noted above, this implementation design reflects changes in the flexiramp design subsequent to the discussion with stakeholders. With the expansion of the EIM over this period, the design was modified to allow the real-time ramp targets of EIM participants, including the California ISO, to be met with ramp capability in other EIM balancing areas if balancing area relying on external ramp had enough unloaded import capability on the ties to utilize the external ramp. However, the new design did not test whether the ramp capability in the other EIM balancing areas could be dispatched to meet California load.

As the number of EIM balancing areas has increased, there is an increased potential for the California ISO to have unutilized import capability from some balancing areas but not to be able to import power from particular balancing areas in which flexiramp was scheduled. This issue was discussed at the September 8, 2017 MSC meeting[80] and at the October 5, 2017 Planning Forum.[81]

A California ISO analysis has shown that only about half of the scheduled flexirramp capacity was typically dispatched during price spikes and power balance violations. Moroever, 90% or more of the undispatched ramp capability could not be dispatched because of transmission congestion.[82]

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80 California ISO, Lin Xu, "Discussion on flexible ramping product," Market Surveillance Committee Meeting, September 8, 2017, pp12-14, available at:http://www.caiso.com/Pages/documentsbygroup.aspx?GroupID=DFA367FE-AFBA-4DF2-8B8D-1417F7E0F33E

81 California ISO, Market Planning and Performance Forum, October 5, 2017, http://www.caiso.com/Documents/Agenda-Presentation-MarketPerformance-PlanningForum-Oct5_2017.pdf Some of this material is repetitive of the MSC meeting materials but some is additional based on the discussion at the meeting.

82 The California ISO analysis also showed that there were some circumstances in which energy was not available from resources scheduled to provide ramp capability because of daily energy limits or interactions with ancillary service schedules in particular intervals. California ISO, Lin Xu, "Discussion on flexible ramping product," Market Surveillance Committee Meeting, September 8, 2017, p 15.

The consequence of these transmission constraints has been that when there is a power balance violation, much of the generation scheduled to provide flexiramp cannot be used to balance load and generation because the resources scheduled to provide flexiramp are constrained down behind a transmission constraint. This transmission congestion likely accounts for many of the situations in the California ISO in which there is a power balance violation in real-time yet the price of ramp not only does not rise to the $247 penalty price, but is zero both in the interval prior to the power balance violation and the interval in which the power balance violation occurs.

MISO

The low price and value of ramp capability in the MISO during the initial implementation period was likely also due at least in part to the lack of locational ramp requirements in the initial design. The data in Table VI-8 above showed that of the 240 intervals with a reference bus price at or above $200 (1374-1134), there were 127 intervals with a 0 ramp price (807-680). In 85 of these 127 intervals there were major zones within the North MISO with a zonal price less than $100 and 67 intervals in which zones in the South had a zonal price less than 100. In 93 of the 127 intervals zones in either the Northern or Southern MISO had a zonal price less than $100. These data suggest that some of the ramp that met the MISO system-wide ramp target may have been located within the lower priced constrained down regions and hence not able to provide ramp at the locations where it was needed in real-time because of tranmission constraints on the MISO transmission grid.

Similarly, over the period April 1, 2017 through April 30, 2018 there were 1289 intervals in which the price equalled or exceeded $200 in a major north zone and the reference bus price was less than $100, implying a high price of energy within a local area but not across the MISO. The price of ramp was equal to zero in 1080 of these intervals, again suggesting that the ramp procured was located where it could not be dispatched to meet load within the high priced zones.

Over the period April 1, 2017 to April 30, 2018 there were 1775 intervals in which one or more load zones in the south had prices at or exceeding $200, and the reference bus prices was less than $100. The price of ramp was 0 in 1597 of these intervals, again suggesting that a portion of the ramp counted to meet the target was likely scheduled in low priced constrained down regions in which it could not be dispatched to meet load price spikes. The conclusion we draw from these analyses is that other system operators implementing ramp capabilility dispatch designs should make an effort to include locational targets in their initial design and seek to incorporate software flexibilty to adjust the structure of these requirements over time.

D. Penalty Price

We observed in section V that a core feature of ramp capability dispatch designs is the penalty price used to determine whether ramp capability will be used to reduce the cost of balancing load and generation in the current dispatch interval or reserved for use in future intervals.

California ISO

We discussed above the very high ($247 per megawatt hour) penalty price used in the California ISO's original implementation of the flexiramp constraint, reduced to $60 per megawatt hour in early 2015. With the implementation of the flexiramp product the California ISO shifted to using a demand curve, with a penalty price reaching $247 for the amount of ramp needed to meet the forecasted change in load, down to zero when more than the amount of ramp needed to meet both the forecast ramp need and to provide the target uncertgainty margin was available.

The methodology the California ISO proposed to use to define this demand curve was to calculate a probability distirbution of load forecast errors based on the difference between the advisory and binding load forecast interval as described above, using ranges such as errors of 0-100 megawatts, 100-200, etc. The value of upward ramp was calculated by the $1000 penalty price for a power balance violation, times the probability of a load forecast error in each range. Thus, if there were a 2.2% probability of a load forecast error in excess of 100 megawatts, the penalty price for having less than 100 megawatts of ramp to cover the uncertainty margin for the interval would be $22.[83]

MISO

The MISO nominally uses a single $5 penalty price for reserving or using ramp capability.[84] However, the MISO ramp dispatch design needs to be assessed in combination with the penalty prices for spinning reserves and regulation. The MISO uses a spinning reserves target that is roughly two hundred megawatts in excess of its reliability requirement and up to 100 megawatts of spinning reserves can be dispatched to meet load at a penalty prices of $65, with the remaining spinning reserves dispatched at a penalty price of $98.[85] In addition, ramp on resources providing regulation would be available for dispatch at a penalty price of $175.[86] Hence the MISO design in practice releases up ramp at a sequence of prices ranging from $5, to $65, to $98 to $175. The ramp capability dispatch design in MISO therefore essentially adds an additional target for ramp capability that is released at a lower shadow price than spinning reserves, reducing the frequency that spinning reserves are used to balance small variations in net load.

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83 See California ISO, Flexible Ramping Product, Draft Final Technical Appendix, January 25, 2016 pp 16-17.

84 See MISO Filing Letter, ER14-2156 June 10, 2014 MISO Tariff Schedule 28 Sections VI and VII.

85 See Potomac Economics, 2016 State of the Market Report for the MISO Electricity Market, Analytic Appendix p. 55; MISO Tariff section 39.2.8A, Schedule 28, MISO, Energy and Operating reserve Markets, Business Practice Manual, Section 5.2.1.5; MISO Filing Letter in Docket Er12-1185, March 2, 2012.

86 MISO, Energy and Operating Reserve Markets, Business Practice Manual, Section 5.2.1.3.

E. Value of Ramp on High Cost Resources

If the ramp capability target is met solely based on an evaluation of the megawatts of deliverable ramp available on a resource, and no account is taken of the energy offer prices of the resources scheduled to provide the ramp, some of the ramp capability that is counted on to balance load and generationcould be very high cost supply whose offer price if dispatch might provide very little production cost savings relative to the production cost of a power balance violation. This possibility raises the question of whether supply offered at very high prices should be included in the calculation of the available ramp and receive a payment.

The value of incremental ramp capability in reducing the cost of meeting load should decrease with increases in the offer price of the dispatchable resource. Hence, if implementation complexity were not a consideration, the ideal design would assign decreasing value to incremental ramp capability based on its offer price.

This issue was discussed in the development of the CAISO flexiramp product and the MISO ramp capability product. In both cases it was decided not to attempt to address this possibility in the initial implementation and examine operating experience to assess if there was a material problem to address in practice. [87]

A potential concern for the California ISO with pondage hydro resources in the Pacific Northwest participating in the western EIM, is that energy limited hydro resources could be offered as sources of ramp, but the energy could have such a high energy offer price that there would be little or no production costs savings from using the ramp available on these resources to balance load and generation. The capacity that is scheduled to provide ramp capability in a ramp capability dispatch design differs from the capacity that is

[87] See, for example, Lin Xu and Donald Tretheway, California ISO, Flexible Ramping Products, Draft Final Proposal, April 9, 2012 section 2.1.4.

scheduled to provide spinning contingency reserves in that the capacity providing ramp is intended to be dispatched to provide energy on an ongoing basis.

Hence, while the energy offer price of the capacity providing contingency reserves has little impact on the production cost of meeting load because it will rarely be dispatched, the value of capacity providing ramp capability depends on the capacity actually being dispatched to reduce the cost of balancing load and generation. If the offer price for the energy on resources providing ramp capability is very high, the resources have little value in providing ramp capability.

The California ISO and MISO may have to address this cost issue not only for pondage hydro resources able to provide ramp but for other types of storage resources which might find it profitable to offer ramp capability at very high prices (the high prices enabling the resource to limit the frequency with which it is dispatched so it would be paid for providing ramp capability in many intervals with non-zero ramp prices).

A similar possibility for supplying ramp capability from resources with very high offer prices exists for demand response resources that do not want to be dispatched to reduce consumption but are willing to be paid for offering to curtail consumption at very high prices.

The application of a local or system market power mitigation test might prevent thermal resources from offering supply at very high prices but mitigation would not address the case of resources with a truly high cost of supplying energy entering the market to supply ramp capability having little or no value. The supply of ramp capability from resources with very high offer prices is not a major concern today with very low ramp prices in RTPD and RTD but if the implementation of locational targets increased ramp prices to a more remunerative level, and the ramp capability dispatch began to better achieve its intended goals, it may be more important to apply some form of limits to supply of ramp from very high cost resources or adjust the compensation in some manner.

The problems with the initial implementations of ramp capability dispatch in the California ISO and MISO have also reduced the value of the current implementations for assessing the potential importance of taking offer prices into account because the price of ramp capability has so often been zero.

As these initial implementation issues are addressed and the potential revenues from providing ramp capabilility become more material, it may become more important to account for the offer price of energy supply in scheduling ramp capability. One possible approach would be to not count ramp capability if the energy is offered at prices above a threshold set by the system operator and perhaps related to the penalty price for power balance violations.[88] Neither the California ISO nor MISO included such a offer cap in their initial implementations.

Another possible approach would be to include a percentage of the energy cost of supply offered as ramp in the evaluation of ramp, so that resources with a high energy price would be treated in the dispatch optimization as having a higher cost to supply ramp capability.

F. Sustained Ramp Capability

The initial implementations of the California ISO and MISO real-time ramp dispatch designs set targets for five minute ramp capability. There is a potential, however, for a ramp dispatch design based solely on a five minute dispatch target to position generation so that the ISO has enough 5 minute ramp in order to avoid power balance violations in the first interval of a change in net load, but to have that ramp capability drained from the

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[88] It is important that putting in such a ceiling does not create any incentive to raise offer prices, as suppliers face the same competition in the energy market with or without a ramp capability dispatch. The issue is simply that of paying the same price for ramp capability which provides lower benefits, and potentially incenting high cost resources to incur costs to increase their ramp rate, when that added ramp rate has limited value.

system over an interval or two of a sustained forecast error, with the consequence that the ramp dispatch only delays the power balance violation for an interval.

The California ISO and MISO ramp designs address the need to maintain ramp over time directly because the penalty price for the ramp target for the next interval will cause the dispatch for the current interval to balance load and generation without reducing the ramp available for the next interval as long as the cost of preserving the ramp does not exceed the penalty price (this would be achieved by using ramp on resources that are limited in the amount of ramp they provide by their ramp rate, rather than by their capacity, to balance load and generation). The California ISO flexiramp design also addresses the need to have ramp available over a period of time by setting a higher ramp target for 15 minute RTPD intervals than is applied in the five minute RTD intervals and by enforcing the ramp target over the multiple interval horizon of the California ISO's real-time dispatch.

VII. Conclusions

Our assessment is that the most valuable near term improvements in both the California ISO and MISO ramp capability dispatch designs would be to begin to implement some form of locational targets so as to schedule ramp where it is likely to have a high value and to avoid paying for ramp capability at locations where incremental ramp capability has little or no value. The second priority, particularly in the California ISO, is to continue refining the process for setting the ramp targets and penalty prices. With the major errors in the California ISO's calculation of the ramp targets hopefully corrected, further improvements can be deferred until the locational target issue has been addressed. A longer run research and development issue is how to account for the cost of the energy that would be available to provide ramp both in scheduling ramp capability and potentially in determining compensation.

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End Note A

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