Flexible Ramping Products

Third Revised Straw Proposal

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1. INTRODUCTION

This paper will describe the ISO's proposal to define the upward and downward flexible ramping products. The purpose of this stakeholder effort is to develop market-based flexible ramping products to address the operational needs in real-time market facing the upcoming challenges from increasing renewable penetration. Prior to these market-based full flexible ramping products, the ISO has proposed to implement a flexible ramping constraint to address certain reliability and operational issues observed in the ISO's operation of the grid.[1] Upon the completion of the Flexible Ramping Constraint stakeholder process, the ISO recognized that greater market effectiveness can be gained by developing market-based products that allow for the identification, commoditization and compensation for the needed flexible capability. The ISO has observed that the unit commitment resulting from the real-time unit commitment process (RTUC), also known as the real-time pre-dispatch (RTPD) process, and the position of units in real-time dispatch (RTD) sometimes lack sufficient ramping capability and flexibility to handle the 5-minute to 5-minute energy imbalances. For example, the insufficient ramping capability sometimes manifests itself in triggering power balance violations, which means the there is no feasible system wide RTD schedule to maintain supply and demand power balance. In this case, the system has to rely on regulation services to resolve the issue in real delivery time after the imbalance has caused

[1] See CAISO Technical Bulletin "Flexible Ramping Constraint" for detailed discussion of the constraint, http://www.caiso.com/Documents/TechnicalBulletin-FlexibleRampingConstraint_UpdatedApr19_2011.pdf, February 2011. See California ISO Tariff Amendment Proposing the Flexible Ramping Constraint and Related Compensation: http://www.caiso.com/Documents/2011-10-07_FlexiRampConstraint_Amend.pdf

frequency deviation or area control error (ACE), which is undesirable outcome. If there is insufficient regulation service, the result of insufficient ramping capability may result in leaning on interconnection. In addition, when power balance is violated, the RTD energy price is not priced by economic bids, but by administrative penalty prices, which may impact market efficiency in the long run.

The flexible ramping products to be developed in this stakeholder process will help the system to maintain dispatchable flexibility in terms of ramping capability. The flexible ramping products specifically target the 5-minute RTD imbalances due to variability and uncertainties. The term "variability and uncertainties" is used in the ISO's 20% renewable portfolio standard study in the context of load following requirements.[2] Specifically, the variability may come from market granularity differences in load profile and variable energy resource supply. Variability may also arise due to unit startup/shut down profile, multi-stage generator transition profile, and inter-tie schedule inter-hour ramping profile. The uncertainties may include everything that has a random nature, such as load forecast error, variable energy resources' forecast error, and other uninstructed deviations. We use the same term to make connections with the ISO's previous study from a conceptual level, and will clarify the differences between flexible ramping products and load following later in the proposal. Scheduling coordinators (SCs) will be allowed to offer ramping capabilities into the market, and the ISO will optimize such offers to economically meet the anticipated 5-minute imbalances. In order to better demonstrate the purpose and characteristics of the flexible ramping products to be developed in this process, this document includes a discussion of prospective products in the context of the existing processes and ancillary services products.

As a balancing authority, the ISO maintains power balance in real-time operations. Due to the complexity of modern power systems and electricity markets, the task of maintaining power balance is handled in a hierarchy of different time frames. The ISO operates the day-ahead market and performs residual unit commitment on the day prior to the actual operating day as the first attempt to establish balanced supply and demand schedules, commit resources adequately, and procure ancillary services. In the actual operating day, as illustrated in Figure 1, the ISO employ several real-time processes to commit resources adequately, dispatch them economically, procure additional ancillary services for system reliability, and deploy them when they are needed. The supply and demand condition at the actual delivery time may have been impacted by the decisions made in the following processes before the actual delivery time.

From about 5 hours to 15 minutes ahead of the actual delivery time, the RTUC processes perform unit commitments every 15 minutes on a 15-minute interval basis, and procure ancillary services (on top of day-ahead and hour-ahead procurements) for the coming 15 minutes.

About 5 minutes ahead of the actual delivery time, the RTD performs economic dispatches every 5 minutes on a 5-minute interval basis.

If a major contingency happens, the operator may choose to perform a special process, the real-time contingency dispatch (RTCD), to economically deploy operating reserves (spinning reserve and non-spinning reserve) in order to restore the system back to normal operating conditions. RTCD performs both unit commitments and dispatches on a 10-minute interval basis.

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[2] CAISO, Integration of Renewable Resources, http://www.caiso.com/2804/2804d036401f0.pdf

At the actual delivery time, a system imbalance will manifest itself in system frequency and inadvertent transfers between other balancing authority areas or Area Control Error (ACE), and will trigger the utilization of automatic generation control on resources that are awarded regulation services in day-ahead for the corresponding hour or in RTUC for the corresponding 15-minute interval.

Electricity is different from other commodities in that it is produced and consumed instantaneously, and both supply and demand are constantly changing. These properties pose a great challenge to the ISO to maintain power balance every minute and every second. That is why it is necessary to have temporal hierarchical processes to look ahead at future supply and demand conditions, and reserve dispatchable capacities as ancillary services. Currently, the look-ahead is performed in a deterministic way to balance expected supply and expected demand in the future. Assuming the load forecast and resource schedules are close to their expected values, this approach should work well. The electric power industry has been operated in this way for a long time. However, with the increased amount of variable energy resources, whose actual outputs may vary, and cannot be accurately forecasted, looking ahead at expected values may be insufficient to maintain power balance in RTD, a reliability concern. In order to operate the grid reliably, the ISO proposes to define the flexible ramping products, which provides a market mechanism for procuring sufficient ramping capability to handle RTD the imbalances.

As illustrated in Figure 1, variability and uncertainties are classified into two categories according to the time they are realized. The market clearing granularity difference between RTUC and RTD results in 5-minute variability to be realized in RTD. In addition, certain uncertainties are also realized after RTUC and before RTD. These post RTUC uncertainties include load forecast changes, variable energy resources production changes, uninstructed deviations, and forced outages. The post RTUC variability and uncertainties are continuously realized in 5-minute steps. Each RTD will "recourse"[3] to the realization in the first 5-minute interval. Approaching actual delivery time after the RTD run, the difference between actual supply/demand outputs and RTD supply/demand schedules results in post RTD variability and uncertainties. This real-time variability is caused by using the 5-minute granularity in RTD to approximate continuous output in real-time. These post RTD uncertainties include deviations of actual load from RTD load forecast, uninstructed deviations, small outages which happen in real-time, and so on. Because RTD is the last opportunity for sending out dispatches under normal operating conditions, the post RTD uncertainties once realized can only be handled by automatic generation controls (AGC), which are procured in day-ahead or corresponding RTUC as regulation services. The difference between the two categories of variability and uncertainties and how to address them are illustrated in Figure 2.

[3] "Recourse function" is a terminology in stochastic optimization, which specifies how to adapt to the realized uncertainties.

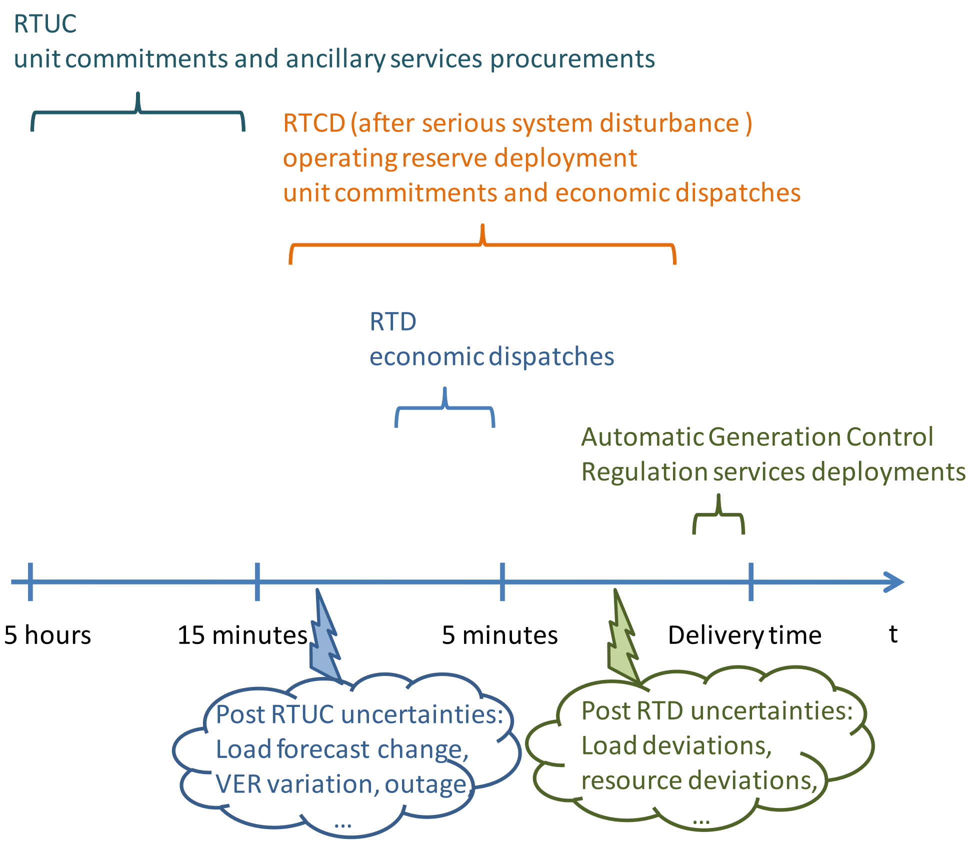

FIGURE 1: REAL-TIME MARKETS TIME FRAME

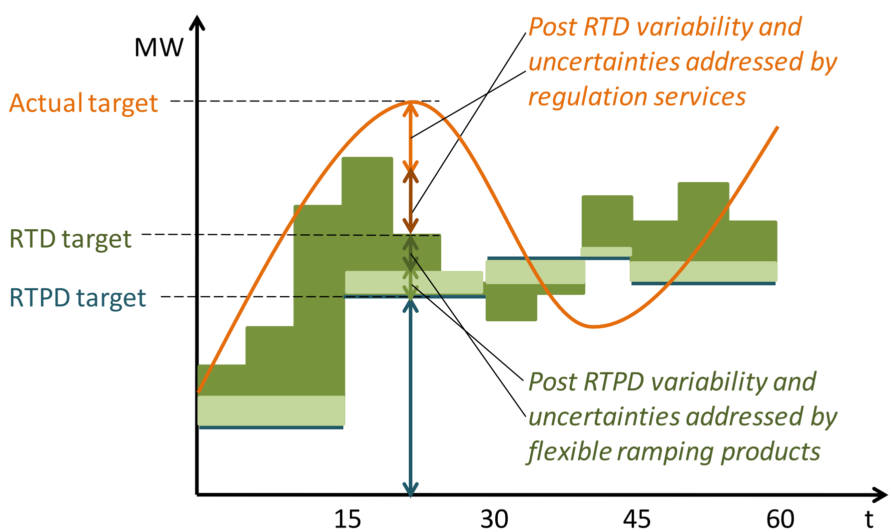

FIGURE 2: HANDLING VARIABILITY AND UNCERTAINTIES WITH FLEXIBLE RAMPING PRODUCTS AND REGULATION SERVICES

The objective of the flexible ramp product is to build dispatch flexibility in terms of ramping capability in RTD to meet imbalances that may arise in the future. Imbalances can arise due to load and supply variability and uncertainties. Variability can be expressed as the difference between hourly (load following) or 15 minute (flexible ramp) average net load and 5 minute average net load. Uncertainties can be expressed as the differences expected net load and the expected net load plus forecast error. Flexible ramping product is similar to load following referred to in renewable integration planning studies except that the load following variability component is based on the difference between hourly average net load and the 5 minute average net load levels accounting for uncertainties while the flexible ramp product variability component is based on the difference between 15 minute average net load and 5 minute average net load. In an operational timeframe that has a 15-minute unit commitment process such as RTUC, it is appropriate to consider the flexible ramp product quantifying the difference between net load in RTUC 15-minute interval and the 5-minute interval. For a particular interval, the difference between load following requirement and flexible ramp requirement is addressed by the RTUC commitment. The following conceptual relationships attempt to illustrate the relationship of load following and flexible ramp product and their associated contributions.

Load Following Up = $\text{Variability}_{\text{up-hourly}} + \text{Uncertainty}_{\text{up}} \approx \text{Flexible RampUp}_{15\text{min}} + \text{RTUCUp}_{15\text{min}}$

where

$\text{Variability}_{\text{up-hourly}} = \max(\text{NetLoad}_{5\text{min}} - \text{NetLoad}_{\text{hourly}})$

$\text{Unctertainty}_{\text{up}} = \text{NetLoad}_{\text{expected+forecast error}} - \text{NetLoad}_{\text{expected}}$

$\text{RTUCUP}_{15\text{min}} = \max(\text{NetLoad}_{15\text{min}} - \text{NetLoad}_{\text{hourly}})$

$\text{Flexible RampUp}_{15\text{min}} = \max(\text{NetLoad}_{5\text{min expected + forecast error}} - \text{NetLoad}_{15\text{ expected}})$

and

Load Following Dn= $\text{Variability}_{\text{dn-hourly}} + \text{Uncertainty}_{\text{dn}} \approx \text{Flexible RampDn}_{15\text{min}} + \text{RTUCDn}_{15\text{min}}$

where

$\text{Variability}_{\text{dn-hourly}} = \max(\text{NetLoad}_{\text{hourly}} - \text{NetLoad}_{5\text{min}})$

$\text{Unctertainty}_{\text{dn}} = \text{NetLoad}_{\text{expected}} - \text{NetLoad}_{\text{expected-forecast error}}$

$\text{RTUCDn}_{15\text{min}} = \max(\text{NetLoad}_{\text{hourly}} - \text{NetLoad}_{15\text{min}})$

$\text{Flexible RampDn}_{15\text{min}} = \max(\text{NetLoad}_{15\text{expected}} - \text{NetLoad}_{5\text{min expected- forecast error}})$

Figure 3a and 3b attempt to graphically illustrate how flexible ramp and load following are determined using the forecast net load.

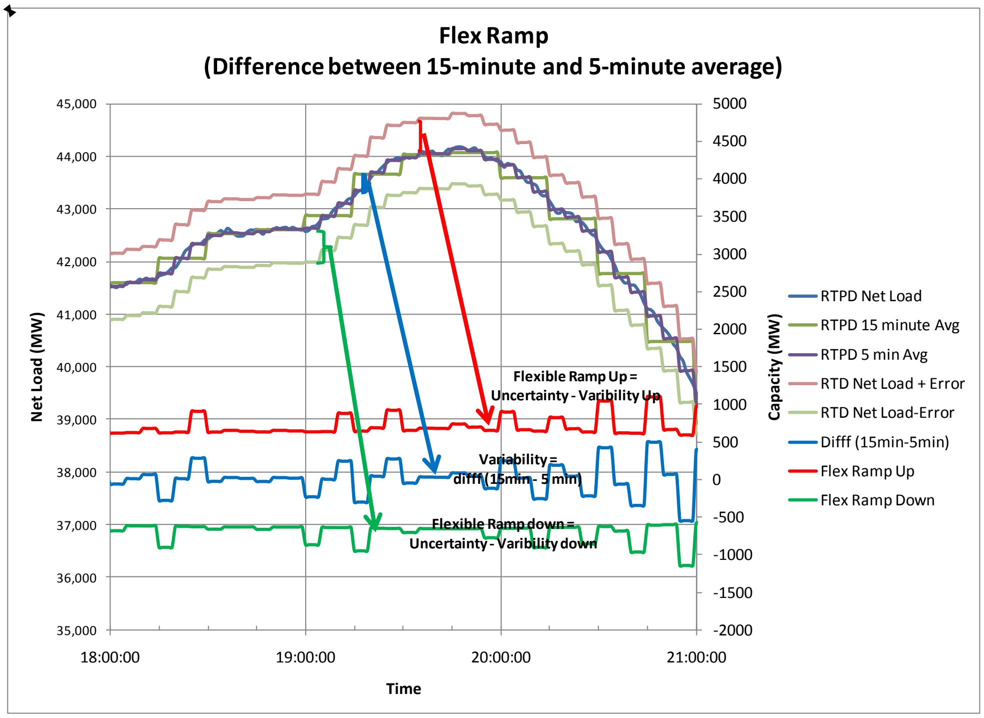

Figure 3a: Flexible Ramp Product Illustration

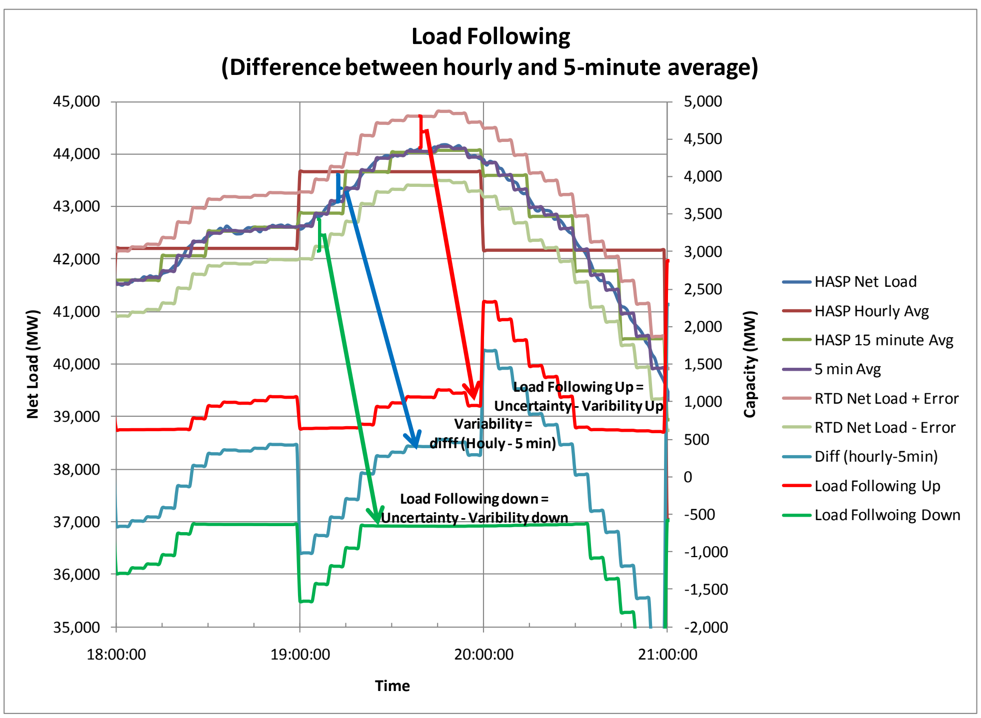

Figure 3b: Load Following Illustration

The ISO intends to first procure the flexible ramping products partially (e.g. with 60% confidence level) in the integrated forward market (IFM), and then procure additional flexible ramping products in RTD to achieve higher confidence level (e.g. 95% confidence). The IFM can commit and acquire flexible capacity from long start units if necessary, so it is an important step to preserve flexible capacity into real-time markets. RTUC can commit short start units to create flexible ramping headroom, but the headroom is not a binding procurement. RTD will re-evaluate the ramping requirement, and bindingly award flexible capacity based on more accurate information. The 95% and 60% confidence levels mentioned in the proposal are illustrative. The ISO will perform statistical study using historical data to determine the requirements in day-ahead and real-time.

The issues addressed in the third revised straw proposal in response to stakeholders' comments include:

Comments	Stakeholders
Bid cap	SCE, DMM
Self provision	PG&E
Relaxation penalty	SCE, DMM
Clarification of conversion v.s. substitution	SCE, NRG, PUC
False opportunity payment discussion for IFM, RTUC, RTD	PG&E, SCE, PUC, DMM, WPTF, NRG
Factoring energy cost into flexible capacity cost	PUC
Linking day-ahead flexible capacity award and real-time energy offer	SCE
No pay rules	SCE
Flexible capacity certification	PG&E
Market power mitigation for flexible capacity	DMM

2. FLEXIBLE RAMPING PRODUCTS DESIGN

Flexible ramping products are flexible capacities that are dispatchable by the ISO. The goal of flexible ramping products is to improve the ISO's dispatch flexibility in maintaining power balance. Specifically, the flexible ramping products are designed to deal with the energy imbalances in RTD. The flexible ramping consists of separate products in the upward and downward directions as the imbalances may be positive and negative. The imbalances can result from variability or uncertainties. From a stochastic programming point of view, faced with the variability and uncertainties, a stochastic program will commit and dispatch units differently than without those variability and uncertainties considered, such as committing more flexible units, positioning units at faster ramping dispatch levels in anticipation of imbalances in RTD. The current technology does not allow detailed modeling of those variability and uncertainties and solving stochastic programs in real-time. Therefore, the flexible ramping products are created as a heuristic way to mimic what a stochastic program would do to deal with those variability and uncertainties. In other words, the flexible ramping products will be able to commit fast ramping units, and position units at fast ramping dispatch levels.

There are three characteristics that distinguish the flexible ramping products from other capacity products, such as ancillary services.

Fast ramping Because RTD is on a 5-minute interval basis, the flexible ramping products are also a 5-minute ramping products[4] meaning that the flexible ramping product award is limited by how much a resource can ramp within 5 minutes. This is to ensure that the procured flexible ramping capacity can be fully utilized in one RTD interval when they are needed. In contrast, all ancillary services in the ISO are based on 10-minute ramping capability.

Dispatched in RTD on a regular basis Flexible ramping capacity is continuously being dispatched in RTD to meet the energy imbalances. In contrast, regulation services are dispatched in real-time by AGC, and operating reserves are dispatched after major contingency happens. Day-ahead procured non-contingent spinning reserve may be dispatched in RTD, but only when there is over procurement. Flexible ramping products can improve the ISO's dispatch flexibility in RTD, while ancillary services cannot.

Capacity preserved now to be used in the future Flexible ramping product is capacity set aside now to be used in the future. Day-ahead procured flexible ramping is capacity not used in IFM, and preserved into real-time markets. RTD procured flexible ramping is capacity not used in the current RTD interval, and preserved into the next RTD interval. In contrast, ancillary services are capacities set aside now for a trade interval, and to be deployed for the same trade interval if the condition to use them is triggered later.

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[4] The flexible ramping products are procured in the day-ahead market on an hourly basis, and in RTD on 5-minute interval basis. In RTPD, flexible ramping headroom is created on a 15-minute interval basis, but it is not a binding procurement.

Flexible ramping products will be modeled in IFM, RTUC, and RTD. The main purpose of modeling flexible ramping products in IFM is to make unit commitment decision for long start units, and award flexible capacities to preserve them into real-time markets. The commitment decisions for long start units and flexible capacity awards are binding in IFM. The purpose of modeling flexible ramping in RTUC is to make real-time unit commitment decisions, and to create flexible ramping headroom so that the system has sufficient flexible capacity. The real-time unit commitment decisions are binding for the first 15-minute interval in RTUC. Similar to energy dispatch, the flexible headroom capacity is not binding in RTUC. It is better to procure flexible capacity in RTD than in RTUC because RTD runs closer to real-time, and thus has more accurate information. RTD will re-evaluate the flexible ramping requirement and bindingly procure flexible capacity based on more accurate information. The flexible ramping products awards will be compensated according to the marginal prices in the procurement processes (IFM and RTD).

2.1 FLEXIBLE RAMPING PRODUCTS BIDDING RULES

The market will accept separate capacity bids on upward flexible ramping product and downward flexible ramping poduct, which express the resources' cost associated with providing such flexible capacities. The upward capacity bid can be different from the downward capacity bid. A resource must have an economic energy bid to back up the flexible ramping capacity. If a resource does not have an explicit flexible ramping bid, it is assumed to have zero cost to provide flexible ramping.

A resource can provide flexible ramping as long as it has an economic energy bid. It does not need to have a certified flexible ramping capacity. Undeliverable flexible ramping capacity will be subject to no-pay settlement. In addition, the ISO has the right to check a resource's ramping rate, and disqualify the resource from providing flexible ramping if the actual ramping rate differs significantly from the submitted ramping rate.

2.1.1 FLEXIBLE RAMPING BID CAP

Similar to ancillary services, a flexible ramping bid will only have one bid segment and a bid cap of $250/MWh. In addition, if a resource also submits non-contingent spinning reserve bid, its upward flexible ramping bid cannot exceed its spinning reserve bid. Some stakeholders pointed out that the capacity bid may have included expected revenue from energy dispatch. Because upward flexible ramping capacity has a higher likelihood of being dispatched than non-contingent spinning reserve, it should have a lower cost than non-contingent spinning reserve.

2.1.2 FLEXIBLE RAMPING SELF PROVISION

In the IFM, a Scheduling Coordinator (SC) can self provide flexible ramping capacity. If a SC chooses to do so, its real-time energy bid will be capped by the minimum of two times its default energy bid and $300/MWh. This is to prevent a SC from self providing flexible ramping in IFM, and then bidding high for energy in real-time.

There is no explicit self provision mechanism for flexible ramping in real-time markets. A SC can bid zero or simply not bid for the amount of flexible ramping it wants to self provide. If the SC is fully awarded flexible ramping, then it effectively hedges its obligation with the payment received. If the SC is not fully awarded flexible ramping (even with bid price zero $/MWh), it implies the marginal price of flexible ramping must be zero $/MWh, so there will be zero cost allocation. In either case, an SC can hedge its cost allocation obligation effectively, so there is no need for an explicit flexible ramping self provision mechanism in real-time markets.

2.1.3 FLEXIBLE RAMPING MARKET POWER MITIGATION

The ISO believes that the implicit flexible ramping offer, bid cap and requirement relaxation (discussed later) should adequately address the concern of market power. Therefore, the ISO will not propose a more sophisticated market power mitigation mechanism at this moment, but may do so if the need arises in the future.

2.1.4 FACTORING ENERGY COST INTO FLEXIBLE RAMPING COST

The previous versions of the proposal do not factor in anticipated energy dispatch cost into the flexible ramping procurement. As a result, the optimization will consider two resources with the same flexible capacity offer but different energy offers equally economic in the procurement process. However, when the flexible capacity is utilized in RTD, the energy costs are different. In other words, even the flexible capacity bids are the same, the resource with higher energy cost should have a higher overall cost anticipating a non-zero dispatch probability. It would be better if the procurement process could recognize the difference in expected energy cost, and give flexible capacity awards to the resource with lower overall cost.

A stochastic optimization can achieve this because the distribution of uncertainty is explicitly modeled so that the energy dispatch probability and cost can be accurately evaluated. However, as discussed earlier, the current technology does not allow solving stochastic programs that models uncertainties in detail in real-time markets, and that is why the flexible ramping products are created as a deterministic model to mimic a stochastic program. The expected energy cost can also be modeled in a simplified manner in the flexible ramping products to mimic a stochastic program.

The simplified method only factors in the expected energy cost when the energy bid is very high, say higher than $300/MWh, or very low, say lower than $0/MWh. Assume with extreme energy bids, a resource will not be dispatched under the normal conditions. By normal conditions, we mean the imbalances that can be covered by the flexible ramping capacity. We have assumed the flexible ramping procurement target is to cover 95% confident level with 2.5% probability of the net load ramping up faster than the upward flexible ramping requirement and 2.5% probability of the net load ramping down faster than the downward flexible ramping requirement. Therefore, if the energy bid is higher than $300/MWh, the capacity can only be dispatched when the upward 2.5% probability events happen; if the energy bid is lower than $0/MWh, the capacity can only be dispatched for energy when the downward 2.5% probability events happen. This means the extreme energy cost will be incurred with 2.5% probability. Therefore, compared with the flexible capacity with energy bids $300/MWh, the flexible capacity with energy bids higher than $300/MWh has a higher expected energy dispatch cost in the amount of

2.5%*(energy bid (at the last upward flexible ramping MW) – 300).

This expected energy dispatch cost should be factored into the flexible ramping bid to properly evaluate the composite upward flexible ramping cost.

composite upward flexible ramp cost = upward flexible ramping bid +

0.5*(1 – confidence level)*max{energy bid (at the last upward flexible ramping MW) – 300, 0}.

The calculation means if the energy bid is higher than $300/MWh, then the upward flexible ramping cost will appear to be more expensive by (2.5%*energy bid) than a resource with energy bid below $300/MWh. The higher the energy bid, the harder the capacity can be awarded upward flexible ramping.

Similarly,

composite downward flexible ramp cost = downward flexible ramping bid –

0.5*(1 – confidence level)*min{energy bid (at the last downward flexible ramping MW), 0}.

Note that the last downward flexible ramping MW is the bottom of the downward flexible ramping capacity. The calculation means if the energy bid is lower than $0/MWh, then the downward flexible ramping cost will be more expensive by (–2.5%*energy bid) than a resource with energy bid higher than $0/MWh. The lower the energy bid, the difficult the capacity can be awarded downward flexible ramping.

Factoring the energy cost at the last flexible ramping MW at 2.5% probability is an approximation of the expected energy cost. This only applies to resources who bid very high or very low. It provides a simple way to fairly compare the expected energy cost from different resources offering flexible capacity.

It may seem that the overall flexible ramping cost would increase with energy cost being factored into it. This is not necessarily true. If a resource wants to get paid $10/MWh for flexible ramping, it can achieve this not matter whether the energy cost is factored in. If the energy cost is not factored in, it can bid $10/MWh. If the energy cost is factored in, say by $1/MWh, it can bid $9/MWh, and the overall cost is still $10/MWh. Therefore, factoring the energy cost will not necessarily increase the total procurement cost because the resources should adjust the capacity bids anticipating some additional expected energy cost will be factored in.

The flexible capacity marginal price may change with the flexible ramping cost being adjusted by energy bid. The composite price is only used in the procurement process. The original capacity bid will be used in bid cost recovery.

2.1.5 LINKING DAY-AHEAD FLEXIBLE RAMPING AWARD AND REAL TIME ENERGY BID

The ISO is concerned that resources with day-ahead awards may have incentive to increase the energy bid in real-time to

- keep the day-ahead flexible ramping payment without really helping improve dispatch flexibility in RTD, or
- if the flexible capacity is needed in real-time, the dispatched energy can receive high energy price.

Stakeholders are aware of the concern, but also pointed out that resources may have different costs in the day-ahead market and the real-time market, so it is inappropriate to lock in the day-ahead bids.

To mitigate the concern and allow resources to have different bids in the day-ahead market and real-time market, the ISO proposes the following method. In the day-ahead market, a resource can specify the real-time energy bid range by a bid floor and bid cap. The resource specific bid cap will be used to calculate the composite upward flexible ramping cost, and resource specific bid floor will used to calculate the composite downward flexible ramping cost in the day-ahead market as discussed in section 2.1.4. In real-time market, the resource must bid within the bid range. A resource is motivated to accurately estimate the real-time bid in order to offer the real-time energy bid range in IFM properly. Offering the resource specific bid cap too high will reduce a resource's chance of being awarded upward flexible ramping, and offering the resource specific bid floor too low will reduce a resource's chance of being awarded downward flexible ramping. On the other hand, if the resource specific bid range is too narrow, it will restrain the real time energy bid. Therefore, a resource should evaluate the bid range accurately in order to get flexible capacity awards in IFM without inadvertently restraining the real-time bid.

2.2 CO-OPTIMIZING FLEXIBLE RAMPING PRODUCTS WITH ENERGY AND ANCILLARY SERVICES IN DAY-AHEAD MARKET

This section will cover the stylized optimization model of co-optimizing the flexible ramping products with energy and ancillary services in the day-ahead market. The interplay between day-ahead market and RTUC will be discussed in section 2.3.

2.2.1 CO-OPTIMIZATION FORMULATION

The convention of the optimization model follows T. Wu and M. Rothleder et al. 2004.[5] The meanings of the variables used in this section are explained in Appendix A. We will discuss the changes to the objective function and constraints on top of Wu and Rothleder's model due to the addition of the flexible ramping products. The detailed equations are presented in Appendix B.

The change to the objective function is to add the bid costs from the flexible ramping products.

The changes to the constraints involving flexible ramping are as follows.

Five-minute upward flexible ramping capability limit This constraint ensures that a resource's upward flexible ramping product award does not exceed what it can ramp in 5 minutes.

Five-minute downward flexible ramping capability limit This constraint ensure that a resource's downward flexible ramping product award does not exceed what it can ramp in 5 minutes.

Ten-minute upward ancillary service and flexible ramping limit This constraint ensures the total amount of upward reserves (regulation-up, spinning, and non-spinning) awards and the upward flexible ramp product award does not exceed what the resource can ramp in 10 minutes.

Ten-minute downward ancillary service and flexible ramping limit This constraint ensures the total amount of regulation-down award and downward flexible ramping product award does not exceed what the resource can ramp in 10 minutes.

Upward ramping sharing[6] This constraint limits the extent to which the awards of regulation-up, spinning reserve, non-spinning reserve and upward flexible ramping product can share the resource's ramping capability with the ramp used to support the changes in energy.

Downward ramping sharing[6] This constraint limits the extent to which the awards of regulation-down and downward flexible ramping product can share the resource's ramping capability with the ramp used to support the changes in energy.

Active power maximum limit This constraint limits the amount of the awards of energy schedule, upward reserves and upward flexible ramping product to be less than or equal to the resource's maximum operating capability.

Active power minimum limit This constraint limits the amount of energy schedule minus the awards of regulation-down and downward flexible ramping product to be greater than or equal to the resource's minimum operating level.

Upward flexible ramping requirement This constraint ensures that the total amount of upward flexible ramping product awards at least meets the requirement.

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[5] Tong Wu, Mark Rothleder, Ziad Alaywan, and Alex D. Papalexopoulos, "Pricing Energy and Ancillary Services in Integrated Market Systems by an Optimal Power Flow," *IEEE Transactions on Power Systems*, pp.339-347, 2004.

[6] See CAISO Technical Bulletin "Simplified Ramping" for details of the ramp sharing constraints and coefficients, http://www.caiso.com/2437/2437db41245c0.pdf, August 2009.

Downward flexible ramping requirement This constraint ensures that the total amount of downward flexible ramping product awards at least meets the requirement.

The upward flexible ramping product shadow price is λ_t^{FRU}, and the downward flexible ramping product shadow price is λ_t^{FRD}. These two shadow prices are non-negative, because increasing the requirements will make the set of feasible solutions smaller, and thus the minimum objective function value (total bid cost) tends to increase.

Note that there is neither substitution between the flexible ramping products and the regulation services, nor substitution between the flexible ramping products and the contingent operating reserves.

The flexible ramping products will be priced at the marginal values of the requirements, which equal the corresponding shadow prices.

Payment to resource *i* providing $FRU_{i,t}$ is $\lambda_t^{FRU} \cdot FRU_{i,t}$, and the total payment in interval *t* is $\lambda_t^{FRU} \cdot \sum_{i \in I_{FR}} FRU_{i,t}$.

Nominal charge could conceptually be associated with variability or uncertainty *u* that incurs flexible ramping need is $\lambda_t^{FRU} \cdot R_{u,t}^{FRU}$, and the total charge is $\lambda_t^{FRU} \cdot \sum_{u \in UU} R_{u,t}^{FRU}$. Note that the charge on variability or uncertainty *u* is a nominal charge meaning *u* would have to pay the charge under perfect cost causation scheme. It is not the real settlement charge under the current ISO's proposal, but serves the purpose of providing an economic signal to indicate that variability or uncertainty *u* should bear the flexible ramping cost. The proposed settlement charge will be discussed later in the cost allocation section.

If there is no flexible ramping scarcity, the complementary slackness holds at the optimal solution

$$\lambda_t^{FRU} \cdot \left(\sum_{u \in UU} R_{u,t}^{FRU} - \sum_{i \in I_{FR}} FRU_{i,t} \right) = 0$$

This means the ISO should be revenue neutral under normal conditions.

If there is flexible ramping scarcity of $SLK_t^{FRU} = \sum_{u \in UU} R_{u,t}^{FRU} - \sum_{i \in I_{FR}} FRU_{i,t} > 0$, then

$$\lambda_t^{FRU} \cdot \left(\sum_{u \in UU} R_{u,t}^{FRU} - \sum_{i \in I_{FR}} FRU_{i,t} \right) = \lambda_t^{FRU} \cdot SLK_t^{FRU} > 0$$

This means the ISO is revenue adequate.

The revenue adequacy and revenue neutral properties also apply to downward flexible ramping.

The day-ahead flexible ramping procurements are financially binding. The opportunity cost of providing energy will be included in the marginal prices of flexible ramping products. This is because a resource that is capacity constrained will lose the opportunity of providing energy in day-ahead market if it is more economic for it to provide flexible ramping.

2.2.2 REQUIREMENT RELAXATION

Just like energy requirement and ancillary services requirements, the flexible ramping products requirement constraints will be allowed to be relaxed to a certain extent at appropriate penalty prices. The ISO will use the following step penalty function:

- requirement violation from 0 MW to 100 MW, penalty price $100
- requirement violation from 100 MW to 200 MW, penalty price $150
- requirement violation from 200 MW to 300 MW, penalty price $200
- requirement violation above 300 MW, penalty price $250

The same requirement relaxation function will be used in both day-ahead and RTD.

2.3 INTERPLAY BETWEEN DAY-AHEAD MARKET AND RTUC

RTUC creates flexible ramping headroom by a co-optimization similar to the day-ahead, and resets the flexible ramping requirement to 95% confidence level on a 15-minute interval basis. The day-ahead procured flexible ramping awards will be protected as self-provision in RTUC so that they can meet the RTUC requirement. This is consistent with how the ancillary services procured in day-ahead market are modeled in RTUC currently.

2.3.1 CONVERSION OF DAY-AHEAD AWARDS IN RTUC

The day-ahead non-contingent reserve awards may be fully or partially converted to upward flexible ramping if the resources have economic energy bids in RTUC. The day-ahead non-contingent reserve awards are from resources who flag them as non-contingent meaning that they are willing to be dispatched for energy rather than be kept as operating reserve if condition permits. Therefore, allowing them to be converted to flexible ramping product and then potentially be dispatched to meet realized imbalance difference is consistent with their intention. On the other hand, upward flexible ramping awards may also be fully or partially converted to contingent spinning reserves if the resources are qualified to provide spinning reserve. The potential conversions are summarized in Figure 3. The non-contingent non-spinning reserve awards in day-ahead that become online in RTUC are treated the same as non-contingent spinning reserve awards, and are allowed to be fully or partially converted to contingent spinning reserve or upward flexible ramping product.

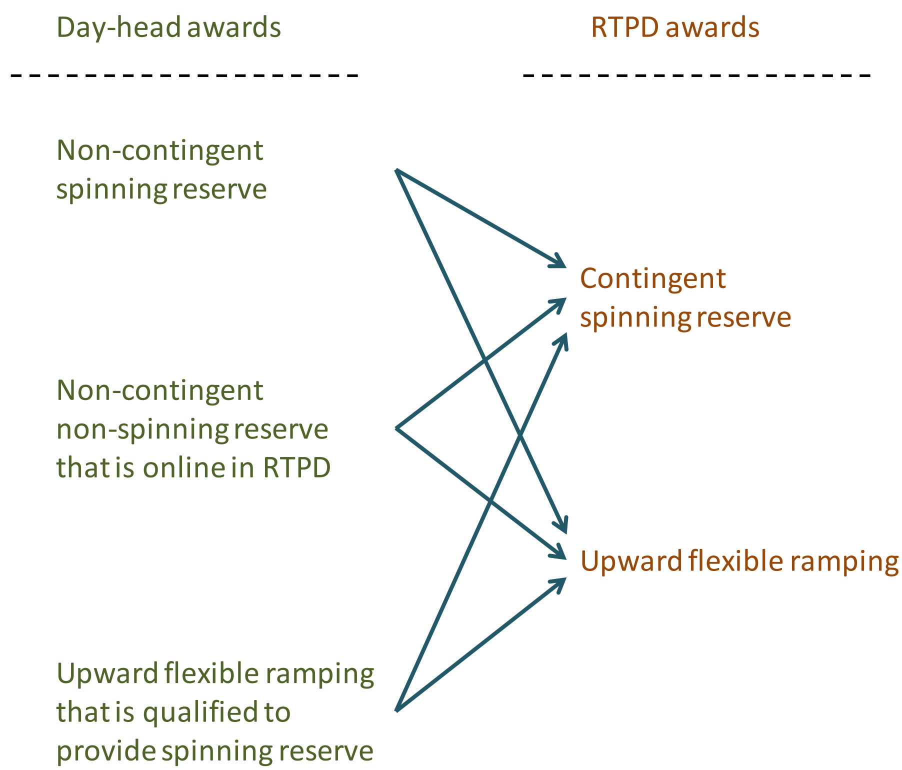

FIGURE 3: CONVERSIONS BETWEEN NON-CONTINGENT RESERVES AND UPWARD FLEXIBLE RAMPING PRODUCT IN RTUC

Allowing non-contingent reserves to be converted to upward flexible ramping product helps deal with ramping scarcity, and allowing upward flexible ramping product to be converted to spinning reserve helps deal with operating reserve scarcity. These conversions will increase the dispatch flexibility and market efficiency by allowing flexible resources to be used in the most valuable way. The conversion can only take place in RTUC, and only applies to day-ahead awards. Basically, the conversion design allows RTUC to make a second decision about the capacity awarded in IFM. This is different from the ancillary service substitution where regulation-up can substitute spinning reserve, and spinning reserve can substitute non-spinning reserve. The differences between conversion and substitution will be discussed in detail in section 2.3.2.

The conversion will only happen in the direction of lower value to higher value. For example, non-contingent spinning reserve can be converted to upward flexible ramping product only when the marginal price of upward flexible ramping is higher than or equal to the marginal price of spinning reserve in RTUC. This can be proved by contradiction. Assume the marginal price of spinning reserve is higher than the upward flexible ramping product, and at least one resource's non-contingent spinning reserve is converted to upward flexible ramping product. In this case, if the conversion is reduced by 1 MW, then the change to the objective function value is equal to the marginal price of upward flexible ramping product minus the marginal price of spinning reserve, which is negative by assumption. This means the objective function value can be improved (reduced) by reversing the conversion, and thus contradicts the optimality of the conversion. Therefore, the conversion should not have taken place. This completes the proof. Conversion from flexible ramping to spinning reserve can be proved in the same way. This also implies that the conversion can only take place in one direction for the same ancillary service region.

Conversion can be modeled in the following way. The day-ahead awards of non-contingent spinning reserve (also non-contingent non-spinning reserve that becomes online in RTUC) and upward flexible ramping will be split into two variables, one represents the contingent spinning reserve, and the other represents the upward flexible ramping product in RTUC. The sum of these two will be less than or equal to the corresponding day-ahead award

$$FRU_{i,t} + SP_{i,t} \le FRU_{i,t}^{DA}, \text{ for all } i \in I_t^{DA,FRU}$$

$$FRU_{i,t} + SP_{i,t} \le SPIN_{i,t}^{DA}, \text{ for all } i \in I_t^{DA,SPIN}$$

The upward flexible ramping portion $FRU_{i,t}$ will be used to meet the upward flexible ramping requirement in RTUC, and the spinning reserve portion $SP_{i,t}$ will be used to meet the spinning reserve requirement (cascading with regulation-up and non-spinning reserve) in RTUC. Note that the upward flexible ramping portion $FRU_{i,t}$ still needs to satisfy the 5-minute ramping capability limit.

The day-ahead spinning reserve and flexible ramping awards are settled in day-ahead market at the corresponding day-ahead marginal prices.

The amount of day-ahead procured upward flexible ramping that becomes spinning reserve in RTUC will be paid in day-ahead market at the day-ahead upward flexible ramping marginal price, and will be paid in RTUC at the difference between the spinning reserve marginal price and the flexible ramping marginal price, i.e. RTUC spinning reserve marginal price – RTUC upward flexible ramping marginal price, which has been proved to be non-negative.

The amount of day-ahead procured non-contingent spinning reserve that becomes upward flexible ramping headroom in RTUC has been paid in day-ahead market at the day-ahead spinning reserve marginal price, and will not be paid in RTUC, but wait till RTD for settlement. If the capacity is dispatched for energy in RTD, it will receive energy payment. If the capacity is held as flexible ramping capability in RTD, it will receive flexible ramping payment.

2.3.2 CONVERSION VS SUBSTITUTION

There has been some confusion and misunderstanding about the two terms: substitution and conversion. We want to clarify that these two terms have different meaning, and are not interchangeable.

Substitution is a term to describe the relationship between two products. Substitution needs to have a direction, such as product A is substitutable for product B. The substitution direction also implies the quality difference: product A is substitutable for product B means product A is of a higher quality than product B. There are two possible substitutions allowed in the ISO: regulation-up substituting spinning reserve, and spinning reserve substituting non-spinning reserve. These substitutions are allowed due to the quality difference in meeting the operational need: regulation-up is a better quality service than spinning reserve, and spinning reserve is a better quality service than non-spinning reserve. Substitution cannot be bi-directional. If product A is substitutable for product B, and product B is also substitutable for product A, they are of equal quality, and should be the same product.

At the beginning of Section 2, we discussed the differences between the flexible ramping products and the ancillary services. Due to these differences, flexible ramping products and ancillary services are not substitutable on a product basis.

Nonetheless, flexible ramping and non-contingent flagged spinning reserve may behave similarly sometimes. For example, when spinning reserve is over procured in day-ahead and some of the day-ahead non-contingent flagged spinning reserve may be dispatchable in RTD, and thus behaves like upward flexible ramping. In this case, it would benefit both the system and the resource to allow the day-ahead non-contingent spinning award to be used as flexible ramping.

The capacity that changes the purpose of usage from day-ahead to real-time, e.g. from day-ahead spinning reserve to real-time upward flexible ramping, is called a conversion. Basically, conversion allows the real-time optimization to make a second decision about the day-ahead awards. We stress that conversion does not apply on a product basis.

Conversions will improve market efficiency by allowing capacity to be used in the most valuable way. Some stakeholder argues that converting from upward flexible ramping to spinning reserve may harm the bidder, because the day-ahead flexible ramping bid may have included anticipated real-time energy revenue. In other words, the day-ahead flexible ramping bid would be higher if they know it is possible that the flexible ramping may be converted into spinning reserve. The ISO agrees that the flexible ramping cost would be different because the conversion changes the likelihood of energy dispatch. However, the ISO disagrees with the conclusion that the conversion may harm the bidder. The correct conclusion should be with the conversion, a resource should revaluate the energy dispatch likelihood plus the conversion likelihood to factor all these revenues into the flexible ramping bid. If a resource does this, the conversion cannot harm the resource.

Some stakeholders would like to use the spinning reserve bid for flexible ramping if the spinning reserve bid is lower. This can be achieved by imposing the bidding rule that upward flexible ramping cannot exceed spinning reserve bid, so the co-optimization will determine the best use of the capacity. However, the ISO stress that this does not mean non-contingent spinning reserve is substitutable for upward flexible ramping capacity.

2.4 PROCURING FLEXIBLE RAMPING IN RTD

In RTD, imbalance differences are realized in three 5-minute intervals. In each of the three 5-minute intervals, RTD will perform economic dispatch in response to realized imbalance for the current 5 minutes, and procure flexible ramping capacity for the next 5 minutes based on more accurate information. The flexible ramping headroom capacity created in RTUC may become RTD flexible capacity award, or become energy dispatch.

The RTD flexible ramping procurement target is calculated as follows:

$$R_t^{FRU,RTD} = \min\{NL_{t+1}^{RTPD} + R_{t+1}^{FRU,RTUC} - NL_t^{RTPD} - RLZ_t^{RTD}, R_t^{FRU,5min}\}$$

$$R_t^{FRD,RTD} = \min\{-NL_{t+1}^{RTPD} - R_{t+1}^{FRD,RTUC} + NL_t^{RTPD} - RLZ_t^{RTD}, R_t^{FRD,5min}\}$$

For the upward flexible ramping procurement target, the first bound $NL_{t+1}^{RTUC} + R_{t+1}^{FRU,RTUC} - NL_t^{RTUC} - RLZ_t^{RTD}$ is the next RTD interval t+1 net load 95% confidence upper bound $NL_{t+1}^{RTUC} + R_{t+1}^{FRU,RTUC}$ (including both RTUC net load and the RTUC 95% confidence flexible ramping headroom) minus the current RTD interval t realized net load (including both RTUC net load and RTD realized imbalance difference). The first bound is the upper 95% confident level for the cumulative imbalance difference in the next RTD interval. The first bound is referred as the 15-minute bound. The second bound $R_t^{FRU,5min}$ is the 5 minutes incremental confidence interval, i.e. it is 95% sure that for the next RTD interval the net load can go up for at most $R_t^{FRU,5min}$ MW. The second bound is referred as the 5-minute bound. The RTD upward flexible ramping procurement target is set to the minimum of the three bounds.

The RTD upward flexible ramping requirement calculation is illustrated in Figure 4. The data used to plot Figure 4 is listed in Table 1. Note that it is possible that the requirement is negative. However, because the sum of flexible ramping flexible ramping awards is greater than equal to the requirement, a negative requirement will only make the constraint non-binding, and will not cause any inadvertent results.

Similarly, there are also two bounds that limit the downward flexible ramping procurement target, i.e. the 15-minute bound and the 5-minute bound as shown in the $R_t^{FRD,RTD}$ equation above. Table 1 also demonstrates how the downward requirement is calculated.

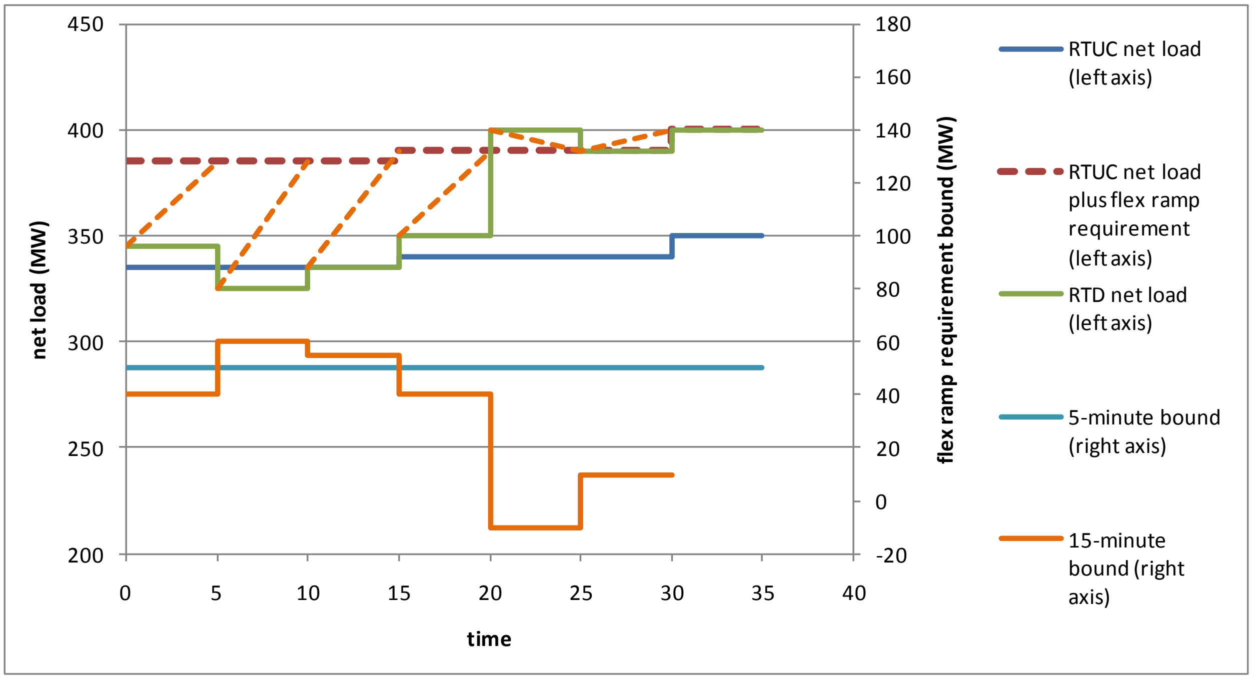

FIGURE 4: RTD UPWARD FLEXIBLE RAMPING REQUIREMENT

		RTUC1			RTUC2			RTUC3
		RTD1	RTD2	RTD3	RTD4	RTD5	RTD6	RTD7
	RTUC net load	335	335	335	340	340	340	350
	RTD realization	10	-10	0	10	60	50	50
	RTD net load	345	325	335	350	400	390	400
upward	RTUC requirement	50	50	50	50	50	50	50
	15 minute bound	40	60	55	40	-10	10	
	5 minute bound	50	50	50	50	50	50	50
	RTD requirement	40	50	50	40	-10	10	
downward	RTUC requirement	40	40	40	40	40	40	40
	15 minute bound	60	40	45	60	110	90	
	5 minute bound	40	40	40	40	40	40	40
	RTD requirement	40	40	40	40	40	40	

TABLE 1: CALCUALTE RTD FLEXIBLE RAMPING REQUREMENT

The real-time flexible ramping bids will be part of the RTD objective function. The day-ahead flexible ramping awards will be modeled as bidding zero for flexible ramping. The additional RTD flexible ramping award on top of the day-ahead unconverted flexible ramping award that contributes to meet the RTD procurement target will be paid the RTD flexible ramping marginal price. If a resource's RTD flexible ramping award is less than or equal to its day-ahead award (the amount remaining after RTUC conversion), it will not have RTD flexible ramping settlement. For example, a resource has day-ahead upward flexible ramping award of 100 MW, and 10 MW is converted into spinning reserve in RTUC, then its remaining day-ahead award is 90 MW. If the resource has 80 MW of flexible ramping award in RTD, which is less than 90, it will not be paid in RTD for flexible ramping. However, if the resource has 95 MW of flexible ramping in RTD, it will receive the RTD flexible ramping payment for 95 – 90 = 5 MW.

Procuring flexible ramping in RTD has several advantages over doing it in RTUC.

- Because RTD has more accurate information than RTUC, the dispersion of imbalance is smaller, so the total procurement amount including both upward and downward should be less than RTUC.
- Flexible ramping capacity can be procured from difference resources in RTD, and the resources that can provide flexible ramping in RTD are not limited to those that have headroom in RTUC.
- RTD flexible ramping price reflects true lost opportunity of providing energy. Only resources that lost the opportunity of providing energy in the current interval due to maintaining ramping capability to meet future variability and uncertainties will be paid for providing flexible ramping.

Some stakeholders expressed concerns about the flexible ramping opportunity cost in RTUC and the potential for such opportunity cost not being lost if resource were dispatched for energy in RTD. By procuring the flexible ramping capability in RTD, and after the imbalance realization in the binding interval, the ISO's new proposal provides a transparent way to price the flexible ramping products considering true opportunity cost. The opportunity cost is appropriately accounted for because a resource that provides flexible ramping in RTD indeed loses the opportunity of being dispatched for energy for the same RTD interval. The false opportunity cost issue will be discussed in more detail in section 2.5.1.

2.5 SETTLEMENT OF FLEXIBLE RAMPING PRODUCTS

Stakeholders have requested additional detail regarding how the ISO will settle and ensure compliance with awarded flexible ramping product service. In response the ISO proposes the following additional detail of settlement of flexible ramping products in previous sections. This section will summarize them, and also briefly discuss the no-pay rules.

The settlement of flexible ramping products can have the following elements.

- Day-ahead procured flexible ramping products will be settled at the day-ahead flexible ramping prices.

- Day-ahead upward flexible ramping award that is converted to spinning reserve in RTUC will receive the difference between the RTUC spinning reserve price and the RTUC upward flexible ramping price for the converted amount.
- RTD procured additional flexible ramping products on top of the unconverted day-ahead awards will be settled at RTD energy price. If the RTD flexible ramping award is less than the day-ahead award (the amount remaining after RTUC conversion), the resource will not receive RTD flexible ramping award.

Payment for flexible ramping products will be included in bid cost recovery to offset the revenue. If the ISO commits a resource to procure flexible ramping products, this is considered as ISO commitment and the resource is allowed to recover the start up cost, minimum lost, energy cost, and flexible ramping cost. If a resource self commits, then the resource is only allowed to recover the energy cost and flexible ramping cost above the self schedule level.

2.5.1 AVOID FALSE OPPORTUNITY PAYMENT

Flexible ramping is fast ramping capacity preserved now to be used in the future. This characteristic is the key to answer the stakeholders' questions about the opportunity cost issue.

Resource capacity may be used to serve load now or be preserved to serve future load. Energy dispatch comes from capacity used to serve load now, while flexible ramping is capacity preserved for future use. Preserving some fast ramping capacity for future use may benefit the system under the circumstances that the energy balance can be maintained now without relying on the fast ramping capacity, and the capacity may be crucial to maintain power balance for the future. Flexible ramping capacity, whether procured in IFM or procured in RTD, has this characteristic. Day-ahead procured flexible ramping is capacity preserved from being dispatched in the day-ahead market, so it can be dispatched in the real-time market. Therefore, if opportunity cost arises because the capacity is economic in the day-ahead market, the resource should be paid the opportunity cost. Similarly, RTD procured flexible ramping is capacity preserved from being dispatched in the current RTD interval, so it can be dispatched in the next RTD interval. Therefore, if opportunity cost arises because the capacity is economic in the current RTD interval, the resource should be paid the opportunity cost. There is no conceptual level inconsistency between the day-ahead procured flexible ramping and real-time procured flexible ramping capacity. It is incorrect to claim that flexible ramping procured in day-ahead is treated differently from flexible ramping procured in RTD.

Some stakeholders argue that the day-ahead procured flexible ramping is paid the capacity price and then the real-time energy price if being dispatched, while the real-time procured flexible ramping is only paid the capacity price, but not the real-time energy price. This is not the case. Flexible ramping capacity procured in RTD cannot be dispatch for energy in the same interval that the flexible ramping is procured. Rather, it may be dispatched for energy in and only in the next RTD interval. Therefore, flexible capacity procured in RTD may also be paid the capacity price and then the energy price. Regardless whether this happens or not, the payment does not constitute a false opportunity cost payment as will be discussed below.

Generally, it is not a problem for the same capacity to get both a capacity payment and an energy payment if it is dispatched as long as the capacity has a higher quality than just energy. For example, RUC capacity is paid both the capacity and the energy if it is dispatched. This is okay because the RUC capacity has a real-time must offer obligation and thus it is of higher quality than regular energy, which can choose to offer or not to offer into the real-time market. Similarly, the flexible ramping is a higher quality product because it can ramp fast. Therefore, flexible ramping should receive the capacity payment, which captures the value of being fast. The difference between flexible ramping capacity price and RUC capacity price is that the flexible ramping capacity price may include opportunity costs, while RUC capacity price does not include opportunity costs. This is because by providing flexible ramping, which means preserve the capacity for future use, may cause the resource to lose the opportunity of being dispatched now, and thus lose the energy profit. RUC capacity does not lose opportunity of any kind.

A comparison between RUC capacity and flexible ramping capacity regarding in which market processes they are procured, compensated and dispatched is summarized in Table 2.

	Procurement time	Dispatch time	Possible energy lost opportunity	Price includes energy opportunity cost	False lost opportunity cost payment
RUC capacity	Day-ahead after IFM	Current RTD	No	No	No
DA flex ramp	In IFM	Current RTD	IFM	Yes	No
RTD flex ramp	In RTD	Next RTD	Current RTD	Yes	No
RTUC flex ramp	In RTUC	Current RTD	No	Yes	Yes

TABLE 2: COMPARING OPPORTUNITY COST OF FLEXIBLE RAMPING CAPACITY AND RUC CAPACITY

RUC capacity is not co-optimized with any other products. As a result, RUC price does not include any opportunity cost. Therefore, RUC capacity does not have false opportunity cost issue. Flexible ramping capacity procured in IFM and RTD also do not have false opportunity cost issue because preserving the capacity does incur lost opportunity. In IFM, if awarding flexible ramping capacity causes the resource to lose the energy dispatch opportunity in IFM, we must compensate the resource for the opportunity cost. In RTD, if awarding flexible ramping capacity causes the resource to lose the energy dispatch opportunity in the current RTD interval, we must also compensate the resource the the opportunity cost. In contrast, if flexible ramping is procured in RTUC, because the energy dispatch is not binding in RTUC, and the corresponding RTD may dispatch the capacity, it does not really incur a lost energy dispatch opportunity. Therefore, the resource should not be compensated for the opportunity cost in RTUC. That is why the ISO proposes not to procure flexible ramping capacity in RTUC.

2.5.2 FLEXIBLE RAMPING NO PAY SETTLEMENT

Flexible ramping no-pay rules are similar to ancillary service no-pay rules. There are four major categories of no-pay including

- undispatchable capacity,
- undelivered capacity,
- unavailable capacity, and
- unsynchronized capacity.

Details about each of the categories will be discussed below.

A resource with flexible ramping awards is illustrated in Figure 5. Its flexible ramping awards under normal conditions should be within [Pmin, Pmax], and also be limited by 5-minute ramping capability. It exactly follows instruction, and there is no payment rescission in this case.

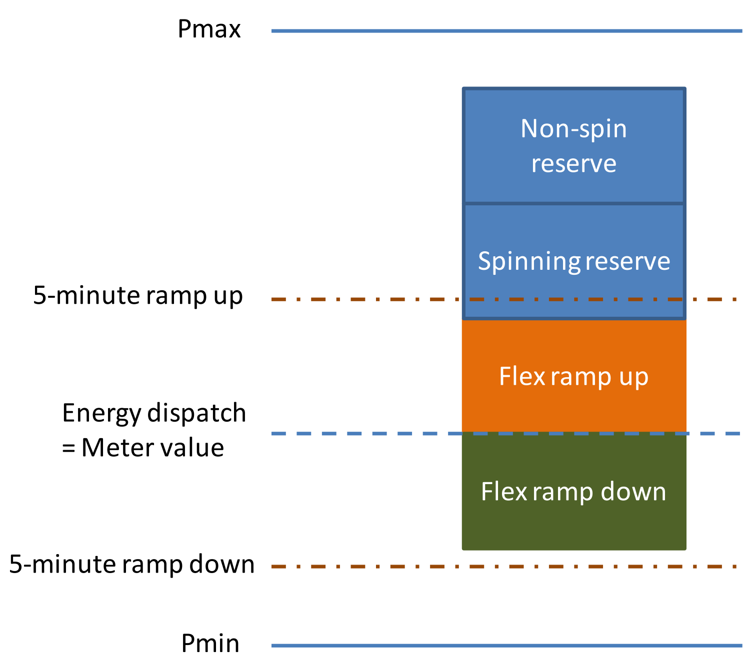

FIGURE 5: A RESOURCE WITH NO FLEXIBLE CAPCITY PAYMENT RECISSIONS

- **Undispatchable Capacity** – There are two subcategories of Undispatchable Capacity:
  - **Availability-Limited Capacity** – If a resource's capacity is re-rated in real-time, the total amount of flexible ramping Awards may not be available in Real-Time for dispatch due to the availability limitation. This is illustrated in Figure 6, where Pmin and Pmax are re-rated,

and cut into the flexible ramping awards. The capacity that is cut off will be subject to no-pay.

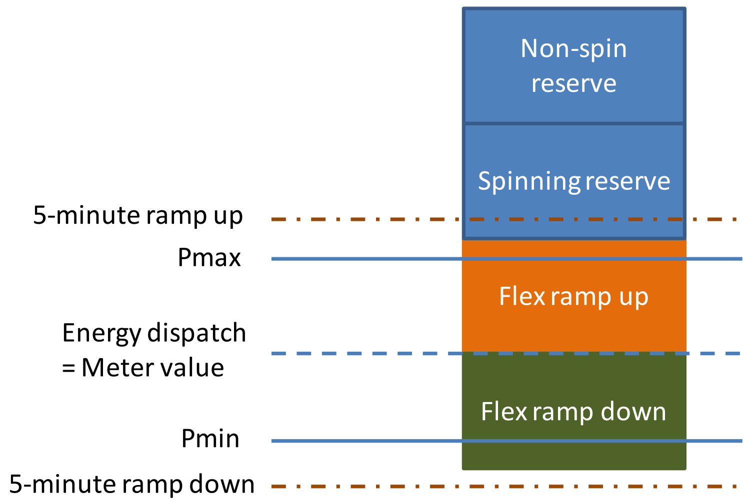

FIGURE 6: A RESOURCE WITH UNAVAILABLE FLEXIBLE CAPACITY NO PAY

- **Ramp-Limited Capacity** – Flexible ramping are required to be delivered in 5 minutes. If a resource does not have the 5-minute Ramp Rate capability in Real-Time to deliver the flexible ramping awarded, then a portion of the flexible ramping capacity is not available due to the Ramp Rate limitations on the resource. This is illustrated in Figure 7.

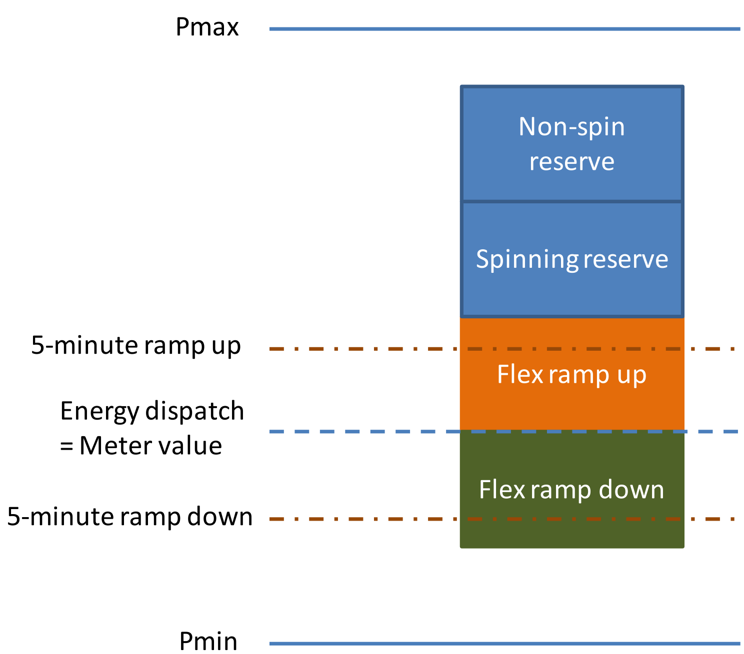

FIGURE 7: A RESOURCE WITH RAMP-LIMITED NO PAY

- **Undelivered Capacity** – If Energy from a resource's flexible ramping award is dispatched, then that resource must follow instructions closely. Otherwise, the flexible ramping awards may be subject to no pay charge. How close a resource follow instruction can be measured by the uninstructed energy = meter value – expected energy.

Within a day, denote the intervals that a resource is dispatched up in the next 5-minute interval, i.e. expected energy (t+5) > expected energy (t), as $T+$, and denote the intervals that a resource is dispatched down in the next 5-minute interval, i.e. expected energy (t+5) < expected energy (t), as $T-$. For a ramp-up interval $t \in T+$, if the uninstructed energy is negative in interval t+5, denoted by UIE^{-}, then the resource's upward flexible ramping award in interval t is not 100% delivered. Similarly, For a ramp-down interval $t \in T-$, if the uninstructed energy is positive in interval t+5, denoted by UIE_5^{+}, then the resource's flexible downward ramping award in interval t is not 100% delivered. Uninstructed energy UIE_5^{+} and UIE_5^{-} can be calculated using a flat 10-minute meter value, or assuming in each of the two 5-minute intervals, real energy is proportional to the expected energy, and the total sums to the 10-minute value. The ISO is open to suggestions from stakeholders on which method is preferable. The choice may also affect other flexible ramping no-pay categories that depend on the meter value.

In order to avoid a no-pay charge for upward flexible ramping capacity, the following equation needs to be satisfied.

$$\frac{\sum_{t\in T+} UIE_5^{-}}{\sum_{t\in T+} FRU} \leq 10\%$$

Note the upward flexible ramping award FRU includes both IFM and RTD awards. If the equation above is violated, the upward flexible ramping awards from both IFM and RTD in all the ramp-up intervals $T+$ will be subject to no pay charge.

In order to avoid a no-pay charge for downward flexible ramping capacity, the following equation needs to be satisfied.

$$\frac{\sum_{t\in T-} UIE_5^{+}}{\sum_{t\in T-} FRD} \leq 10\%$$

Note the downward flexible ramping award FRD includes both IFM and RTD awards. If the equation above is violated, the downward flexible ramping awards from both day-ahead market and RTD in all the ramp-down intervals $T-$ will be subject to no pay charge.

▪ **Unavailable Capacity** – No Pay charges apply when flexible ramping capacity is unavailable because it is converted to Energy without Dispatch Instructions from CAISO. Uninstructed Deviations in Real-Time may cause flexible ramping capacity to be unavailable to CAISO.

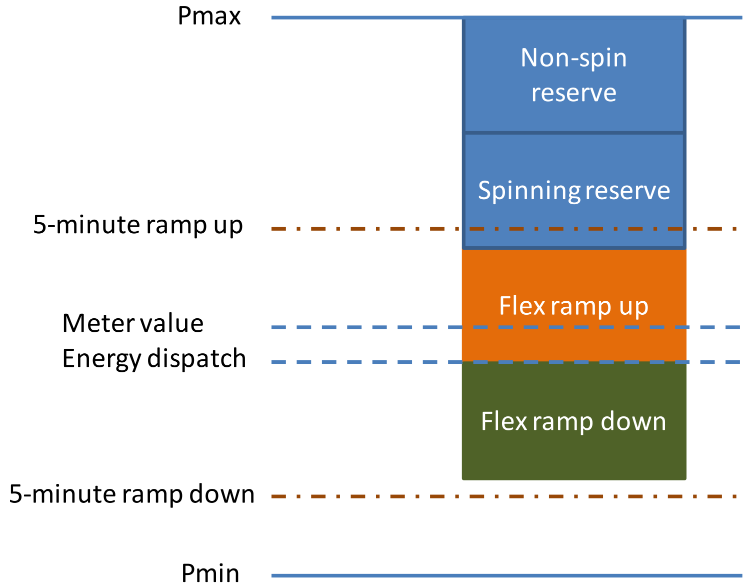

FIGURE 8: A RESOURCE WITH UNAVAILABLE CAPACITY NO PAY

▪ **Unsynchronized Capacity** – A resource's flexible ramping award will be subject to no pay if the resource does not comply with the synchronization standards.

3. EXAMPLE

In this section, a numerical example will be discussed to illustrate how the flexible ramping products interact with energy and ancillary services, how they are priced, and how they are settled. The example will go through day-ahead market and real-time markets continuously. Readers should pay close attention to the data change in each market, such as load, flexible ramping requirements, unit outage, and so on.

3.1 DAY-AHEAD MARKET

There are seven units in the system: G1, G2, G3, G4, G5, G6 and G7. The day-ahead awards are listed in Table 3, in which only non-zero values are shown. The day-ahead market prices are listed in Table 4. Note that the marginal price for regulation-up is not equal to the corresponding shadow price due to ancillary service substitution. The regulation-up marginal price ($2) is equal to the sum of the regulation-up shadow price ($1), the spinning reserve shadow price ($1) and the non-spin reserve shadow price ($0).

To make the example concise, only the day-ahead awards and prices are provided, but the bids and optimization details are omitted. We will demonstrate the market co-optimization with energy and ancillary services through the RTUC market.

gen	Energy	Reg-up	Reg-down	Spinning reserve	Non-spin reserve	Flex-ramp up	Flex-ramp down
G1	20						
G2	190						
G3	10						
G4	10						
G5	35					30	30
G6	1			9 non-contingent			
G7	15	10	10	11 non-contingent			

TABLE 3: DAY-AHEAD MARKET AWARDS

Product	Shadow Price ($/MWh)	Marginal Price ($/MWh)
Energy	40	40
Regulation-up	1	2
Regulation-down	1	1
Spinning reserve	1	1
Non-spinning reserve	0	0
Upward flexible ramping product	2	2
Downward flexible ramping product	2	2

TABLE 4: DAY-AHEAD MARKET PRICES

3.2 RTUC MARKET

Now consider the RTUC market with the day-ahead awards listed in Table 3. For simplicity, consider only one interval in RTUC with $T = 1$, and neglect the transmission network impacts and power losses.

The requirements are

- load is 340 MW,
- regulation up requirement is 10 MW,
- regulation down requirement is 10 MW,
- spinning reserve requirement is 20 MW,
- non-spinning reserve requirement is 0 MW,
- upward flexible ramping product requirement is 50 MW,
- downward flexible ramping product requirement is 40 MW.

Assume G7 is offline in RTUC due to forced outage, so it cannot provide regulation services and spinning reserve. G7's day-ahead ancillary services need to be replaced by other resources.

The RTUC ramp sharing coefficients are

- $\alpha = 0.75$, which means ramp sharing between regulation and energy is not allowed,
- $\beta = 0$, which means ramp sharing between spinning reserve and energy is allowed,
- $\gamma = 1.0$, which means ramp sharing between flexible ramping product and energy is not allowed,
- $\eta = 0$, which means ramp sharing between non-spinning reserve and energy is allowed.

The bids and generator parameters are listed in Table 5 and Table 6. Note that in Table 5, "no bid" for flexible ramping products means that the bid will be assumed to be zero, while "no bid" for ancillary services means the resources are not qualified to provide such ancillary services.

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gen	EN Bid	RU bid	RD bid	SP bid	NS bid	FRU bid	FRD bid	En init	RU init	RD init	SP init	NS init	FRU init	FRD init
G1	25	10	10	10	10	1.4	3	20	0	0	0	0	0	10
G2	30	1.1	1.2	0	0	4	2	180	10	10	0	0	10	0
G3	35	3	3	0	0	3	1	89	10	0	0	0	0	0
G4	50	2	2	0	0	2.3	3	10	0	0	0	0	5	0
G5	53	No	No	No	No	SS	SS	30	0	0	0	0	30	30
G6	60	No	No	SS	No	No	No	1	0	0	9	0	0	0

EN – energy RU – regulation up RD – regulation down SP – spinning reserve
NS – non-spinning reserve FRU – flexible ramping up FRD – flexible ramping down
No – no bid SS – self schedule/provision

TABLE 5: RTUC BIDS AND GENEARTOR INITIAL OPERATING CONDITIONS

gen	Pmin	Pmax	operational ramp rate	regulation ramp rate
G1	10	45	5	5
G2	10	200	3	3
G3	10	300	1	1
G4	10	21	8	8
G5	5	65	6	6
G6	1	10	1	1

TABLE 6: GENERATOR OPERATING LIMITS AND RAMP RATES

Given the system requirements, the optimal RTUC schedules of energy, ancillary services and flexible ramping products are listed in Table 7, and the corresponding marginal prices are listed in Table 8.

gen	Energy	Reg-up	Reg-down	Spinning reserve	Non-spin reserve	Flex-ramp up	Flex-ramp down
G1	45						10
G2	175	10	10	5		5	
G3	74			10			
G4	10			1		10	
G5	35					30	30
G6	1			4		5	

TABLE 7: RTUC OPTIMAL SCHEDULES

Product	Shadow Price ($/MWh)	Marginal Price ($/MWh)
Energy	30	30
Regulation-up	1.1	1.1
Regulation-down	1.2	1.2
Spinning reserve	0	0
Non-spinning reserve	0	0
Upward flexible ramping product	2.3	2.3
Downward flexible ramping product	1.4	1.4

TABLE 8: RTUC PRICES

Because G7 is offline due to forced outage, it cannot provide regulation services and spinning reserve. G2 replaces G7 to provide regulation services in RTUC. G7's spinning reserve is also replaced by other resources.

G6 has 9 MW non-contingent spinning reserve award in day-ahead. As discussed in section 2.3.1, this 9 MW of non-contingent spinning reserve may be converted to upward flexible ramping product if upward flexible ramping is more valuable than spinning reserve. As shown in Table 8, upward flexible ramping marginal price is $2.3/MWh, while spinning reserve marginal price is $0/MWh. Therefore, it is economic to convert G6's non-contingent reserve into upward flexible ramping product. As expected, 5 MW from G6's day-ahead award is converted into upward flexible ramping, and 4 MW remains as spinning reserve. This is because G4 has 1 MW/minute ramp rate, and thus can only provide 5 MW flexible ramping. The 5 MW of award converted into upward flexible ramping will not be settled in RTUC, but will be re-evaluated in RTD.

The flexible ramping headroom is created in RTUC, but it is not financially binding. In other words, the resources that are meeting the RTUC flexible ramping requirements will not be paid in RTUC.

3.3 PROCURING FLEXIBLE RAMPING PRODUCTS IN RTD

In RTD, the imbalance difference is fully realized for the binding interval. The flexible ramping capability kept in previous RTD interval will be fully released in the current RTD interval to meet the realized imbalance difference. Also, the current RTD interval needs to procure flexible ramping capability to meet the imbalance difference to be realized in the next RTD interval.

Again, assume RTD performs a single interval optimization. Let's consider binding interval RTD4. The data for calculating the RTD flexible ramping requirement has been listed in Table 1, and we relist the table here for convenience. In RTD4, the realized imbalance difference is 10 MW, and the upward and downward flexible ramping requirements are both 40 MW.

The RTD dispatch and flexible ramping award are listed in Table 9, in which the zero values are omitted. The lower and upper operating limits are the resources' adjusted Pmin and Pmax due to providing ancillary services. The RTD prices are listed in Table 10.

		RTUC1			RTUC2			RTUC3
		RTD1	RTD2	RTD3	RTD4	RTD5	RTD6	RTD7
	RTUC net load	335	335	335	340	340	340	350
	RTD realization	10	-10	0	10	60	50	50
	RTD net load	345	325	335	350	400	390	400
upward	RTUC requirement	50	50	50	50	50	50	50
	15 minute bound	40	60	55	40	-10	10	…
	5 minute bound	50	50	50	50	50	50	50
	RTD requirement	40	50	50	40	-10	10	…
downward	RTUC requirement	40	40	40	40	40	40	40
	15 minute bound	60	40	45	60	110	90	…
	5 minute bound	40	40	40	40	40	40	40
	RTD requirement	40	40	40	40	40	40	…

This table is the same as Table 1.

gen	Energy	Lower operating limit	Upper operating limit	Flex-ramp up	Flex-ramp down
G1	45	10	45		25
G2	185	20	185		
G3	94	10	290		5
G4	15	10	20	5	5
G5	10	5	65	30	5
G6	1	1	6	5	

TABLE 9: RTD DISPATCH AND FLEXIBLE RAMPING AWARD

Product	Marginal Price ($/MWh)
Energy	49
Upward flexible ramping product	3.3

Downward flexible ramping product	4

TABLE 10: RTD PRICES

3.4 SETTLEMENT OF FLEXIBLE RAMPING PRODUCTS

In this section, we summarize the settlement for flexible ramping awards in day-ahead market and RTD. The day-ahead award will be paid the day-ahead flexible ramping price. The RTD incremental award from day-ahead award will be paid the RTD flexible ramping price. G1, G2 and G4 do not have day-ahead flexible ramping award, so they only receive RTD payments. G5 has day-ahead upward and downward flexible ramping award 30 MW, and its RTD flexible ramping award is less than 30 MW, so it only receives day-ahead payment but receives no RTD payment.

	Day-ahead market settlement (award times price)		RTD incremental award (5/60 times award times price)	
gen	flex-ramp up (price = $2)	flex-ramp down (price = $2)	Flex-ramp up (price = $3.3)	Flex-ramp down (price = $4)
G1				5/60*25*4
G2				
G3				5/60*5*4
G4			5/60*5*3.3	5/60*5*4
G5	30*2	30*2	5/60*0*3.3	5/60*0*4
G6			5/60*5*3.3	
G7				

TABLE 11: FLEXIBLE RAMPING AWARD SETTLEMENT

4. OTHER DESIGN ELEMENTS

4.1 GRID MANAGEMENT CHARGES

The flexible ramping product will be subject to the bid segment fee and the market services fee based upon awarded MW of flexible ramping products. The treatment is the same as will be implemented for other ancillary services in January 2012.

4.2 FLEXIBLE RAMPING PRODUCT DATA RELEASE

The ISO will publish procurement targets, prices, and other data similar to what is currently provided for other ancillary services products.

5. COST ALLOCATION

The ISO has commenced a stakeholder initiative to develop Cost Allocation Guiding Principles. The Draft Final Proposal will be reviewed at a stakeholder meeting on March 19th. At this meeting, the ISO will review a cost allocation straw proposal for the Flexible Ramping Product consistent with the cost allocation guiding principles. The Draft Final Proposal for the Flexible Ramping Product to be posted on April 2 will include the final cost allocation proposal for the Flexible Ramping Product.

6. PLAN FOR STAKEHOLDER ENGAGEMENT

Item	Date
Post Third Revised Straw Proposal	March 7, 2012
Stakeholder Conference Call	March 14, 2012
Stakeholder Comments Due	March 21, 2012
Post Flexible Ramping Product Design Draft Final Proposal (together with Cost Allocation Draft Final Proposal)	April 2, 2012
Stakeholder Meeting	April 9, 2012
Stakeholder Comments Due	April 16, 2012
Board Meeting	May 16, 2012

7. NEXT STEPS

The ISO will discuss the revised straw proposal with stakeholders at a meeting to be held on December 5, 2011. The ISO is seeking written comments on the revised straw proposal by December 12, 2011. Stakeholder comments should be sent to FRP@caiso.com.

APPENDIX A: NOMENCLATURE

$FRU_{i,t}$ upward flexible ramping from resource *i* at time interval t

$FRD_{i,t}$ downward flexible ramping from resource *i* at time interval t

$RU_{i,t}$ regulation-up from resource *i* at time interval t

$RD_{i,t}$ regulation-down from resource *i* at time interval t

$SP_{i,t}$ spinning reserve from resource *i* at time interval t

$NS_{i,t}$ non-spinning reserve from resource *i* at time interval t

$P_{i,t}$ active power from resource *i* at time interval t

P_i^{Min} active power lower limit of resource *i*

P_i^{Max} active power upper limit of resource *i*

RR_i^{OP} operational ramp rate of resource *i*

RR_i^{REG} regulation ramp rate of resource *i*

R_u^{FRU} upward flexible ramping requirement from variability or uncertainty source u

R_u^{FRD} downward flexible ramping requirement from variability or uncertainty source u

$R_t^{FRU,RTUC}$ total upward flexible ramping requirement in RTUC interval t

$R_t^{FRD,RTUC}$ total downward flexible ramping requirement in RTUC interval t

$R_t^{FRU,5min}$ upward 5-minute ramp-able bound in RTD interval t

$R_t^{FRD,5min}$ downward 5-minute ramp-able bound in RTD interval t

NL_t^{RTPD} net load in RTUC interval t

RLZ_t^{RTD} realized total imbalance difference in RTD interval t

UU the set of upward variability or uncertainty sources

UD the set of downward variability or uncertainty sources

I_{FR} the set of resources that bid into the market to provide flexible ramping

I_{FRU}^{DA} the set of upward flexible ramping awards in day-ahead market

I_{SPIN}^{DA} the set of non-contingent spinning awards in day-ahead market and non-contingent non-spinning awards in day-ahead market that become online in RTUC

$FRU_{i,t}^{DA}$ upward flexible ramping procured in day-ahead from resource *i* at time interval t

$SPIN_{i,t}^{DA}$ non-contingent spinning reserve procured in day-ahead market or non-contingent non-spinning reserve procured in day-ahead market that is online in RTUC from resource *i* at time interval $t\lambda_t^{FRU}$ shadow price of upward flexible ramping constraint at time interval t

λ_t^{FRD} shadow price of downward flexible ramping constraint at time interval t

$C_{i,t}^{FRU}(FRU_i)$ bid cost of upward flexible ramping from resource *i* at time interval t

$C_{i,t}^{FRD}(FRD_i)$ bid cost of downward flexible ramping from resource *i* at time interval t

MT market clearing interval length: $MT = 60$ for day-ahead market, $MT = 15$ for RTUC, $MT = 5$ for RTD

T total intervals in the look-ahead optimization: $T = 24$ for day-ahead market, $T \in [4,18]$ for RTUC

α regulation ramp sharing coefficient

β spinning reserve ramp sharing coefficient

γ flexible ramping product ramp sharing coefficient

η non-spinning reserve ramp sharing coefficient

SLK_t^{FRU} relaxed amount of upward flexible ramping product requirement

SLK_t^{FRD} relaxed amount of downward flexible ramping product requirement

APPENDIX B: CO-OPTIMIZING FLEXIBLE RAMPING PRODUCTS WITH ENERGY AND ANCILLARY SERVICES

The convention of the optimization model follows T. Wu and M. Rothleder et al. 2004.[7] We will discuss the changes to the objective function and constraints on top of Wu and Rothleder's model due to the addition of the flexible ramping products. The meanings of the variables used in this section are explained in Appendix A.

For simplicity in this discussion, assume the operational ramp rate is a constant for each resource. The ISO is able model dynamic ramp rates,[8] which is a function of the generation output level, and the following model can be generalized to dynamic ramp rates without problem. As a convention, assume ramp rates are specified in MW/minute.

The change to the objective function is to add the bid costs from the flexible ramping products:

$$\sum_{t=1}^{T} \sum_{i \in I_{FR}} C_{i,t}^{FRU}(FRU_{i,t}) + \sum_{i \in I_{FR}} C_{i,t}^{FRD}(FRD_{i,t})$$

The changes to the constraints involving flexible ramping are as follows.

Five-minute upward flexible ramping capability limit This constraint ensures that a resource's upward flexible ramping product award does not exceed what it can ramp in 5 minutes.

$$\frac{FRU_{i,t}}{RR_i^{OP}} \leq 5$$

Five-minute downward flexible ramping capability limit This constraint ensure that a resource's downward flexible ramping product award does not exceed what it can ramp in 5 minutes.

$$\frac{FRD_{i,t}}{RR_i^{OP}} \leq 5$$

Ten-minute upward ancillary service and flexible ramping limit This constraint ensures the total amount of upward reserves (regulation-up, spinning, and non-spinning) awards and the upward flexible ramp product award does not exceed what the resource can ramp in 10 minutes.

$$\frac{RU_{i,t}}{RR_i^{REG}} + \frac{FRU_{i,t} + SP_{i,t} + NS_{i,t}}{RR_i^{OP}} \leq 10$$

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[7] Tong Wu, Mark Rothleder, Ziad Alaywan, and Alex D. Papalexopoulos, "Pricing Energy and Ancillary Services in Integrated Market Systems by an Optimal Power Flow," *IEEE Transactions on Power Systems*, pp.339-347, 2004.

[8] See CAISO Technical Bulletin "Dynamic Ramp Rate in Ancillary Service Procurement" for details, http://www.caiso.com/Documents/TechnicalBulletin-DynamicRampRate_AncillaryServiceProcurement.pdf

Ten-minute downward ancillary service and flexible ramping limit This constraint ensures the total amount of regulation-down award and downward flexible ramping product award does not exceed what the resource can ramp in 10 minutes.

$$\frac{RD_{i,t}}{RR_i^{REG}} + \frac{FRD_{i,t}}{RR_i^{OP}} \leq 10$$

Upward ramping sharing[9] This constraint limits the extent to which the awards of regulation-up, spinning reserve, non-spinning reserve and upward flexible ramping product can share the resource's ramping capability with the ramp used to support the changes in energy.

$$P_{i,t} - P_{i,t-1} + \alpha \cdot \left(RU_{i,t} + RU_{i,t-1}\right) + \beta \cdot \left(SP_{i,t} + SP_{i,t-1}\right) + \gamma \cdot \left(FRU_{i,t} + FRU_{i,t-1}\right) + \eta \cdot \left(NS_{i,t} + NS_{i,t-1}\right) - MT \cdot RR_i^{OP} \leq 0$$

Downward ramping sharing[1] This constraint limits the extent to which the awards of regulation-down and downward flexible ramping product can share the resource's ramping capability with the ramp used to support the changes in energy.

$$-P_{i,t} + P_{i,t-1} + \alpha \cdot \left(RD_{i,t} + RD_{i,t-1}\right) + \gamma \cdot \left(FRD_{i,t} + FRD_{i,t-1}\right) - MT \cdot RR_i^{OP} \leq 0$$

Active power maximum limit This constraint limits the amount of the awards of energy schedule, upward reserves and upward flexible ramping product to be less than or equal to the resource's maximum operating capability.

$$P_{i,t} + RU_{i,t} + FRU_{i,t} + SP_{i,t} + NS_{i,t} \leq P_i^{Max}$$

Active power minimum limit This constraint limits the amount of energy schedule minus the awards of regulation-down and downward flexible ramping product to be greater than or equal to the resource's minimum operating level.

$$P_{i,t} - RD_{i,t} - FRD_{i,t} \geq P_i^{Min}$$

Upward flexible ramping requirement This constraint ensures that the total amount of upward flexible ramping product awards at least meets the requirement.

$$\sum_{i \in I_{FR}} FRU_{i,t} \geq \sum_{u \in UU} R_{u,t}^{FRU}$$

Downward flexible ramping requirement This constraint ensures that the total amount of downward flexible ramping product awards at least meets the requirement.

$$\sum_{i \in I_{FR}} FRD_{i,t} \geq \sum_{u \in UD} R_{u,t}^{FRD}$$

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[9] See CAISO Technical Bulletin "Simplified Ramping" for details of the ramp sharing constraints and coefficients, http://www.caiso.com/2437/2437db41245c0.pdf, August 2009.