RCSTF Supplement: Incentive Compatibility via Interactions between Reserve and Energy Prices

Key Takeaways:

- When the same resource clears both SR and 10-Min RUR (Up) products, then the clearing price of SR is equal to the sum of the clearing price of 10-Min RUR (Up) product and the incremental SR offer of the resource
- When the same resource clears both 10-Min RUR (Up) and 30-Min RUR products:
  - The 10-Min RUR (Up) clearing price may be greater than the 30-Min RUR clearing price if the 10-Min ramp rate constraint is binding for the resource
  - The 10-Min RUR clearing price is equal to the 30-Min RUR clearing price if the 10-Min ramp rate constraint is not binding
- If a resource is infra-marginal for energy and clears 10-Min RUR (Up) and 30-Min RUR products without binding on the 10-Min or 30-Min ramp rate constraints, then the clearing price of the 10-Min RUR and 30-Min RUR products equal the infra-marginal energy rent of the resource (the difference between the clearing price of energy and the incremental energy offer of the resource)
- If a resource is marginal for energy, but binding on the 10-Min or 30-Min ramp rate constraints and there is a systemwide reserve shortage, indicating that the system is more constrained on flexibility than on capacity, then the clearing price of energy can potentially be lower than the clearing price of the reserve products
- If a resource is dispatched above its ECOMIN to provide 10-Min RUR Down reserves, then the energy price can potentially be lower than the incremental energy offer of the resource at its dispatch point, but this difference is "made whole" through the clearing price of the 10-Min RUR Down product.

Contents

1. Purpose

This document discusses the interactions between the prices of the reserve products and the price of energy in the context of the RCSTF proposal. We focus on the price interactions in the real-time market, where resources can have non-zero energy and SR offers, but cannot submit non-zero offers for the RUR products. The concepts can be trivially extended to the day-ahead market with the appropriate inclusion of the additional day-ahead reserve products and the day-ahead offer rules.

To understand incentive compatibility between energy and reserve prices and the respective allocations, we derive the necessary conditions for optimality of the resource-level profit maximization problem. The concepts are illustrated via specific cases in which the resource is marginal or infra-marginal for energy and/or reserves.

Disclaimer: The formulation has been simplified for expositional purposes, with some constraints omitted for simplicity. In case the exposition in this document contradicts the tariff language, the tariff has precedence.

2. Preliminaries

This section provides the notation used throughout this appendix.

$\mathcal{T} := \{\text{SR}, \text{10-RUR-U(p)}, \text{10-RUR-D(own)}, \text{30-RUR}, \text{30-SecR}, \text{60-Spin}, \text{60-NonSpin}\}$ denotes the set of reserve products

$\mathcal{S} := \{\text{SR}, \text{10-RUR-U(p)}, \text{10-RUR-D(own)}, \text{30-RUR}, \text{30-Min-Reserves}, \text{EG}, \text{DASR}\}$ denotes the set of reserve services

$\mathcal{G}^{\text{ON}}$ denotes the set of resources that are online

$\mathcal{G}^{\text{OFF}}$ denotes the set of all offline resources

$E_i^{\text{MAX}}(t), E_i^{\text{MIN}}(t)$ denote the ECOMAX and ECOMIN (in MW) of the unit i at time t, respectively

$\text{RR}_i(t)$ is the ramp rate in MW/min of unit i at time t (up and down ramp rates assumed symmetric in this document for expositional simplicity). At any time t, the ramp rate for a unit i is assumed to be scalar valued for simplicity

$g_i(t) \in \mathfrak{R}_+$ is the energy dispatch of unit i at time t

$c_i(g_i(t))$ is the total cost of energy at dispatch level $g_i(t)$, while its (weak[1]) derivative $c_i'(g_i(t))$ is the incremental cost of energy. The cost function $c_i : [E_i^{\text{MIN}}, E_i^{\text{MAX}}] \to \mathfrak{R}$ is assumed to be Lipschitz and convex over its domain (we are assuming this structure to account for monotonic

[1]For expositional purposes, we will avoid some of the nuances associated with weak derivatives for the optimality conditions in these notes.

segmented offers)

$r_i^{\text{type}}(t) \in \mathfrak{R}_+$ is the reserve assignment (in MW) of unit i of a given reserve product $\text{type} \in \mathcal{T}$ at time t; e.g., $r_i^{\text{10-RUR-U}}(t)$ is the 10-min RUR (Up) assignment for unit i at time t

The incremental cost of the SR product for resource i at time t is a scalar, denoted $k_i^{\text{SR}}(t)$

The nodal price of energy (LMP) for resource i at time t is denoted $\rho_i^e(t)$, while $\rho_i^{\text{type}}(t)$ denotes the nodal price of reserves of $\text{type} \in \mathcal{T}$

The superscript $\star$ is used with a variable to denote its value at the optimal solution.

3. Profit Maximization and Incentive Compatibility for Online Resources

This section provides an overview of the profit-maximization problem for a resource dispatched for energy and reserves and the associated dual problem. The first order conditions of optimality provide the interactions between the prices of energy and the different reserve products. Incentive compatibility among the different prices is demonstrated by considering different cases in which the resource is either marginal or infra-marginal for energy and reserves.

For expositional clarity, we will discuss the profit maximization of a resource providing energy and up-ramping reserves separately from a resource providing energy and down ramping reserves, while noting that the same resource can potentially provide both up and down ramping reserves.

In order to focus on the interaction between the energy and reserve prices, any resource-level constraints that do not feature reserves are assumed to be non-binding and omitted in this section (for example, in the up-ramping reserves sub-section that follows, the energy constraints on ECOMIN are assumed non-binding and omitted, while in sub-section on 10-Min RUR Down, similar assumptions hold for the energy constraints on ECOMAX).

3.1. SR and RUR Up

Recall that an online resource can have three up-ramping reserve products assigned to it in the real-time market: SR, 10-Min RUR (Up), and 30-Min RUR.

For a resource $i \in \mathcal{G}^{\text{ON}}$ at time t, let the price tuple for energy, SR, 10-Min RUR (Up), and 30-Min RUR be $\left(\rho_i^e(t), \rho_i^{\text{SR}}(t), \rho_i^{\text{10-RUR-U}}(t), \rho_i^{\text{30-RUR}}(t)\right)$, respectively. Then, its profit-maximization problem at time t is given by:

$$\max_{\{g_i, r_i\}} \quad \rho_i^e(t)\, g_i(t) - c_i(g_i(t)) + \left(\rho_i^{\text{SR}}(t) - k_i^{\text{SR}}(t)\right) r_i^{\text{SR}}(t)$$

$$+\rho_i^{\text{10-RUR-U}}(t)\, r_i^{\text{10-RUR-U}}(t) + \rho_i^{\text{30-RUR}}(t)\, r_i^{\text{30-RUR}}(t) \tag{1.1}$$

$$\text{s.t.} \quad E_i^{\text{MAX}}(t) - g_i(t) - r_i^{\text{SR}}(t) - r_i^{\text{10-RUR-U}}(t) - r_i^{\text{30-RUR}}(t) \geq 0 \tag{1.2}$$

$$10\,\mathrm{RR}_i(t) - r_i^{\mathrm{SR}}(t) - r_i^{\text{10-RUR-U}}(t) \geq 0 \tag{1.3}$$

$$30\,\mathrm{RR}_i(t) - r_i^{\mathrm{SR}}(t) - r_i^{\text{10-RUR-U}}(t) - r_i^{\text{30-RUR}}(t) \geq 0 \tag{1.4}$$

The objective function (1.1) represents the surplus of resource i at time t from energy and up-ramping reserves. The constraint on ECOMAX is given by (1.2), while (1.3) and (1.4) provide the constraints on the 10-Min and 30-Min ramp rates, respectively.[2]

To present the dual of the profit-maximization problem (1), we need to introduce the optimized Lagrangian $\varphi\big(\mu_i^{\overline{E}}(t), \mu_i^{\text{10-Up}}(t), \mu_i^{30}(t)\big)$, with $\mu_i^{\overline{E}}(t), \mu_i^{\text{10-Up}}(t), \text{and } \mu_i^{30}(t) \in \mathfrak{R}_+$ denoting the dual variables (Lagrange multipliers) corresponding to (1.2), (1.3), and (1.4), respectively. The optimized Lagrangian is given by:

$$\begin{aligned}
\varphi\big(\mu_i^{\overline{E}}(t), \mu_i^{\text{10-Up}}(t), \mu_i^{30}(t)\big) :=\\
\max_{\{g_i, r_i\}}\ & \rho_i^e(t)\, g_i(t) - c_i(g_i(t)) + \big(\rho_i^{\mathrm{SR}}(t) - k_i^{\mathrm{SR}}(t)\big)\, r_i^{\mathrm{SR}}(t) \\
& + \rho_i^{\text{10-RUR-U}}(t)\, r_i^{\text{10-RUR-U}}(t) + \rho_i^{\text{30-RUR}}(t)\, r_i^{\text{30-RUR}}(t) \\
& + \mu_i^{\overline{E}}(t)\, \big(E_i^{\mathrm{MAX}}(t) - g_i(t) - r_i^{\mathrm{SR}}(t) - r_i^{\text{10-RUR-U}}(t) - r_i^{\text{30-RUR}}(t)\big) \\
& + \mu_i^{\text{10-Up}}(t)\, \big(10\,\mathrm{RR}_i(t) - r_i^{\mathrm{SR}}(t) - r_i^{\text{10-RUR-U}}(t)\big) \\
& + \mu_i^{30}(t)\, \big(30\,\mathrm{RR}_i(t) - r_i^{\mathrm{SR}}(t) - r_i^{\text{10-RUR-U}}(t) - r_i^{\text{30-RUR}}(t)\big) \quad (2)
\end{aligned}$$

The dual problem minimizes $\varphi\big(\mu_i^{\overline{E}}(t), \mu_i^{\text{10-Up}}(t), \mu_i^{30}(t)\big)$ over the dual variables. The following proposition provides the necessary conditions for optimality.

Proposition 3.1. *For a price tuple* $\big(\rho_i^e(t), \rho_i^{\mathrm{SR}}(t), \rho_i^{\text{10-RUR-U}}(t), \rho_i^{\text{30-RUR}}(t)\big)$, *let* $\big(g_i^\star(t), r_i^{\mathrm{SR}\star}(t), r_i^{\text{10-RUR-U}\star}(t), r_i^{\text{30-RUR}\star}(t)\big)$, *respectively, be the tuple of optimal energy and reserve allocation, for a resource* $i \in \mathcal{G}^{\mathrm{ON}}$ *which is allocated all three up-ramping reserve products at time* t*. Then, the optimal allocation satisfies the following:*

$$\rho_i^e(t) = c_i'(g_i^\star(t)) + \mu_i^{\overline{E}\star}(t) \tag{3.1}$$

$$\rho_i^{\text{10-RUR-U}}(t) = \rho_i^{\mathrm{SR}}(t) - k_i^{\mathrm{SR}}(t) = \mu_i^{\overline{E}\star}(t) + \mu_i^{\text{10-Up}\star}(t) + \mu_i^{30\star}(t) \tag{3.2}$$

$$\rho_i^{\text{30-RUR}}(t) = \rho_i^{\text{10-RUR-U}}(t) - \mu_i^{\text{10-Up}\star}(t) = \mu_i^{\overline{E}\star}(t) + \mu_i^{30\star}(t) \tag{3.3}$$

$$0 = \mu_i^{\overline{E}\star}(t)\, \big(E_i^{\mathrm{MAX}}(t) - g_i^\star(t) - r_i^{\mathrm{SR}\star}(t) - r_i^{\text{10-RUR-U}\star}(t) - r_i^{\text{30-RUR}\star}(t)\big) \tag{3.4}$$

$$0 = \mu_i^{\text{10-Up}\star}(t)\, \big(10\,\mathrm{RR}_i(t) - r_i^{\mathrm{SR}\star}(t) - r_i^{\text{10-RUR-U}\star}(t)\big) \tag{3.5}$$

$$0 = \mu_i^{30\star}(t)\, \big(30\,\mathrm{RR}_i(t) - r_i^{\mathrm{SR}\star}(t) - r_i^{\text{10-RUR-U}\star}(t) - r_i^{\text{30-RUR}\star}(t)\big) \tag{3.6}$$

[2]Detailed discussion on resource-level constraints can be found in the supplemental material: https://www.pjm.com/-/media/DotCom/committees-groups/task-forces/rcstf/postings/supplement-product-nesting-and-resource-level-constraints.pdf

$$0 \leq \mu_i^{\overline{E}\star}(t), \mu_i^{\text{10-Up}\star}(t), \mu_i^{30\star}(t), \tag{3.7}$$

along with the conditions for primal feasibility given in (1.2) – (1.4).

Proof. The proof follows from Karush-Kuhn-Tucker (KKT) conditions: (3.1) – (3.3) follow from the stationarity conditions, (3.4) – (3.6) are the complementary slackness conditions, and (3.7) is the dual feasibility condition. ∎

3.1.1. Energy and Reserve Price Interactions

On the basis of Proposition 3.1, we can infer interactions among the prices of the different reserve products.

SR and 10-Min RUR Up Prices. From (3.2), we can infer that if a resource clears both 10-Min RUR (Up) and SR products, then the price of the SR product will equal the sum of price of the 10-Min RUR product and the incremental SR offer of the resource.

10-Min RUR Up and 30-Min RUR Prices. From (3.3), we can infer that if a resource clears both 10-Min RUR (Up) and 30-Min RUR products, then: (i) the 10-Min RUR (Up) price is greater than the 30-Min RUR price when the 10-Min ramp rate constraint (1.3) is binding, and the resource is infra-marginal on the 10-Min RUR product due to this binding; and (ii) the 10-Min RUR (Up) price is equal to the 30-Min RUR price when the 10-Min ramp rate constraint (1.3) is not binding.

In the following, we will describe incentive compatibility under the interactions between the energy and reserve prices for different scenarios (the list of scenarios is not exhaustive).

Scenario A: Resource is marginal for both energy and reserves. In this scenario, the system has sufficient inexpensive flexibility. When the resource is marginal for both energy and all the reserve products, the values of the dual variables $\left(\mu_i^{\overline{E}}(t), \mu_i^{\text{10-Up}}(t), \mu_i^{30}(t)\right)$ are 0. Consequently, from (3.1), it follows that the price of energy is equal to the incremental offer of the resource. From (3.2), we can infer that (i) the price of the SR product is equal to the incremental SR offer of the resource, and (ii) the price of the 10-Min RUR Up product is zero. From (3.3), it follows that the price of the 30-Min RUR product is also zero.

Scenario B: Resource is infra-marginal for energy but marginal for SR, 10-Min RUR, and 30-Min RUR, with sufficient reserves cleared to exactly meet the reserve requirements (all segments of the reserve demand curves are cleared). Since the resource is infra-marginal for energy, it follows from (3.1) that the dual variable $\mu_i^{\overline{E}}(t) = \rho_i^e(t) - c_i'(g_i^\star(t))$ will be strictly positive and equal to the infra-marginal energy rent. Since the resource is marginal for the reserve products, the dual variables $\mu_i^{\text{10-Up}}(t)$ and $\mu_i^{30}(t)$ are both 0. Then, from (3.2) and (3.3), we have the following implications.

- The price of 10-Min RUR Up and 30-Min RUR are both equal to the infra-marginal energy rent (or the opportunity cost of clearing for the reserve products instead of energy):

$$\rho_i^{\text{10-RUR-U}}(t) = \rho_i^{\text{30-RUR}}(t) = \rho_i^e(t) - c_i'(g_i^\star(t)) \tag{4}$$

- The price of the SR product is equal to the sum of the infra-marginal energy rent and the incremental SR offer:

$$\rho_i^{\text{SR}}(t) = \rho_i^e(t) - c_i'(g_i^\star(t)) + k_i^{\text{SR}}(t) \tag{5}$$

Scenario C: Resource is infra-marginal for energy and marginal for SR, 10-Min RUR, and 30-Min RUR, with sufficient SR and 10-Min RUR cleared to meet the reserve requirements, but the 30-Min RUR demand curve sets the 30-Min RUR price. This implies that across the system, there are sufficient flexible, inexpensive resources, but 4-hour duration capacity is at a premium. In this case, the dual variables $\mu_i^{\text{10-Up}}(t) = \mu_i^{30}(t) = 0$, but $\mu_i^{\overline{E}}(t) > 0$. Following (3.1) and (3.3), we can express the energy price in terms of the 30-Min RUR prices as follows:

$$\rho_i^e(t) = c_i'(g_i^\star(t)) + \rho_i^{\text{30-RUR}}(t) \tag{6}$$

In other words, the energy price reflects the incremental cost of the resource as well as the opportunity cost of clearing for energy instead of 30-Min RUR.

From (3.2), we have:

$$\rho_i^{\text{10-RUR-U}}(t) = \rho_i^{\text{SR}}(t) - k_i^{\text{SR}}(t) = \rho_i^{\text{30-RUR}}(t) \tag{7}$$

In other words, the opportunity cost of clearing for 10-Min RUR (Up) instead of 30-Min RUR is reflected in the 10-Min RUR price, leading to a positive 10-Min RUR price even though the system is not constrained on 10-Min flexibility. Similarly, the SR price includes the incremental SR offer as well as the opportunity cost of clearing for SR instead of the 30-Min RUR.

Scenario D: Resource is marginal for energy and 30-Min RUR, but binding on 10-Min ramp rate constraint and clears 10-Min RUR as well as SR. In this case, the system values the 10-Min flexibility at a premium. This scenario implies that the dual variables $\mu_i^{\overline{E}}(t) = \mu_i^{30}(t) = 0$, but $\mu_i^{\text{10-Up}}(t) > 0$. Consequently, we can infer from (3.3) that the price of 30-Min RUR is zero, while (3.2) implies that the price of 10-Min RUR Up is positive. The price of SR is the sum of the price of 10-Min RUR Up and the incremental SR offer of the resource. Moreover, it follows from (3.1), that the price of energy equals the incremental energy offer of the resource.

Scenario E: Resource is marginal for energy, SR, and 10-Min RUR (Up), but infra-marginal for 30-Min RUR. This scenario implies that the system places a premium on 30-Min flexibility. In this case, the dual variables $\mu_i^{\overline{E}}(t) = \mu_i^{\text{10-Up}}(t) = 0$, while $\mu_i^{30}(t) > 0$. From (3.2) and (3.3), it follows that the price of the 10-Min RUR and 30-Min RUR are equal and positive-valued. As before, the price of SR is the sum of the price of 10-Min RUR Up and the incremental SR offer of the resource. In other words, the opportunity cost of clearing for 10-Min RUR (Up) or SR instead of 30-Min RUR is reflected in the prices of 10-Min RUR (Up) and SR products. Since the resource has enough headroom (it is marginal for energy), the price of energy equals the incremental offer of the resource.

3.2. 10-Min RUR Down

For a resource $i \in \mathcal{G}^{\text{ON}}$ at time t, let $\rho_i^e(t)$ be the energy LMP and $\rho_i^{\text{10-RUR-D}}(t)$ be the nodal price of 10-Min RUR Down. Then, its profit-maximization problem at time t only considering terms and constraints that include the 10-Min RUR Down product is given by:

$$\max_{\{g_i, r_i\}} \quad \rho_i^e(t)\, g_i(t) - c_i(g_i(t)) + \rho_i^{\text{10-RUR-D}}(t)\, r_i^{\text{10-RUR-D}}(t) \tag{8.1}$$

$$\text{s.t.} \quad g_i(t) - r_i^{\text{10-RUR-D}}(t) - E_i^{\text{MIN}}(t) \geq 0 \tag{8.2}$$

$$10\,\text{RR}_i(t) - r_i^{\text{10-RUR-D}}(t) \geq 0 \tag{8.3}$$

The objective function represents the surplus from energy and 10-Min Down RUR for resource i at time t. The constraint that the energy dispatch accounting for 10-Min RUR Down be above ECOMIN is given in (8.2), while (8.3) represent the 10-Min ramp-rate constraint on the 10-Min RUR Down product.

To present the dual of the profit-maximization problem (8), we need to introduce the optimized Lagrangian $\psi\big(\mu_i^{E}(t), \mu_i^{\text{10-D}}(t)\big)$, with $\mu_i^{E}(t)$ and $\mu_i^{\text{10-D}}(t) \in \mathfrak{R}_+$ denoting the dual variables (Lagrange multipliers) corresponding to (8.2) and (8.3), respectively. The optimized Lagrangian is given by:

$$\begin{aligned}\psi\big(\mu_i^{E}(t), \mu_i^{\text{10-D}}(t)\big) := \max_{\{g_i, r_i\}} \quad & \rho_i^e(t)\, g_i(t) - c_i(g_i(t)) + \rho_i^{\text{10-RUR-D}}(t)\, r_i^{\text{10-RUR-D}}(t) \\ & + \mu_i^{E}(t)\,\big(g_i(t) - r_i^{\text{10-RUR-D}}(t) - E_i^{\text{MIN}}(t)\big) \\ & + \mu_i^{\text{10-D}}(t)\,\big(10\,\text{RR}_i(t) - r_i^{\text{10-RUR-D}}(t)\big)\end{aligned} \tag{9}$$

The dual problem minimizes the optimized Lagrangian in (9) over the dual variables. The following proposition provides the necessary conditions for optimality.

Proposition 3.2. *For energy price $\rho_i^e(t)$ and 10-Min RUR Down price $\rho_i^{\text{10-RUR-D}}(t)$, let $g_i^\star(t)$and $r_i^{\text{10-RUR-D}\star}(t)$ be the optimal energy and 10-Min RUR Down allocations, respectively, for a resource $i \in \mathcal{G}^{\text{ON}}$ at time t. Then, the optimal allocation satisfies the following:*

$$\rho_i^e(t) = c_i'(g_i^\star(t)) - \mu_i^{E^\star}(t) \tag{10.1}$$

$$\rho_i^{\text{10-RUR-D}}(t) = \mu_i^{E^\star}(t) + \mu_i^{\text{10-D}^\star}(t) \tag{10.2}$$

$$0 = \mu_i^{E^\star}(t)\,\big(g_i^\star(t) - r_i^{\text{10-RUR-D}\star}(t) - E_i^{\text{MIN}}(t)\big) \tag{10.3}$$

$$0 = \mu_i^{\text{10-D}^\star}(t)\left(10\,\mathrm{RR}_i(t) - r_i^{\text{10-RUR-D}^\star}(t)\right) \tag{10.4}$$

$$0 \le \mu_i^{\underline{E}^\star}(t), \mu_i^{\text{10-D}^\star}(t), \tag{10.5}$$

along with the conditions for primal feasibility given in (8.2) and (8.3).

Proof. The proof follows from Karush-Kuhn-Tucker (KKT) conditions: (10.1) and (10.2) follow from the stationarity conditions; (10.3) and (10.4) are the complementary slackness conditions; and (10.5) is the dual feasibility condition. ∎

The implications of Proposition 3.2 are shown using the following scenarios.

Scenario A: The resource is marginal for energy as well as 10-Min RUR Down. In this case, there is sufficient 10-Min down ramp flexibility in the system. Since neither the ECOMIN nor the 10-Min ramp rate constraints are binding, we have $\mu_i^{\underline{E}}(t) = \mu_i^{\text{10-D}}(t) = 0$. It follows from (10.1) that the energy price equals the incremental energy offer of the resource, while (10.2) implies that the price of the 10-Min RUR Down product is zero.

Scenarios B and C that follow represent a system that places a premium on 10-Min down ramp flexibility.

Scenario B: The resource is marginal for 10-Min RUR Down, but has to supply energy above its ECOMIN in order to provide 10-Min RUR Down. In this scenario, the ECOMIN constraint is binding while the 10-Min ramp rate constraint is non-binding (since the resource is marginal for 10-Min RUR Down). Consequently, we have $\mu_i^{\underline{E}}(t) > 0$ and $\mu_i^{\text{10-D}}(t) = 0$. From (10.2), it follows that the 10-Min RUR Down price is strictly positive. In consequence of (10.1), the energy price can be represented as the difference between the incremental energy offer and the 10-Min RUR Down price:

$$\rho_i^{\text{10-RUR-D}}(t) = c_i'(g_i^\star(t)) - \rho_i^e(t) \tag{11}$$

This implies that the resource is operating above its economic energy point in order to serve the 10-Min down ramp flexibility needs of the system, and the 10-Min RUR Down price represents the make-whole price for this flexible resource.

Scenario C: The resource is marginal for energy, but infra-marginal for 10-Min RUR Down. This scenario is indicative of a system with insufficient 10-Min down ramp capability. Since the resource is not binding on ECOMIN, the dual variable $\mu_i^{\underline{E}}(t) = 0$. However, since the resource is infra-marginal for 10-Min RUR Down, it is binding on the 10-Min ramp constraint leading to $\mu_i^{\text{10-D}}(t) > 0$. From (10.2), it follows that the 10-Min RUR Down price is strictly positive, while (10.1) implies that the energy price equals the incremental offer price of that resource.

3.3. General Inferences from Proposition 3.1 and 3.2

From the propositions and the scenarios described above, for the limited setup of (1) and (8), we can infer that the optimal solution prioritizes clearing up-ramping reserves on the resources with the highest incremental energy costs and down-ramping reserves on resources with the lowest incremental energy costs.

Moreover, in a ramp-constrained system with sufficient capacity, the SR and RUR Up reserve prices incorporate the opportunity cost of clearing reserves instead of energy on infra-marginal energy resources. On a capacity-limited system with up-ramping reserve shortage, the energy price incorporates the opportunity cost of clearing for energy instead of reserves at reserve scarcity prices.

The 10-Min RUR Down prices incorporate the make-whole payment for dispatching a flexible resource above its economic energy point in order to maintain flexibility for the 10-Min down ramp.