JUNE, 2020

A Multi-Period Market Design for Markets with Intertemporal Constraints and Nonconvexity

Harvard Electricity Policy Group Conference

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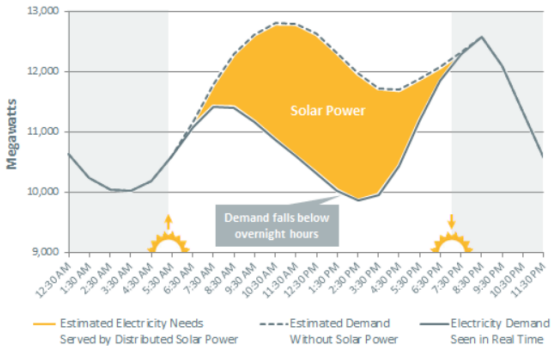
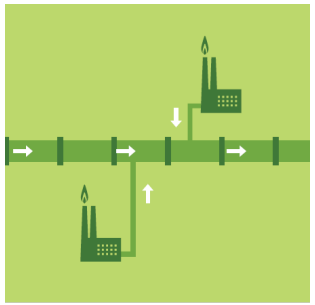
Recent Industry Trends

- "Duck curve" load shape caused by renewable integration
  - More frequent ramping capability concerns
- Growing participation of energy storage resources
  - ISO-managed storage operations
- Fuel delivery system and inventory limitations
  - Manage limited fuel supply over a day or multiple days





Temporal Market Coupling

- Intertemporal constraints enforce operational limits between time periods
  - Ramping constraints
  - State-of-charge constraints
  - Limited energy constraints
- Currently, these constraints are only enforced over the market's time horizon (plus initial conditions)
- Recent industry trends have increased the importance of temporal coupling beyond the market's time horizon

Existing Market Clearing Approaches

- Single-period Real-Time Market (RTM)
  - Each RT market clearing solves for one time period
  - Intertemporal linkages are not explicitly modeled
  - ISO-NE, MISO, PJM, SPP
- Multi-period single-settlement
  - Each RT market clearing solves for multiple time periods
  - Only the first period is settled, prices for later periods are advisory
  - NYISO, CAISO
- Flexibility product
  - Procure additional ramp-up and ramp-down capability by holding a portion of generating capability at a high or low output level
  - Procure flexibility on behalf of load to prepare for uncertainty
  - MISO, CAISO

Issues with the Existing Approaches

- Dispatch may be economically inefficient over a longer time horizon
  - Both single-period and flexibility product approaches optimize over a short look-ahead horizon
- Dispatch may push the system toward future infeasibility
  - Manual actions may be required under the single-period approach
  - Increases uplift payments
- Dispatch may lack dispatch-following incentives
  - Opportunity costs are not reflected in the LMP
    - Clearing prices are inconsistent with manual actions under the single-period approach
  - Opportunity costs are not compensated in the market
    - Multi-period single-settlement approach

Coordinated Multi-Period Scheduling and Pricing

Forward Step

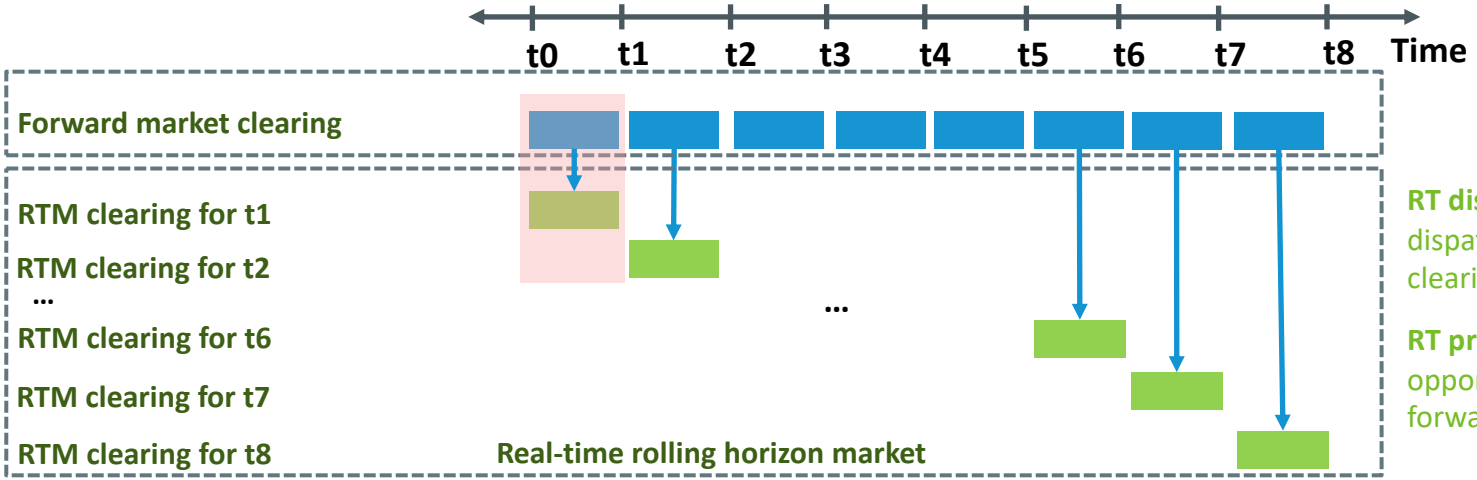
- Solve a **multi-period problem** using forecasted system conditions

RTM Step

- Solve **single-period problems** guided by the Forward Step's quantities and prices
- Separate dispatch and pricing runs

Settlement Step

- Settle Forward Step quantities at Forward Step prices
- Settle RTM Step quantity deviations from Forward Step quantities at RTM Step prices



RT dispatch: limit RT dispatch at t by forward clearing dispatch at $t + 1$

RT pricing: Incorporate opportunity costs from forward clearing in RT offers

Benefits of Coordinated Multi-Period Market Design

- ***Dispatch consistency***: RTM dispatch matches the forward clearing quantities assuming perfect foresight
- ***Price consistency***: RTM prices match the forward clearing prices assuming perfect foresight
- **Dispatch-following incentives**
  - Prices account for opportunity costs of intertemporal constraints
  - The true marginal cost of a resource is
    marginal production cost + intertemporal opportunity cost
  - Reduce uplift payments for out-of-market actions
- **Economic efficiency and reliability**
  - Dispatch considers future system conditions

Reference: J. Zhao, T. Zheng, and E. Litvinov, "A Multi-Period Market Design for Markets with Intertemporal Constraints," in *IEEE Transactions on Power Systems*, doi: 10.1109/TPWRS.2019.2963022.

Forward Step

- Without non-convexity, the forward clearing quantity and price constitute a competitive equilibrium.
- The forward result is the best solution assuming perfect foresight
- The true marginal cost of a resource is marginal production cost + intertemporal opportunity cost

Multi-Period Forward Market Clearing

Maximize: $\sum_{t=1}^{T} Social\ welfare$

Subject to: Energy balance $t = 1, \ldots, T$ (forward LMP)

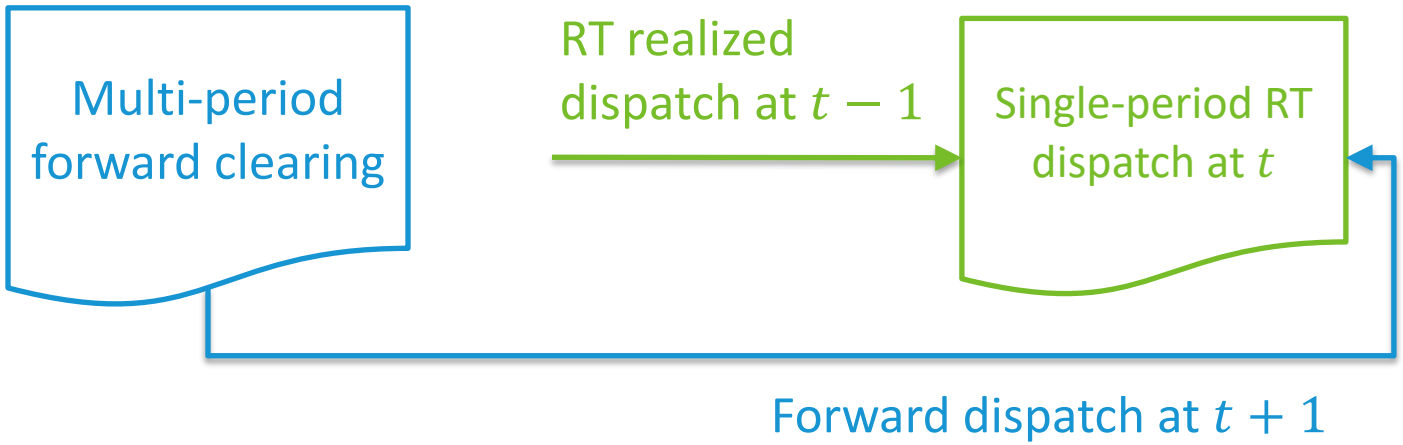
Resource capacity $t = 1, \ldots, T$

Intertemporal constraints linking dispatch between t and t + 1 (intertemporal opportunity cost)

RTM Step (Dispatch)

- The RTM uses a single-period horizon
- Optimal dispatch from the Forward Step limits the RTM Step dispatch solution
- Result: ***Dispatch consistency***

  RTM dispatch matches the Forward Clearing assuming perfect foresight



RTM Step (Pricing)

- RTM pricing incorporates forward intertemporal opportunity costs as offer adjustments
- Result: ***Price consistency***

  RTM prices match the Forward Clearing assuming perfect foresight

Single-period RTM pricing problem at t

Maximize: Consumer surplus –
(Marginal production cost + intertemporal opportunity cost) × production MW

Subject to: Energy balance at t (RT LMP)

Resource capacity at t

Extension 1: Nonconvexity

- If the ISO wants to calculate prices that reflect commitment costs, the Convex Hull Pricing approach could be used
  - Derived from the commitment problem
  - Produces a multi-period price sequence that minimizes out-of-market payments (opportunity cost + ISO revenue shortfall)
- The Coordinated Multi-Period Market Design should remain applicable
- Unfortunately, this implementation would be computationally challenging
  - The Coordinated Design would require Convex Hull Prices for the Forward Clearing
  - Identification of Convex Hull Prices remains challenging for realistic multi-period problems

Extension 2: Load uncertainty

- If the ISO wants to calculate quantities and prices that ensure feasibility under load uncertainty, flexibility products could be added to the multi-period dispatch problem
  - Conceptually, flexibility products are similar to reserves
- The Coordinated Multi-Period Market Design should remain applicable
- The time horizon of the flexibility product is important

Conclusion

- Intertemporal constraints are becoming more important
- Existing methods for addressing intertemporal constraints are inefficient
- The Coordinated Multi-Period Market Design allows a single-period market clearing problem to reproduce a multi-period market clearing result
- The Coordinated Multi-Period Market Design can be used in combination with other emerging market concepts
  - Convex Hull Pricing, flexibility products
- The Coordinated Multi-Period Market Design can reduce the need for out-of-market actions, avoiding uplift