A Multi-Period Market Design for Markets with Intertemporal Constraints

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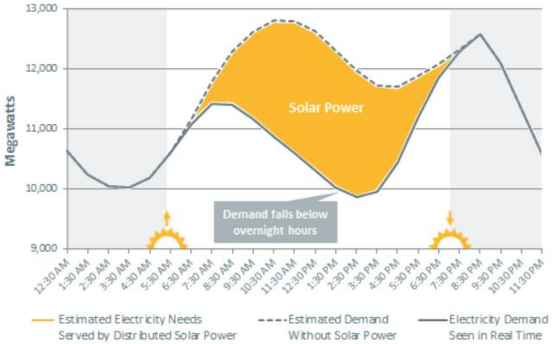
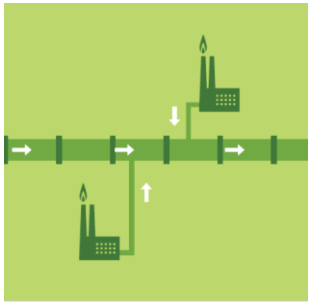
INTRODUCTION

Temporal market coupling under the recent industry trends

Recent Industry Trends

- “Duck curve” load shape resulting from a large amount of renewable integration
  - More frequently constrained by ramping capability
- Increasing participation of energy storage resources
  - ISO-managed energy storage
- The nation increasingly relies on natural gas fired units
  - Managing limited energy resources





Temporal Market Coupling

- Intertemporal constraints couple the markets in different time intervals
  - ❑ Ramping constraints
  - ❑ State-of-charge constraints
  - ❑ Limited energy constraints
- Temporal market coupling has become stronger under the recent industry trends.
- Call for careful studies of scheduling and pricing methods for markets with intertemporal constrains.

MOTIVATION

Issues with the existing multi-period market designs

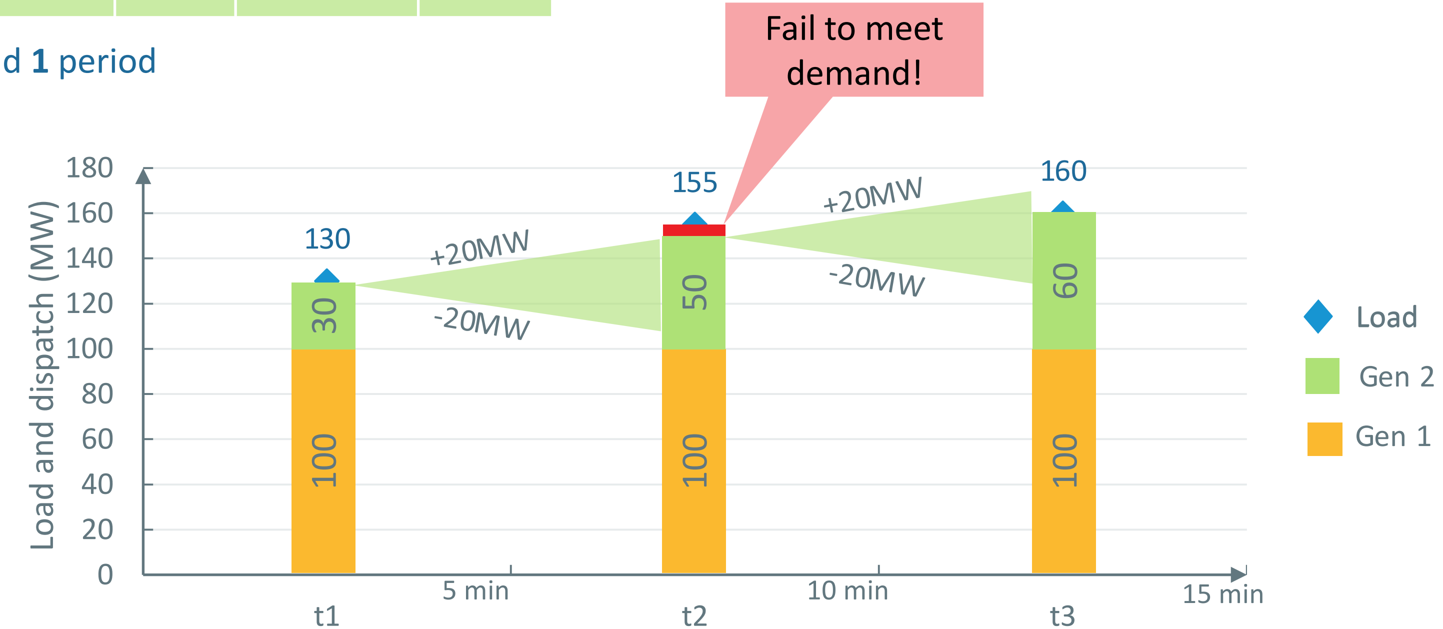
The Myopic Approach

- Each RT market clearing solves for one time period
  - ISO NE, MISO, PJM, and SPP
- Intertemporal linkages are not explicitly modeled

The Myopic Approach - Example

Gen	Offer ($/MWh)	p^{max} (MW)	Ramping (MW/min)	P_0 (MW)
1	28	100	3	95
2	30	100	4	35

Look ahead **1** period



RTM clearing at t1: LMP $30/MWh

RTM clearing at t2: LMP $30/MWh

RTM clearing at t3: LMP $30/MWh

Issues of the Myopic Approach

- Can result in economically inefficient dispatch or unreliable operation
- Manual actions are taken to adjust dispatch
  - Subjective, suboptimal, or infeasible
- Lack of dispatch-following incentives
  - Clearing prices are inconsistent with manual actions

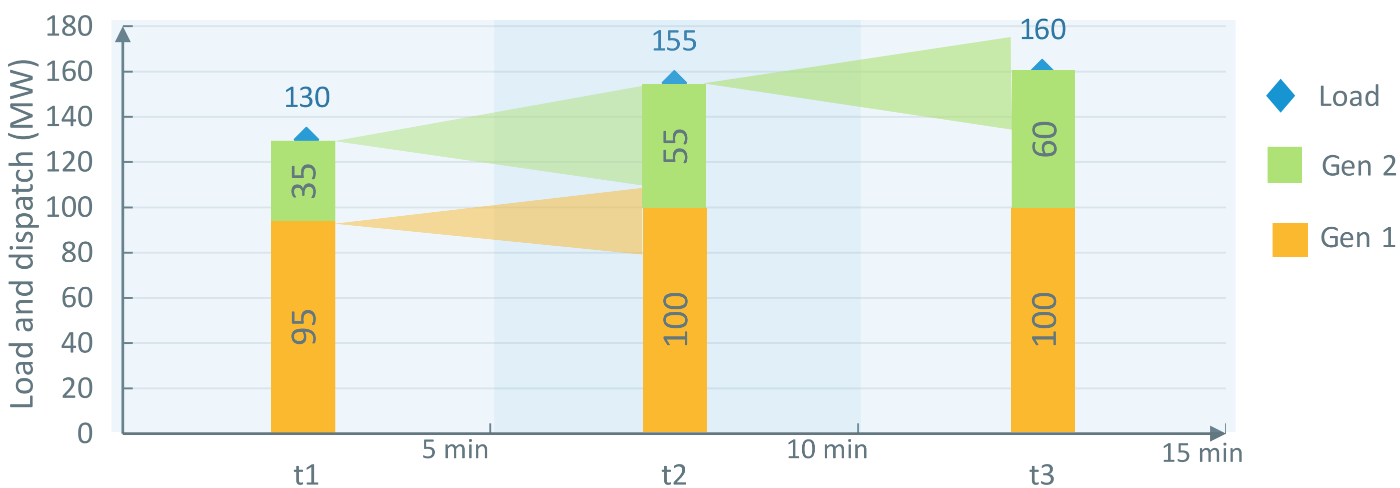
The Multi-Period Single-Settlement Approach

- Each RT market clearing solves for multiple time periods
- Only the first period is settled, prices for later periods are advisory
  - NY ISO and CA ISO

The Multi-Period Single-Settlement Approach - Example

Gen	Offer ($/MWh)	p^{max} (MW)	Ramping (MW/min)	P_0 (MW)
1	28	100	3	95
2	30	100	4	35

Look ahead **2** periods



RTM clearing at t1: LMP $28/MWh $32/MWh

Gen 2 offer > LMP at RTM t1, incurring lost opportunity cost

RTM clearing at t2: LMP $30/MWh $30/MWh

Gen 2's lost opportunity cost is not compensated at RTM t2

Issues of the Multi-Period Single-Settlement Approach

- Lack of dispatch-following incentives
  - Opportunity costs are not compensated. Each RT market clearing solves for multiple time periods
- Trade-offs have to be made between computational efficiency and operational reliability
  - If the look-ahead horizon is too short, the dispatch may not be efficient or reliable.
  - If the look-ahead horizon is too long, the dispatch problem becomes very large.

Summary of the Existing Approaches

- Economically inefficient
- Unreliable schedules
- Tradeoff between computational efficiency and reliable schedules
- Lacking dispatch-following incentives
  - Opportunity costs are not reflected in the LMP
  - Opportunity costs are not compensated in the market
- The coordination between forward and real-time markets is weak
  - RTM only relies on the information within a short RT look-ahead time horizon

A COORDINATED MULTI-PERIOD SCHEDULING AND PRICING DESIGN

Coordinated Multi-Period Scheduling and Pricing Framework

Forward level– Multi-Period clearing

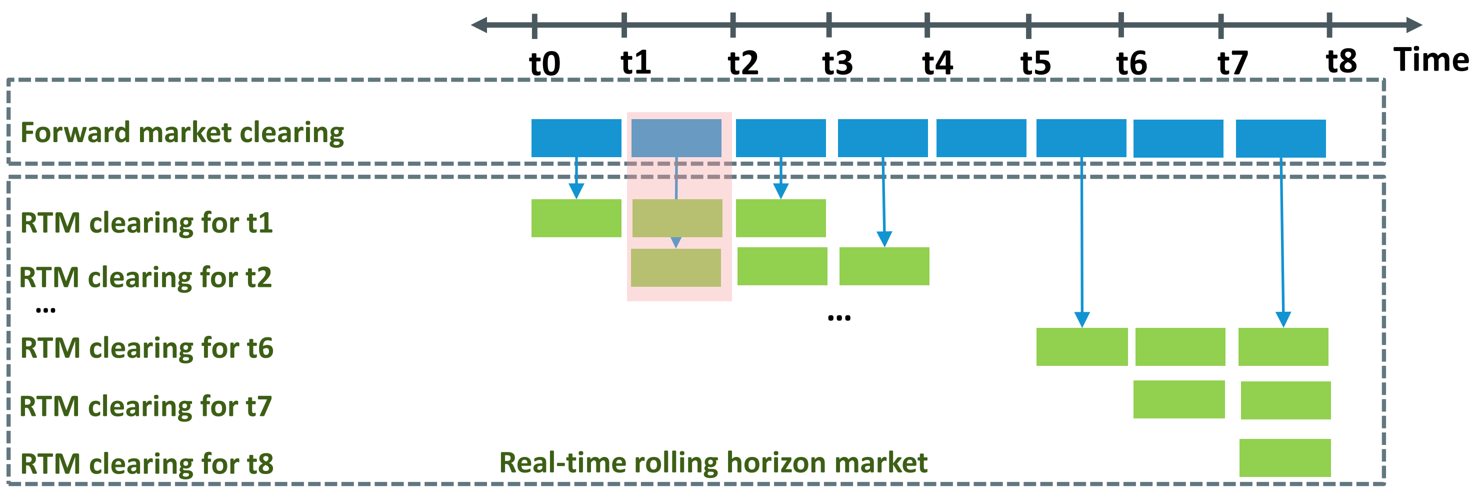
- ❑Produce dispatch and prices for multiple time periods simultaneously under the forecasted system condition

RTM level – Coordinate with forward market

- ❑Dispatch is guided by the forward schedules
- ❑Pricing takes into account intertemporal opportunity costs

Multi-Settlement – Reducing risk exposure

- ❑ Settle deviation from previous market clearing in each rolling-horizon



Benefits of Coordinated Multi-Period Market Design

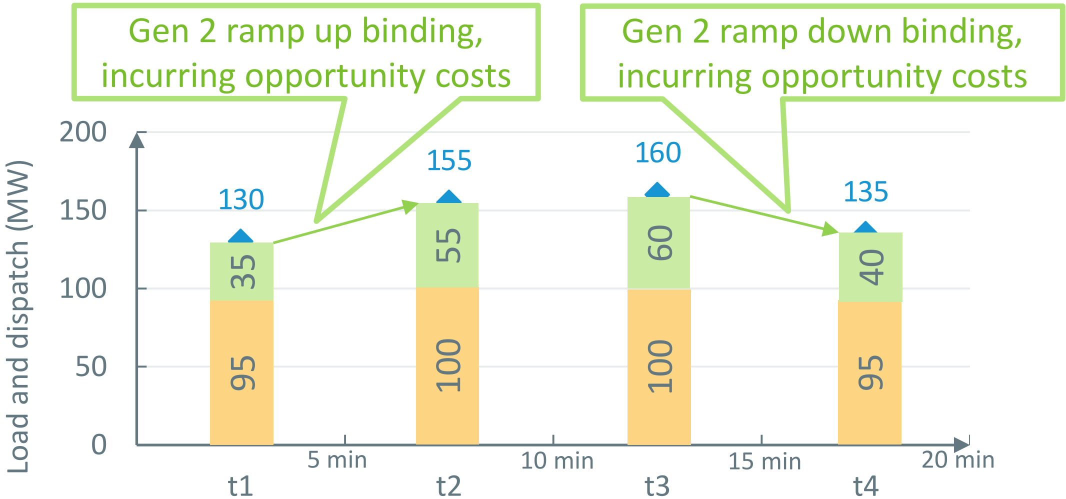
- Provide proper dispatch-following incentives
  - Pricing takes into account the opportunity cost associated with the intertemporal constraints
- Ensure the system reliability and efficiency
  - Dispatch considers future system conditions
- No need for the ISO to make tradeoffs between computational efficiency and operational reliability.

Reference: “A Multi-Period Market Design for Markets with Intertemporal Constraint ,” J. Zhao, T. Zheng, and E. Litvinov, available at Arxiv.

Illustrative Example: Forward Market Clearing

Gen	Offer ($/MWh)	p^{max} (MW)	Ramping (MW/min)	P_0 (MW)
1	28	100	3	95
2	30	100	4	35

Forward market time horizon is **4** periods



Forward Market Clearing

$$Minimize \sum_t c_t g_t$$

$s.t.$	$Energy\ balance$	$t = 1, \dots, T$	(LMP_t)
	$Resource\ capacity$	$t = 1, \dots, T$	
	$g_t - g_{t-1} \le RR$	$t = 1, \dots, T$	$(\pi^{up}_{t-1:t})$
	$g_{t-1} - g_t \le RR$	$t = 1, \dots, T$	$(\pi^{dn}_{t-1:t})$

Illustrative Example: Forward Market Clearing

Gen2 is a marginal resource:

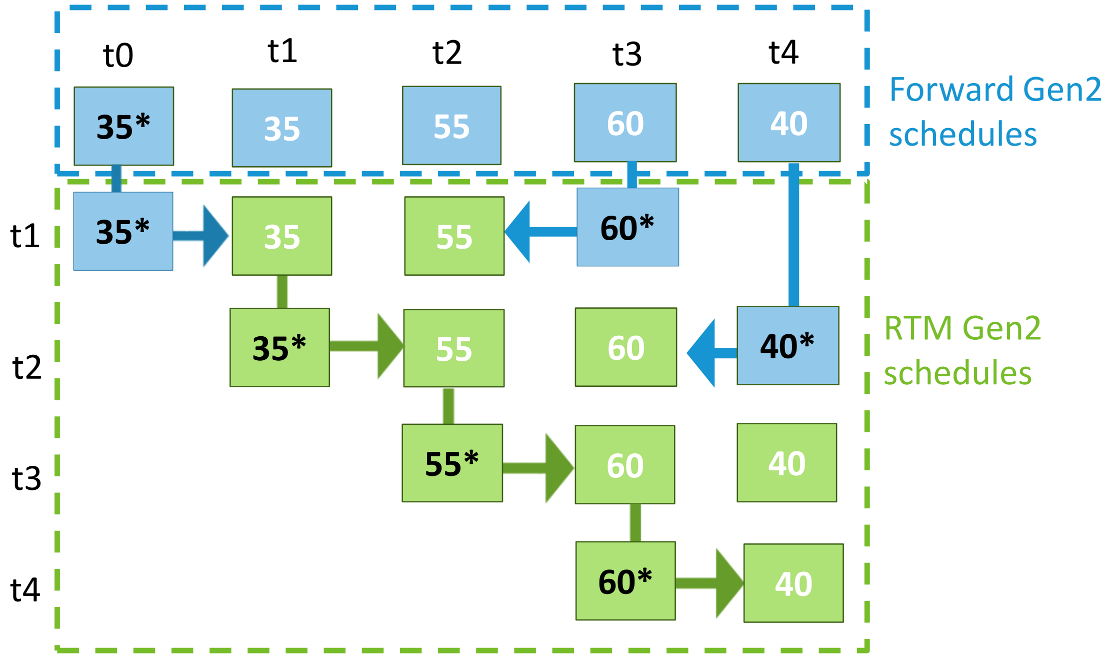
$LMP_t =$ Marginal production cost + Intertemporal opportunity cost

	$LMP_t =$	$c_{gen2,t}$	$+(\pi^{up}_{t-1:t} - \pi^{dn}_{t-1:t} - \pi^{up}_{t:t+1} + \pi^{dn}_{t:t+1})$
t1	28 =	30	-2
t2	32 =	30	+2
t3	32 =	30	+2
t4	28 =	30	-2

Gen2's lost \$2 at t1

\$2 lost opportunity cost is compensated at t2

Illustrative Example: RTM Scheduling



RTM Scheduling at t1

$$Minimize \quad c_{t1} g_{t1} + c_{t2} g_{t2}$$

$$s.t. \quad Energy\ balance \quad t = t1, t2$$

$$Resource\ capacity \quad t = t1, t2$$

$$-RR \le g_{t1} - g_{t0}^{*} \le RR$$

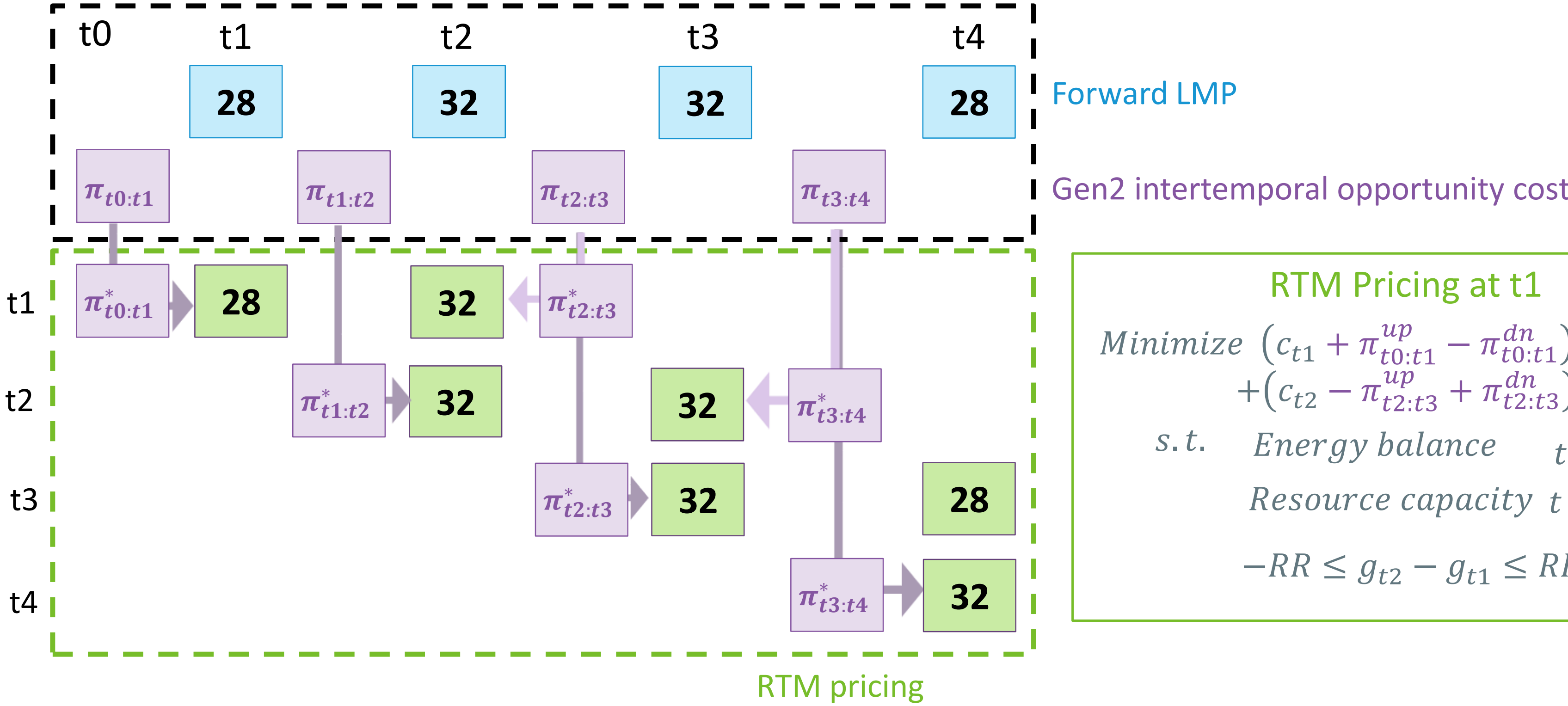
$$-RR \le g_{t2} - g_{t1} \le RR$$

$$-RR \le g_{t2} - g_{t3}^{*} \le RR$$

- ❑ Shorter look-ahead horizon in the RTM
- ❑ Forward schedules are used as a guideline for RTM scheduling
- ❑ *Dispatch consistency*

RTM schedules are consistent with forward schedules under the perfect forecast.

Illustrative Example – RTM Pricing



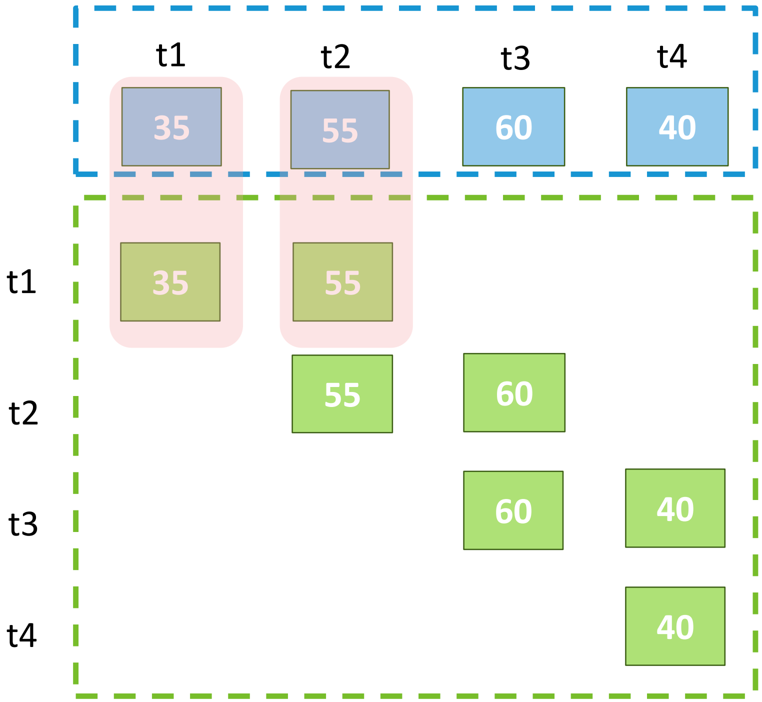
RTM Pricing at t1

$$
\begin{aligned}
\text{Minimize}\ & \left(c_{t1} + \pi^{up}_{t0:t1} - \pi^{dn}_{t0:t1}\right) g_{t1} \\
& + \left(c_{t2} - \pi^{up}_{t2:t3} + \pi^{dn}_{t2:t3}\right) g_{t2} \\
s.t.\ & \text{Energy balance} \quad t = t1, t2 \\
& \text{Resource capacity} \quad t = t1, t2 \\
& -RR \le g_{t2} - g_{t1} \le RR
\end{aligned}
$$

- ❑ RTM pricing incorporates intertemporal opportunity costs as offer adders
- ❑ *Provide proper compensation*
- ❑ *Price consistency*

RTM prices are consistent with the forward prices under the perfect forecast.

Illustrative Example – Multi-Settlement



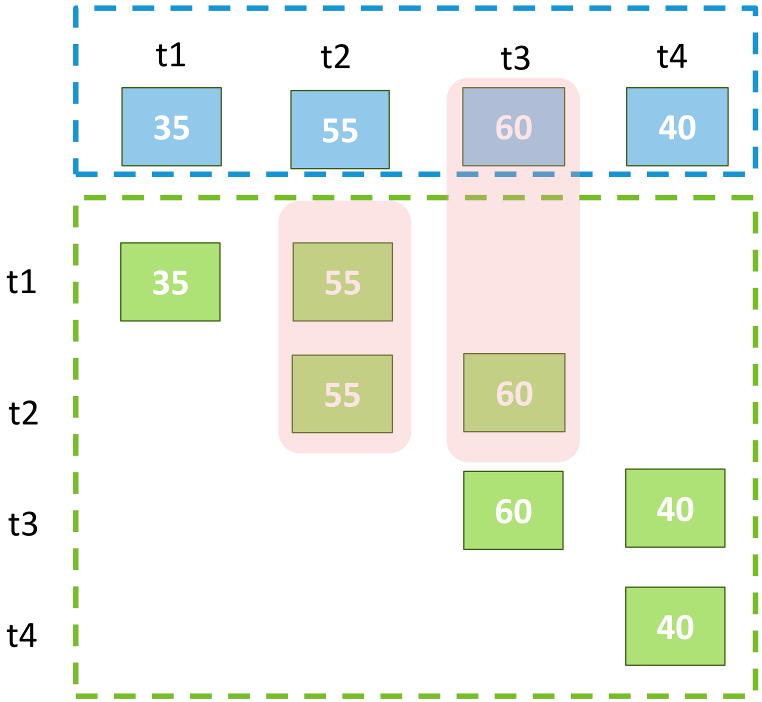
Settle all forward Gen2 schedules

$$LMP^f_{t1} \times p_{t1} + LMP^f_{t2} \times p_{t2} + LMP^f_{t3} \times p_{t3} + LMP^f_{t4} \times p_{t4}$$

Settle the schedule deviation at RTM

$$LMP'_{t1} \times \Delta p'_{t1} + LMP'_{t2} \times \Delta p'_{t2}$$

Illustrative Example – Multi-Settlement



Settle all forward Gen2 schedules

$$LMP_{t1}^{f} \times p_{t1} + LMP_{t2}^{f} \times p_{t2} + LMP_{t3}^{f} \times p_{t3} + LMP_{t4}^{f} \times p_{t4}$$

Settle the schedule deviation at RTM

$$LMP_{t1}' \times \Delta p_{t1}' + LMP_{t2}' \times \Delta p_{t2}'$$

$$LMP_{t2}'' \times \Delta p_{t2}'' + LMP_{t3}'' \times \Delta p_{t3}''$$

$$LMP_{t3}''' \times \Delta p_{t3}''' + LMP_{t4}''' \times \Delta p_{t4}'''$$

$$LMP_{t4}'''' \times \Delta p_{t4}''''$$

- Reduce risk exposure for market participants

NUMERICAL EXAMPLES

ISO New England System

- Setup
  - Forward market
    - 24-hour multi-period problem with forecasted load
  - RTM
    - 25 random realizations: sampling load deviating uniformly 10% above forecasted load
    - Hourly granularity
  - Resources
    - Pumped-storage units: SOC constraint, end-of-the-day target SOC
    - Resources with ramping constraints

Comparison Measures

- Alternative approaches
  - ❑ Myopic
    look ahead 1 hour in RTM
  - ❑ Multi-period single-settlement
    look ahead 2 hours in RTM
  - ❑ Coordinated
    Forward 24-hour multi-period, look ahead 2 hours in RTM
- Comparison measures
  - ❑ Computational efficiency → computation time
  - ❑ Reliability → constraint violation instances
  - ❑ Economic efficiency → social surplus
  - ❑ Dispatch-following incentives → uplift: lost opportunity cost

Computational Efficiency

	Avg. CPU time for pricing (seconds)	Avg. CPU time for dispatch (seconds)
Myopic	1.9	1.9
2-period single-settlement	3.8	3.8
2-period coordinated	3.8	3.9

- The coordinated approach is computationally efficient, and practical for real-time implementation.

Reliability

- Myopic approach does not yield reliable schedules
  - Pumped-storage's end-of-day SOC is violated in every scenarios
  - Future schedule is not taken into account
- 2-period single-settlement approach does not yield reliable schedules
  - Pumped-storage's end-of-day SOC is violated in every scenarios
  - Does not look far enough
- 2-period coordinated approach yields reliable schedules
  - Compensate the short look-ahead horizon by using forward schedules as guidelines.

Economic Efficiency

	Avg. Storage surplus	Avg. Social surplus
Myopic	$0.031 M	$2,246 M
2-period single-settlement	+ 87.5%	+ 0.7%
2-priod coordinated	+ 119.0%	+ 1.4%

- The coordinated approach improves economic efficiency, especially for storage resources.

Dispatch-Following Incentive

	Avg. Storage LOC payment	Avg. Total LOC payment
Myopic	$84,167	$97,368
2-period single-settlement	- 65%	- 67%
2- period coordinated	- 98%	- 90%

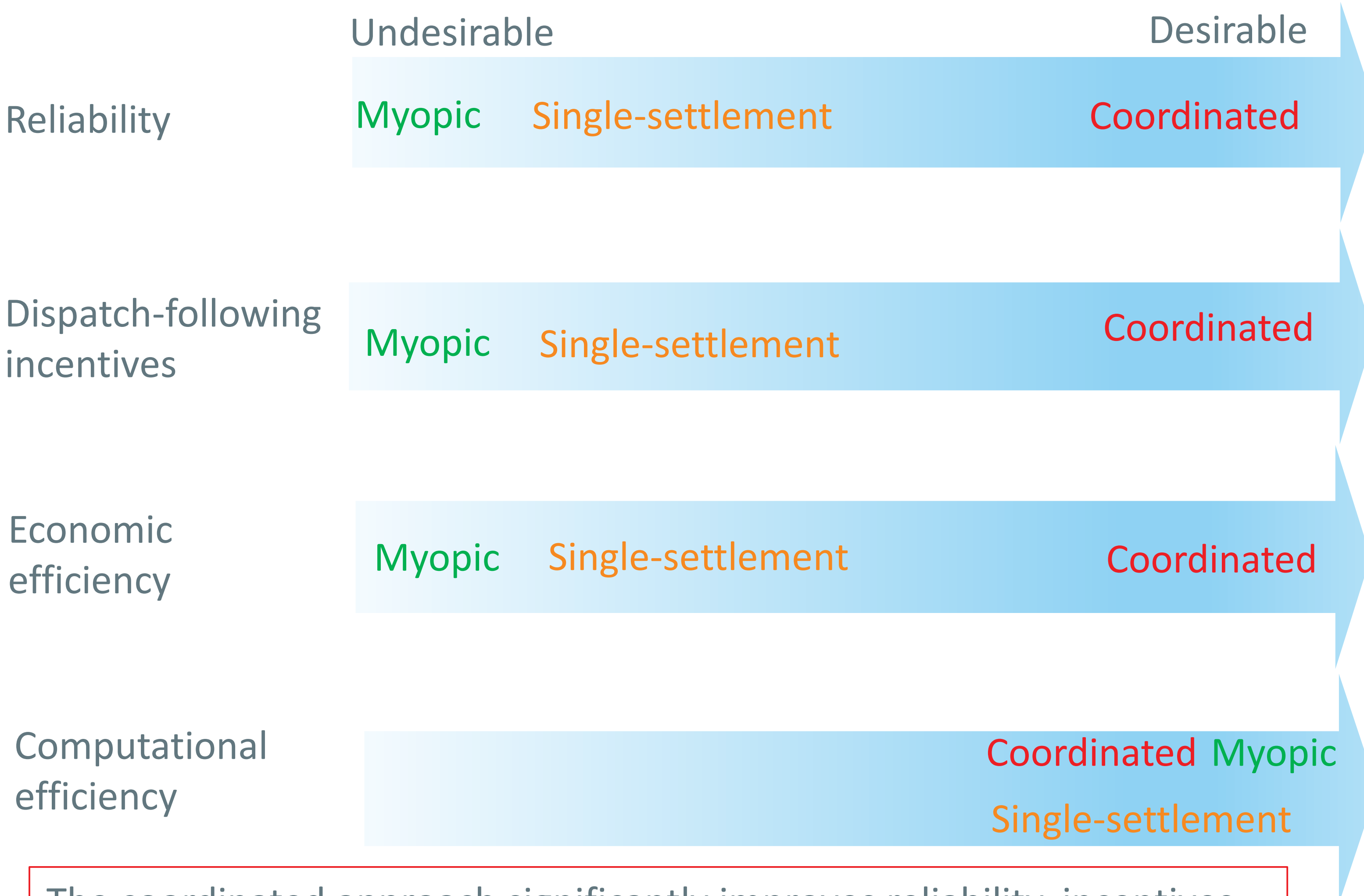
- The myopic approach provides poor dispatch-following incentives.
- The coordinated approach provides stronger dispatch-following incentives
  - Much less LOC payments.

Look-Ahead Horizon

	Social surplus	LOC payment	Reliability	Pricing CPU time (second)
Myopic	$2246 M	$97,368	25 violation instances	2.0
1-period coordinated	+1.3%	-88%	No violation	1.9
2-period coordinated	+1.4%	-90%	No violation	3.8
3-period coordinated	+1.4%	-93%	No violation	6.3
4-period coordinated	+1.4%	-93%	No violation	7.6

- A longer look-ahead horizon of the coordinated approach improves economic efficiency and dispatch following incentives.
- The coordinated approach with single look-head time period outperforms the myopic approach.

Summary of the Comparisons



The coordinated approach significantly improves reliability, incentives, and economic efficiency without sacrificing computational efficiency.

Conclusion

- A coordinated multi-period scheduling and pricing scheme is proposed
  - ❑ Address the challenges of scheduling and pricing of intertemporal constraints
  - ❑ Computationally efficient
- The coordinated scheme is a significant enhancement of the myopic approach as well as multi-period single-settlement approach
  - ❑ Improve economic efficiency and reliability, dispatch-following incentives

Questions