PRICING SCHEMES FOR TWO-STAGE MARKET CLEARING MODELS

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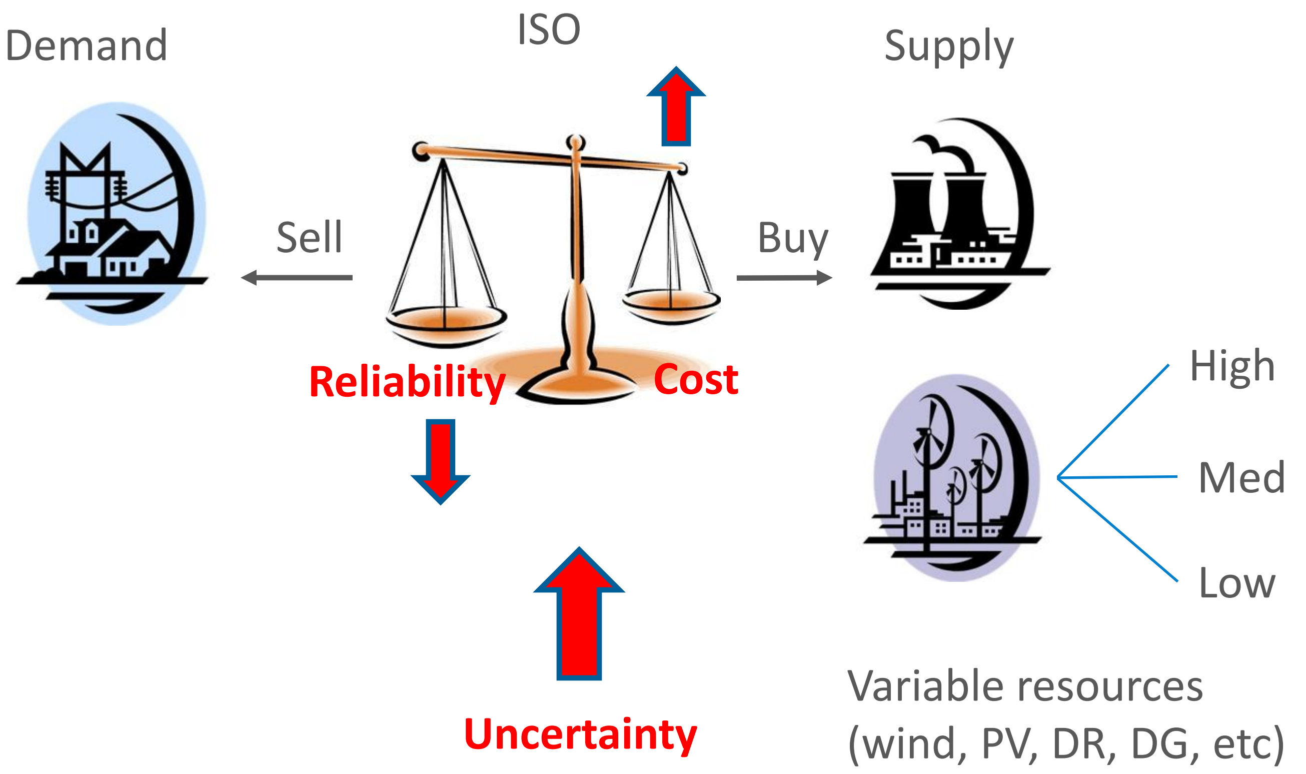
Motivation

- Pricing in two-stage market clearing models is a novel and challenging problem
- The goals of this talk
  - Advantages of two-stage market clearing models
  - Discussion of the pricing in two-stage market clearing models
  - Propose a framework

The Problem of One-Stage Market Clearing Models



Advantages of Two-Stage Market Clearing Models

- One-stage market clearing model is limited
  - Does not explicitly consider future system and resource conditions
  - May not lead to the most economic solution
  - May not result in a reliable system state
- Two-stage market clearing model has been drawing attention
  - Explicitly formulates future system and resource conditions
  - Leads to more economic solutions
  - Results in a reliable system state

Potential Applications

- Two-stage market clearing models can accommodate a variety of processes in electricity market operation.

The 1st Stage	The 2nd Stage
Day Ahead Market	Real Time Market
Slow-Moving Resource Commitment and Dispatch	Fast-Start Resource Commitment and Dispatch
Pre-Contingency Operation	Post-Contingency Operation
RT Look-Ahead Commitment and Dispatch	RT Dispatch

A General Two-Stage Market Clearing Model

$$\min_{P^{1st}, P^{2nd}} C^{1st}(P^{1st}) + C^{2nd}(P^{2nd}, P^{1st})$$

P^{1st} is the 1st stage decision

P^{2nd} is the 2nd stage decision

s.t. $(\lambda^{1st} \le 0)$: $S^{1st}(P^{1st}) \le 0$ ←The 1st stage system level constraints

$(\rho_i^{1st} \le 0)$: $R_i^{1st}(P_i^{1st}) \le 0 \quad \forall i$ ←The 1st stage resource level constraints

$(\lambda^{2nd} \le 0)$: $S^{2nd}(P^{2nd}, P^{1st}) \le 0$ ←The 2nd stage system level constraints

$(\rho_i^{2nd} \le 0)$: $R_i^{2nd}(P_i^{2nd}, P_i^{1st}) \le 0 \quad \forall i$ ←The 2nd stage resource level constraints

- A stochastic programming problem where c is the index for scenarios:

$$C^{2nd}(P^{2nd}, P^{1st}) = \sum_c \Pr_c \cdot \sum_i C_{i,c}^{2nd}(P_{i,c}^{2nd}, P_i^{1st})$$

- A multi-interval look-head problem where c is the index for time intervals:

$$C^{2nd}(P^{2nd}, P^{1st}) = \sum_c \sum_i C_{i,c}^{2nd}(P_{i,c}^{2nd}, P_i^{1st})$$

Pricing Challenges

- In one-stage model, clearing quantities and prices are only affected by the current (or expected) system condition.
- Pricing schemes for one-stage models NO LONGER work for two-stage models because of
  - Multi-stage structures
  - Multiple scenarios
- The prices may be affected by the future system condition through coupling constraints
- Framework for pricing in two-stage market clearing models is not fully constructed

Literature Review

- Two-stage stochastic models with energy and reserve
- [1] and [2] proposed an energy only pricing scheme
- [3] and [4] emphasized nodal energy and reserve prices
- [5] proposed multiple schemes
  - Real-time only, day-ahead only, and hybrid schemes
- Lack a systematic framework to determine which pricing schemes are better.

[1] G. Pritchard, G. Zakeri and A. Philpott, “A single-settlement, energy-only electric power market or unpredictable and intermittent participants”, Operations Research, vol. 58, no. 4, pp. 1210-1219, 2010.
[2] J. M. Morales, A. J. Conejo, K. Lui, J. Zhong , “Pricing Electricity in Pools with Wind Producers”, IEEE Transactions on Power Systems, Vol. 27, no. 3, pp. 1366-1376, 2012.
[3] J. M. Arroyo and F. D. Galiana, “Energy and reserve pricing in security and network-constrained electricity market”, IEEE Transactions on Power Systems, vol. 20, no. 2, pp. 634-643, 2005.
[4] F. Bouffard, F. D. Galiana, A. J. Conejo, “Market clearing with stochastic security-Part II: Case study”, IEEE Transactions on Power Systems, vol.20, pp. 1827-1835, 2005.
[5] S. Wong and J. D. Fuller, “Pricing Energy and Reserve using stochastic optimization in an alternative electricity market,” IEEE Transactions on Power System, vol. 20, no. 2, pp. 631-638, 2007.

Proposed Framework

- Explore the roles of dual variables to derive prices
- Desirable pricing properties
  - Efficiency
  - Incentive compatibility
  - Individual rationality
  - Revenue adequacy
  - Transparency (no price discrimination)
  - Low information requirement and cost
- Trade-off between these properties
- Assume truthful bidding
- Assume that the two-stage model is a convex problem.

Properties of the Existing Pricing Schemes

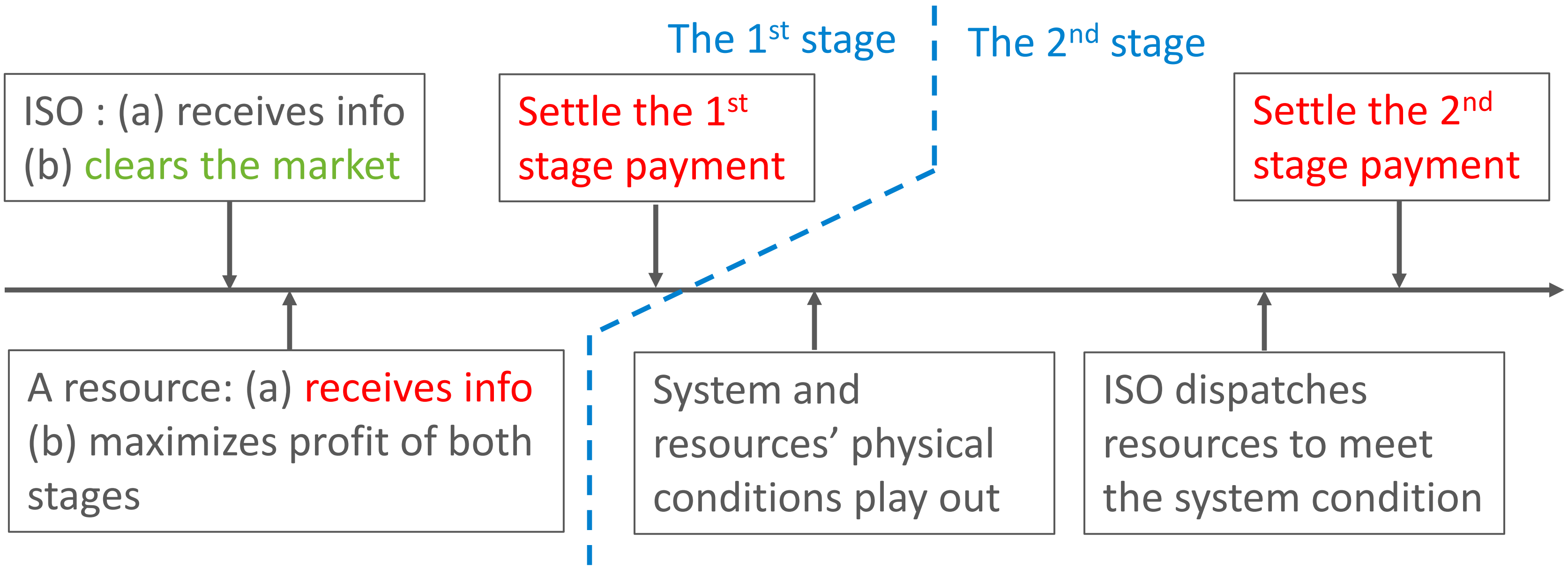
Reference	[1,2]	[3,4]	[5]
	Energy only price scheme	Nodal energy and reserve prices	Multiple pricing schemes
Efficiency	Yes	No	No
Individual rationality	Yes	Maybe	Some are yes
Revenue adequacy	Yes	Maybe	Maybe
Transparency	Nodal prices	Nodal prices	Nodal prices
Information requirement	High	Not discussed	Not discussed

Proposed Pricing Schemes

- Pricing Scheme A
  - The 1st stage payment: $P^{1st} \times CP_A^{1st}$
  - The 2nd stage pay as bid: $P^{2nd} \times \mathrm{bid}$
  - The clearing price CP_A^{1st} is a resource specific price
- Pricing Scheme B
  - The 1st stage payment: $P^{1st} \times CP_B^{1st}$
  - The 2nd stage payment: $P^{2nd} \times CP_B^{2nd}$
  - The clearing prices CP_B^{1st} and CP_B^{2nd} are nodal level prices

	Scheme A	Scheme B
Efficiency	Yes	Yes
Individual rationality	Yes	Yes
Revenue adequacy	Yes	Yes
Transparency	Individual price	Nodal price
Information requirement	Low	High

Market Clearing Sequence



- The quantities and prices of commodities to be traded in the 1st and 2nd stages are simultaneously determined in a single shot.
- What information is released to resources is an important issue.

Pricing Scheme A: Base Price + Swing Option Price

- The 1st stage clearing price

$$CP_A^{1st} = \text{a base price + a swing option price}$$

- The base price
  - Indicates the price of meeting the 1st stage system condition
  - Is a nodal level price
- The swing option price
  - Indicates the price of a resource’s variable volume within the two stage time frame
  - Is a resource dependent price
- Resources’ commodities are not perfect substitutes since resources’ characteristics are different.

Pricing Scheme A: Formulation

- CP_A^{1st} for the 1st stage clearing quantity P^{1st} is defined as

$$CP_A^{1st} = \underbrace{\boxed{\left(\frac{\partial S^{1st}}{\partial P^{1st}}\right)^T \lambda^{1st} + \left(\frac{\partial S^{2nd}}{\partial P^{1st}}\right)^T \lambda^{2nd}}}_{\text{base price}} + \underbrace{\boxed{\left(\frac{\partial R^{2nd}}{\partial P^{1st}}\right)^T \rho_i^c - \frac{\partial C^{2nd}}{\partial P^{1st}}}}_{\text{swing option price}}$$

- Pay as bid at the 2nd stage

An Illustrative Example: Current Practice

- The current practice clears the 1st and 2nd stage markets sequentially.

	EcoMax	Offer price	Ramping capability
G1	40 MW	\$5/MWh	20 MW
G2	100 MW	\$10/MWh	40 MW

	The 1st stage	The 2nd stage
Load	50 MW	100 MW

- System is not reliable at the 2nd stage!

		The 1st stage	The 2nd stage
Clearing quantities	G1	40 MW	40 MW
	G2	10 MW	50 MW
LMP		\$10/MWh	Penalty price

An Illustrative Example: Pricing Scheme A

The two-stage model clears the 1st and 2nd stage markets simultaneously.

$$\min_{p_1, p_2, \bar{p}_1, \bar{p}_2} \quad 5\times p_1 + 10\times p_2 + 5\times \bar{p}_1 + 10\times \bar{p}_2$$

$$\text{s.t.} \quad p_1 + p_2 = 50 \leftarrow (\lambda^{1st})$$ Balance constraint

$$\boxed{\begin{array}{l} 0 \le p_1 \le 40 \\ 0 \le p_2 \le 100 \end{array}}$$ EcoMin and EcoMax constraints

$$\bar{p}_1 + \bar{p}_2 = 100 \leftarrow (\lambda^{2nd})$$ Balance constraint

$$\boxed{\begin{array}{l} 0 \le \bar{p}_1 \le 40 \\ 0 \le \bar{p}_2 \le 100 \end{array}}$$ EcoMin and EcoMax constraints

$$\boxed{\begin{array}{l} \bar{p}_1 - p_1 \le 20 \leftarrow (\rho_1^{ramp} \ge 0) \\ \bar{p}_2 - p_2 \le 40 \leftarrow (\rho_2^{ramp} \ge 0) \end{array}}$$ Ramping constraints

- The 1st stage price for G1: $CP_{A,G1}^{1st} = \lambda^{1st} + \rho_1^{ramp}$
- The 1st stage price for G2: $CP_{A,G2}^{1st} = \lambda^{1st} + \rho_2^{ramp}$
- Pay as bid at the 2nd stage

Pricing Scheme A: Clearing Prices and Quantities

	EcoMax	Offer price	Ramping capability
G1	40 MW	$5/MWh	20 MW
G2	100 MW	$10/MWh	40 MW

	The 1st stage	The 2nd stage
Load	50 MW	100 MW

		The 1st stage	The 2nd stage
Clearing quantities	G1	30 MW	40 MW
	G2	20 MW	60 MW

Clearing prices	Base price λ^{1st}	Swing option price ρ^{ramp}	The 1st stage price	The 2nd stage price
G1	$5/MW	0	$5/MWh	$5/MWh
G2	$5/MW	$5/MW	$10/MWh	$10/MWh

G1 and G2 are NOT perfect substitutes since their physical limits are different .

Pricing Scheme B: Base Contract + Balancing Contract

- The 1st stage payment is a base contract, and the 2nd stage payment is a balancing contract

$$P^{1st} \times CP_B^{1st} = \underbrace{\boxed{P^{1st} \times \text{base price}}}_{\text{base contract}}$$

$$P^{2nd} \times CP_B^{2nd} = \underbrace{\boxed{P^{2nd} \times \text{balancing price}}}_{\text{balancing contract}}$$

- The base and balancing contracts specify
  - The amount of commodity needed to meet the 1st and the 2nd stage system conditions, respectively
  - The associated prices: base price and balancing price
- Although there is no swing option, each resource needs to have enough variable volume to ensure the delivery of commodities at both stages.

Pricing Scheme B: Formulation

- CP_B^{1st} for the 1st stage clearing quantity P^{1st} is defined as

$$CP_B^{1st} = \boxed{\left(\frac{\partial S^{1st}}{\partial P^{1st}}\right)^T \lambda^{1st} + \left(\frac{\partial S^{2nd}}{\partial P^{1st}}\right)^T \lambda^{2nd}} \longleftarrow \text{base price}$$

- CP_B^{2nd} for the 2nd stage clearing quantity P^{2nd} is equal to

$$CP_B^{2nd} = \boxed{\left(\frac{\partial S^{2nd}}{\partial P^{2nd}}\right)^T \lambda^{2nd}} \longleftarrow \text{balancing price}$$

An Illustrative Example: Pricing Scheme B

$$\min_{p_1, p_2, \overline{p}_1, \overline{p}_2} \ 5\times p_1 + 10\times p_2 + 5\times \overline{p}_1 + 10\times \overline{p}_2$$

s.t. $p_1 + p_2 = 50 \leftarrow (\lambda^{1st})$ Balance constraint

$\boxed{\begin{array}{l} 0 \le p_1 \le 40 \\ 0 \le p_2 \le 100 \end{array}}$ EcoMin and EcoMax constraints

$\overline{p}_1 + \overline{p}_2 = 100 \leftarrow (\lambda^{2nd})$ Balance constraint

$\boxed{\begin{array}{l} 0 \le \overline{p}_1 \le 40 \\ 0 \le \overline{p}_2 \le 100 \end{array}}$ EcoMin and EcoMax constraints

$\boxed{\begin{array}{l} \overline{p}_1 - p_1 \le 20 \leftarrow (\rho_1^{ramp} \ge 0) \\ \overline{p}_2 - p_2 \le 40 \leftarrow (\rho_2^{ramp} \ge 0) \end{array}}$ Ramping constraints

- The 1st stage price: $CP_B^{1st} = \lambda^{1st}$
- The 2nd stage price: $CP_B^{2nd} = \lambda^{2nd}$

Pricing Scheme B: Clearing Prices and Quantities

	EcoMax	Offer price	Ramping capability
G1	40 MW	\$5/MWh	20 MW
G2	100 MW	\$10/MWh	40 MW

	The 1st stage	The 2nd stage
Load	50 MW	100 MW

		The 1st stage	The 2nd stage
Clearing quantities	G1	30 MW	40 MW
	G2	20 MW	60 MW
Clearing prices	G1	\$5/MWh	\$15/MWh
	G2	\$5/MWh	\$15/MWh

An Illustrative Example with Load Uncertainty

	EcoMax	Offer price	Ramping capability
G1	40 MW	\$5/MWh	20 MW
G2	100 MW	\$10/MWh	40 MW

The 1st stage

The 2nd stage

Load =50 MW

100 MW, prob = 0.3

50 MW, prob = 0.5

30 MW, prob = 0.2

A two-stage stochastic model

$$\min_{p_1, p_2, \bar{p}_1^i, \bar{p}_2^i} 5p_1 + 10p_2 + \sum_{i=1}^{3} prob_i \times (5\bar{p}_1^i + 10\bar{p}_2^i)$$

$$\text{s.t.} \quad p_1 + p_2 = 50 \leftarrow (\lambda^{1st})$$

$$0 \le p_1 \le 40$$

$$0 \le p_2 \le 100$$

$$\bar{p}_1^i + \bar{p}_2^i = d_i \leftarrow (\lambda_i^{2nd}), i = 1, 2, 3$$

$$0 \le \bar{p}_1^i \le 40, i = 1, 2, 3$$

$$0 \le \bar{p}_2^i \le 100, i = 1, 2, 3$$

$$\bar{p}_1^i - p_1 \le 20 \leftarrow (\rho_{1,i}^{ramp} \ge 0), i = 1, 2, 3$$

$$\bar{p}_2^i - p_2 \le 40 \leftarrow (\rho_{2,i}^{ramp} \ge 0), i = 1, 2, 3$$

Clearing Prices and Quantities of the Stochastic Model

- Pricing Scheme A

$$CPA_1^{1st} = \lambda^{1st} + \sum_{i=1}^{3} \rho_{1,i}^{ramp}$$

$$CPA_2^{1st} = \lambda^{1st} + \sum_{i=1}^{3} \rho_{2,i}^{ramp}$$

- Pricing Scheme B

$$CPB^{1st} = \lambda^{1st}$$

$$CPB_i^{2nd} = \lambda_i^{2nd} / \mathrm{Prob}_i, i = 1, 2, 3$$

  - Pritchard, et al(2010)

	The 1st stage price	The 2nd stage price
G1	\$5/MWh	\$5/MWh
G2	\$10/MWh	\$10/MWh

The 1st stage price	Load scenarios	The 2nd stage price
\$5/MW	High	\$26.67/MWh
	Med	\$10/MWh
	Low	\$5/MWh

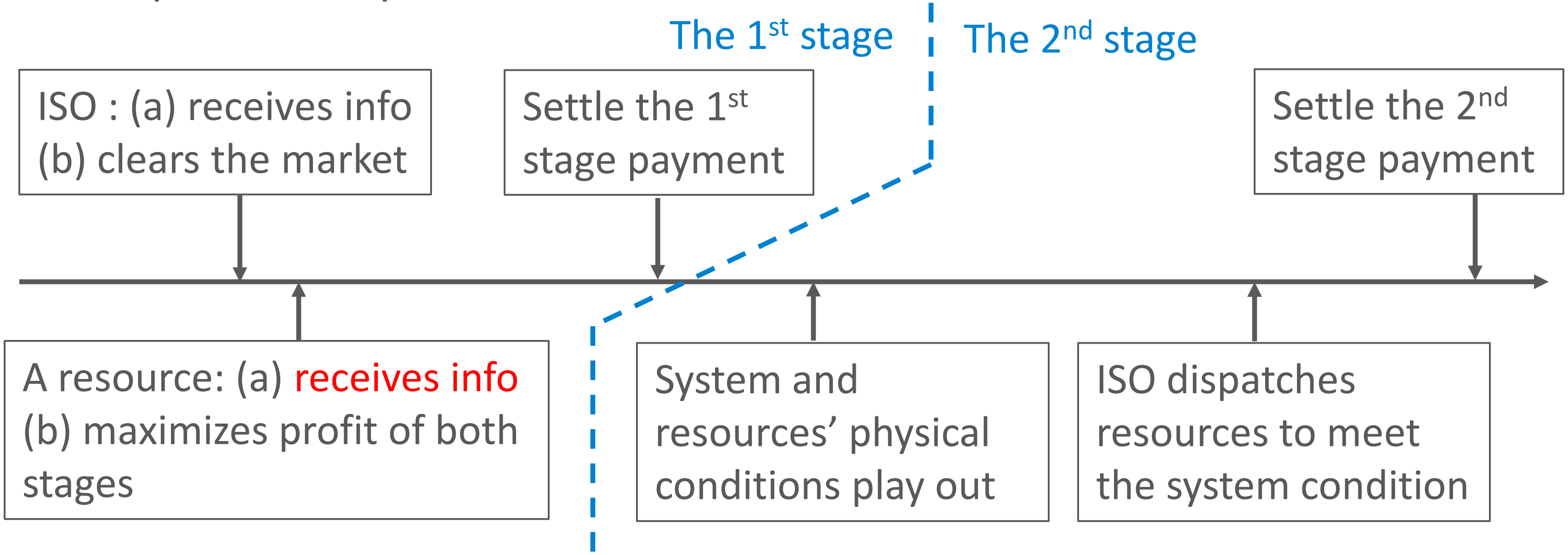
		The 1st stage
Clearing quantities	G1	30 MW
	G2	20 MW

Comparison of Pricing Schemes A and B

	Scheme A	Scheme B
Efficiency	Yes	Yes
Individual rationality	Yes	Yes
Revenue adequacy	Yes	Yes
Transparency	Individual price	Nodal price
Information requirement	Low	High

Information Requirement

- Scheme A: low information requirement
  - A resource needs to know its current resource limit and price
- Scheme B: high information requirement
  - A resource needs to know its current and future resource limits, prices, and probabilities



Summary

- A framework is proposed for two-stage market clearing models.
- Pricing schemes A and B meet efficiency, individual rationality, and revenue adequacy properties.
- Pricing scheme A results in individual prices while pricing scheme B leads to nodal prices.
- Pricing scheme A is still deemed to be an attractive scheme because of low information requirement.

Questions

Lagrangian Function of the Two-Stage Model

$$\min_{P^{1st},P^{2nd}} C^{1st}(P^{1st})+C^{2nd}(P^{2nd},P^{1st})$$

$$\text{s.t.}\quad (\lambda^{1st}\le 0):\ S^{1st}(P^{1st})\le 0$$

$$(\lambda^{2nd}\le 0): S^{2nd}(P^{2nd},P^{1st})\le 0$$

$$(\rho_i^{1st}\le 0):\ R_i^{1st}(P_i^{1st})\le 0 \quad \forall i$$

$$(\rho_i^{2nd}\le 0):\ R_i^{2nd}(P_i^{2nd},P_i^{1st})\le 0 \quad \forall i$$

$$L=C^{1st}(P^{1st})+C^{2nd}(P^{2nd},P^{1st})-\left(\lambda^{1st}\right)^T S^{1st}(P^{1st})-\left(\lambda^{2nd}\right)^T S^{2nd}(P^{2nd},P^{1st})$$

$$-\left(\rho_i^{1st}\right)^T R_i^{1st}(P_i^{1st})-\left(\rho_i^{2nd}\right)^T R_i^{2nd}(P_i^{2nd},P_i^{1st})$$

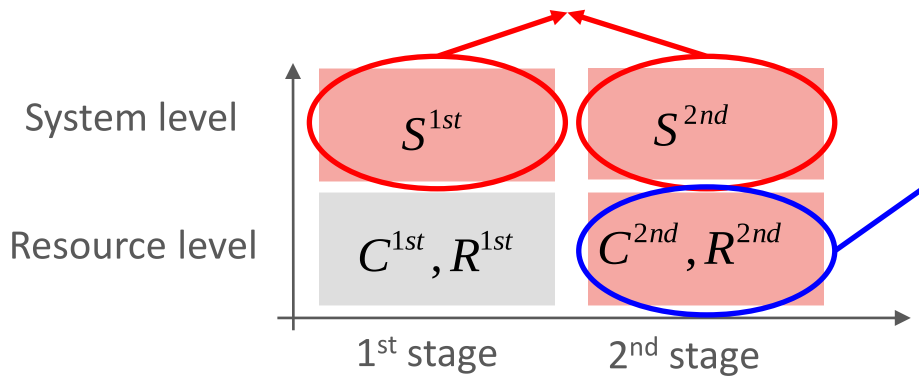
$$\frac{\partial L}{\partial P_i^{1st}}=\frac{\partial C^{1st}}{\partial P_i^{1st}}+\frac{\partial C^{2nd}}{\partial P_i^{1st}}-\left(\frac{\partial S^{1st}}{\partial P_i^{1st}}\right)^T\lambda^{1st}-\left(\frac{\partial S^{2nd}}{\partial P_i^{1st}}\right)^T\lambda^{2nd}-\left(\frac{\partial R_i^{1st}}{\partial P_i^{1st}}\right)^T\rho_i^{1st}-\left(\frac{\partial R_i^{2nd}}{\partial P_i^{1st}}\right)^T\rho_i^{2nd}$$

$$\frac{\partial L}{\partial P_i^{2nd}}=\frac{\partial C^{2nd}}{\partial P_i^{2nd}}-\left(\frac{\partial S^{2nd}}{\partial P_i^{2nd}}\right)^T\lambda^{2nd}-\left(\frac{\partial R_i^{2nd}}{\partial P_i^{2nd}}\right)^T\rho_i^{2nd}$$

Pricing Scheme A

- CP_A^{1st} for the 1st stage clearing quantity P^{1st} is defined as

$$CP_A^{1st} = \underbrace{\boxed{\left(\frac{\partial S^{1st}}{\partial P^{1st}}\right)^T \lambda^{1st} + \left(\frac{\partial S^{2nd}}{\partial P^{1st}}\right)^T \lambda^{2nd}}}_{\text{base price}} + \underbrace{\boxed{\left(\frac{\partial R^{2nd}}{\partial P^{1st}}\right)^T \rho_i^c - \frac{\partial C^{2nd}}{\partial P^{1st}}}}_{\text{swing option price}}$$



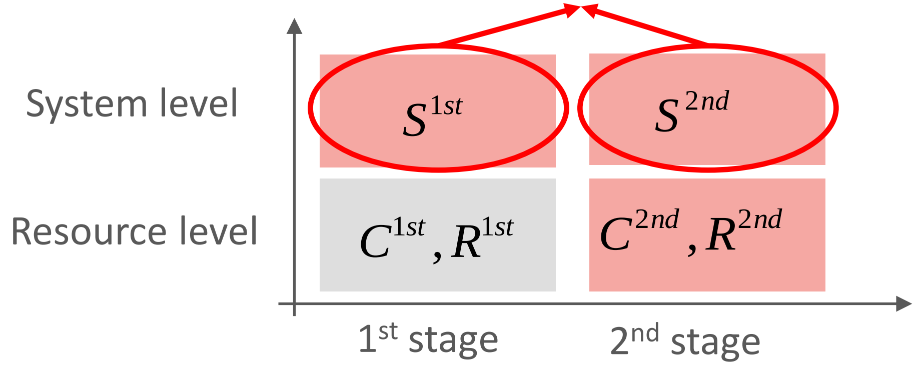
- Pay as bid at the 2nd stage

Pricing Scheme B

- CP_B^{1st} for the 1st stage clearing quantity P^{1st} is defined as

$$CP_B^{1st} = \boxed{\left(\frac{\partial S^{1st}}{\partial P^{1st}}\right)^T \lambda^{1st} + \left(\frac{\partial S^{2nd}}{\partial P^{1st}}\right)^T \lambda^{2nd}}$$

base price

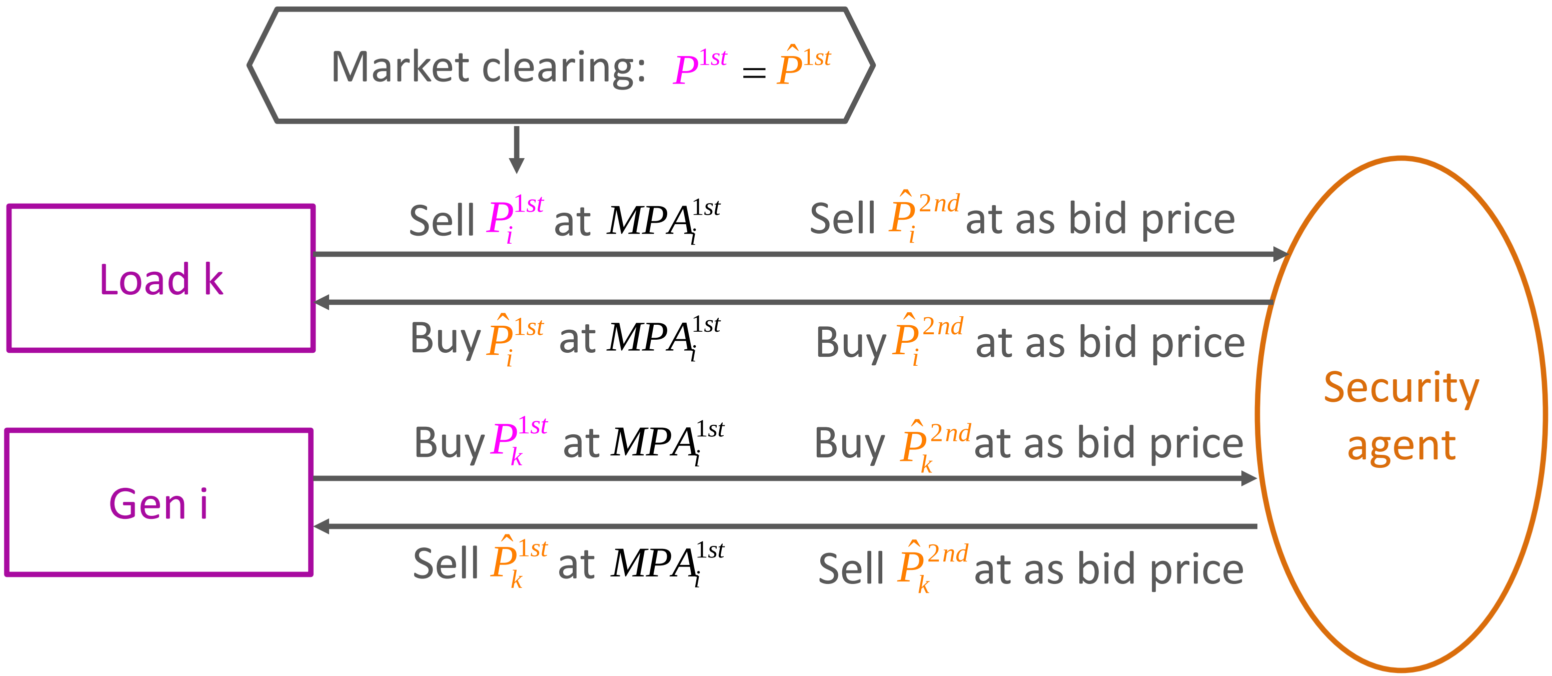


- CP_B^{2nd} for the 2nd stage clearing quantity P^{2nd} is equal to

$$CP_B^{2nd} = \boxed{\left(\frac{\partial S^{2nd}}{\partial P^{2nd}}\right)^T \lambda^{2nd}}$$

balancing price

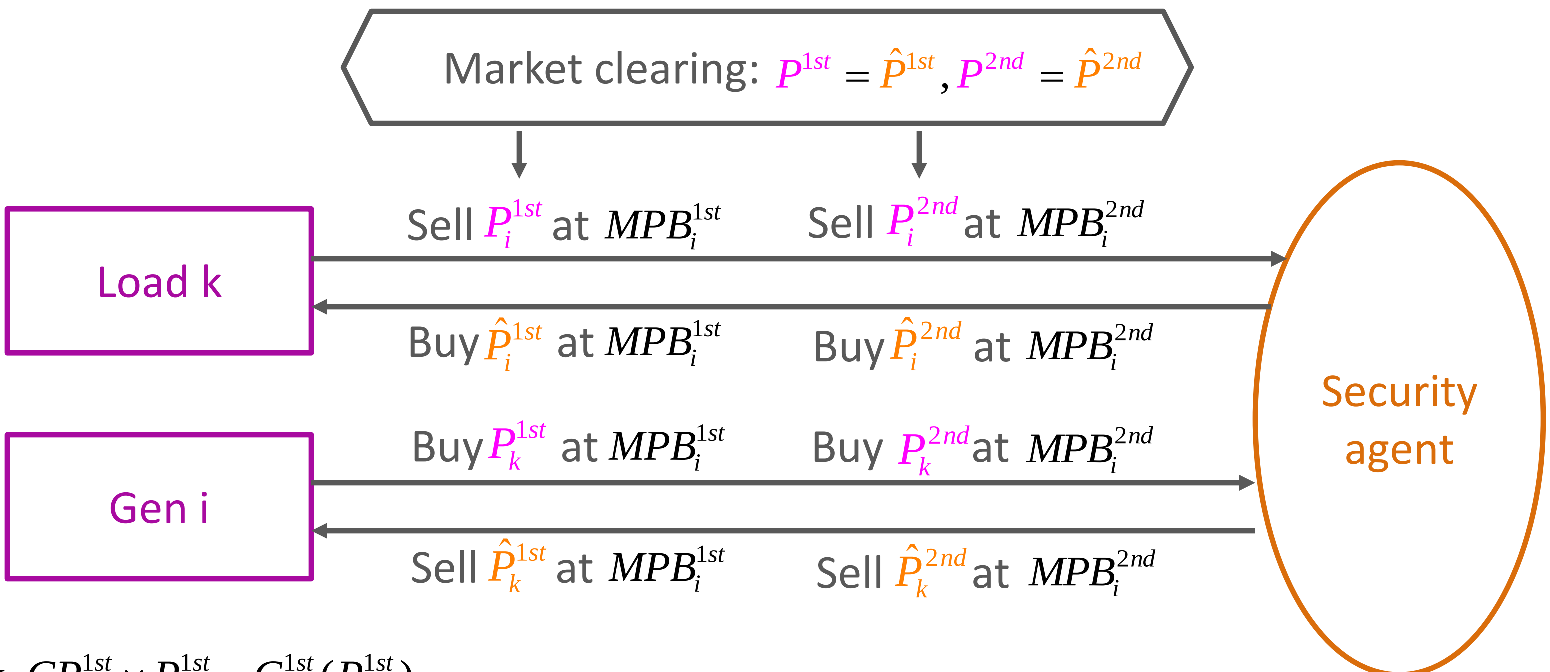
Pricing Scheme A: Efficiency



$$\begin{aligned} \max_{P_i^{1st}} \; & CP_{A,i}^{1st} \times P_i^{1st} - C_i^{1st}(P_i^{1st}) \\ & + C_i^{2nd}(\hat{P}_i^{2nd}, P_i^{1st}) - C_i^{2nd}(\hat{P}_i^{2nd}, P_i^{1st}) \\ \text{s.t.} \;\; & R_i^{1st}(P_i^{1st}) \le 0 \end{aligned}$$

$$\begin{aligned} \max_{\hat{P}^{1st}, \hat{P}^{2nd}} \; & -CP_A^{1st} \times \hat{P}^{1st} - C^{2nd}(\hat{P}^{2nd}, \hat{P}^{1st}) \\ \text{s.t.} \;\; & S^{1st}(\hat{P}^{1st}) \le 0 \\ & S^{2nd}(\hat{P}^{2nd}, \hat{P}^{1st}) \le 0 \\ & R_i^{2nd}(\hat{P}_i^{2nd}, \hat{P}_i^{1st}) \le 0 \quad \forall i \end{aligned}$$

Pricing Scheme B: Efficiency



$$\max_{P_i^{1st}, P_i^{2nd}} CP_B^{1st} \times P_i^{1st} - C_i^{1st}(P_i^{1st})$$

$$+ \sum_{\omega \in \Omega} \text{Prob}_\omega \times \left(CP_{B,\omega}^{2nd} \times P_{i,\omega}^{2nd} - C_i^{2nd}(P_{i,\omega}^{2nd}, P_i^{1st}) \right)$$

$$\text{s.t.} \quad R_i^{1st}(P_i^{1st}) \le 0$$

$$R_i^{2nd}(P_i^{2nd}, P_i^{1st}) \le 0$$

$$\max_{\hat{P}^{1st}, \hat{P}^{2nd}} -CP_B^{1st} \times \hat{P}^{1st} - \sum_{\omega \in \Omega} \text{Prob}_\omega \times CP_B^{2nd} \times \hat{P}^{2nd}$$

$$\text{s.t.} \quad S^{1st}(\hat{P}^{1st}) \le 0$$

$$S^{2nd}(\hat{P}^{2nd}, \hat{P}^{1st}) \le 0$$