



Optimal Generation Scheduling in a Carbon Dioxide Allowance Market Environment

Project M21 Part III

Wei Sun

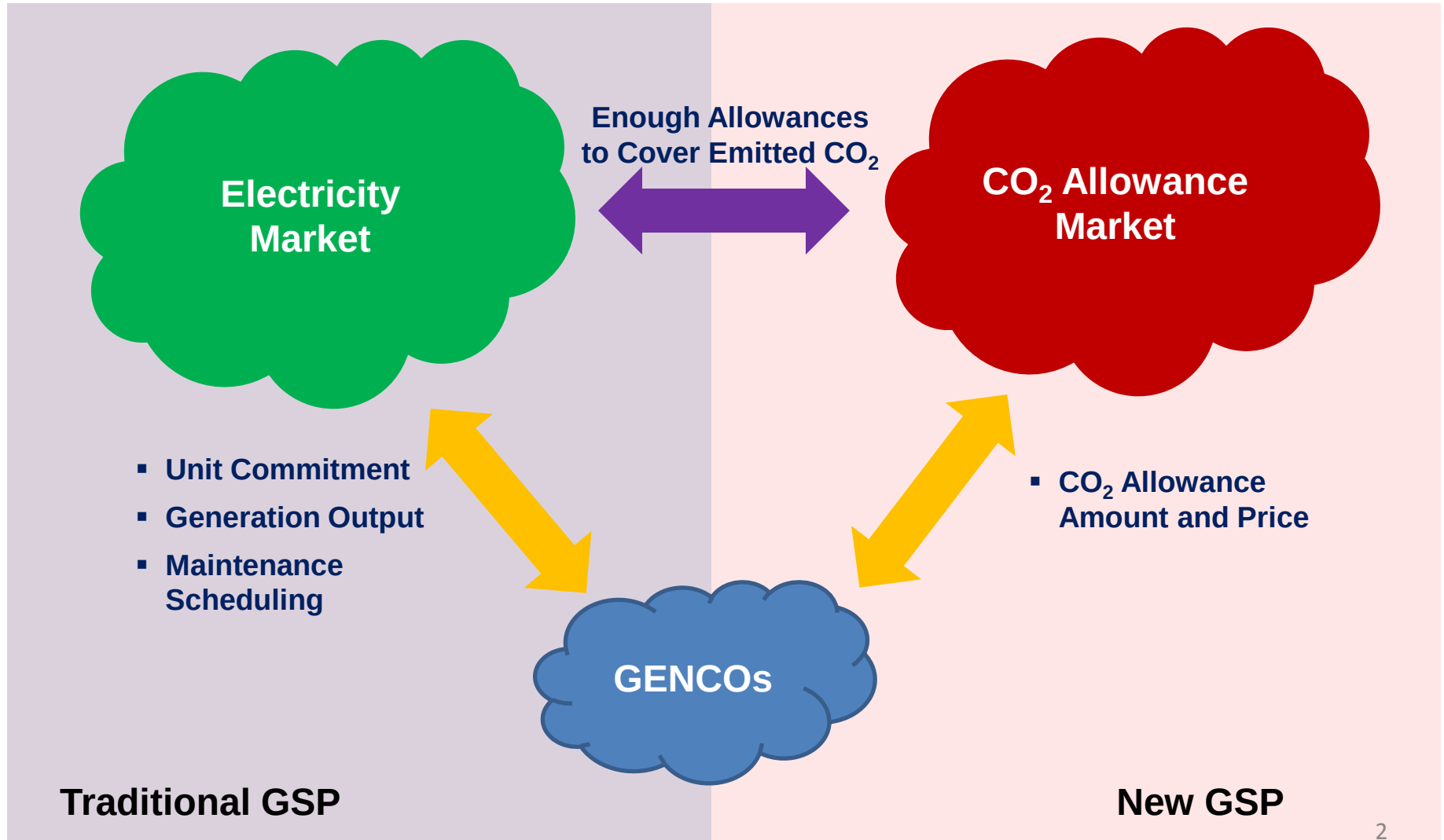
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PSERC Webinar, April 5, 2011

New Generation Scheduling Problem (GSP)

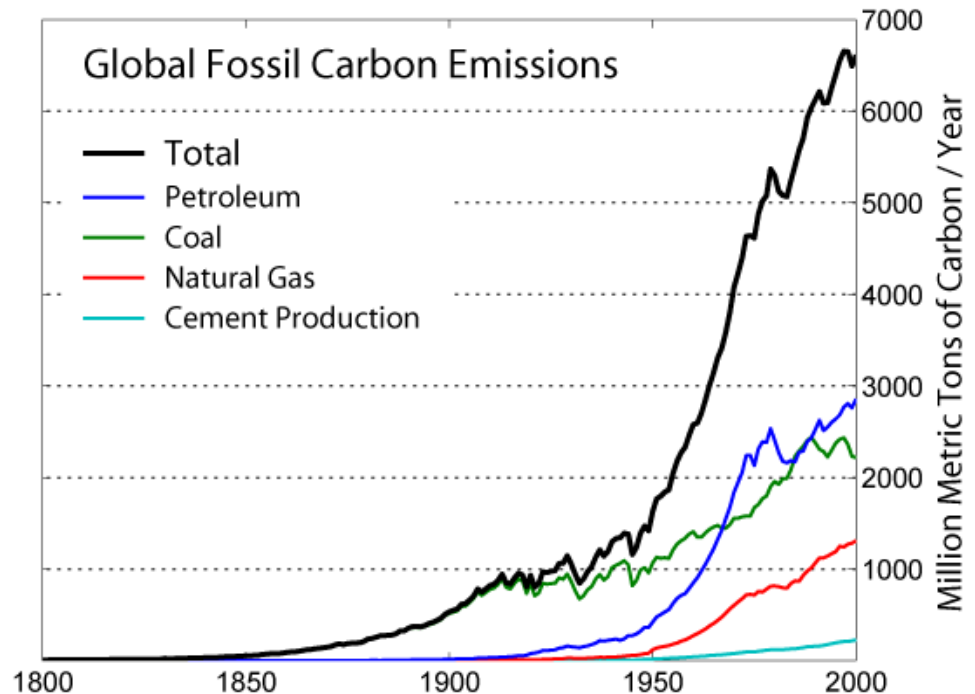
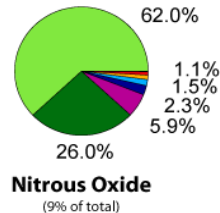
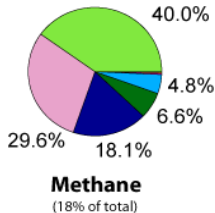
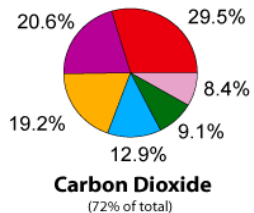
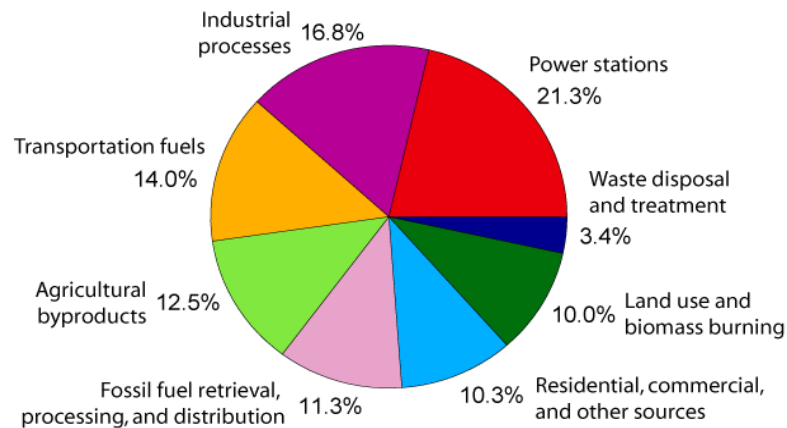


Outline

- Motivation
- Carbon Dioxide (CO₂) Allowance Market
- New ***Generation Scheduling Problem*** considering CO₂ Cap-And-Trade
- Conclusions

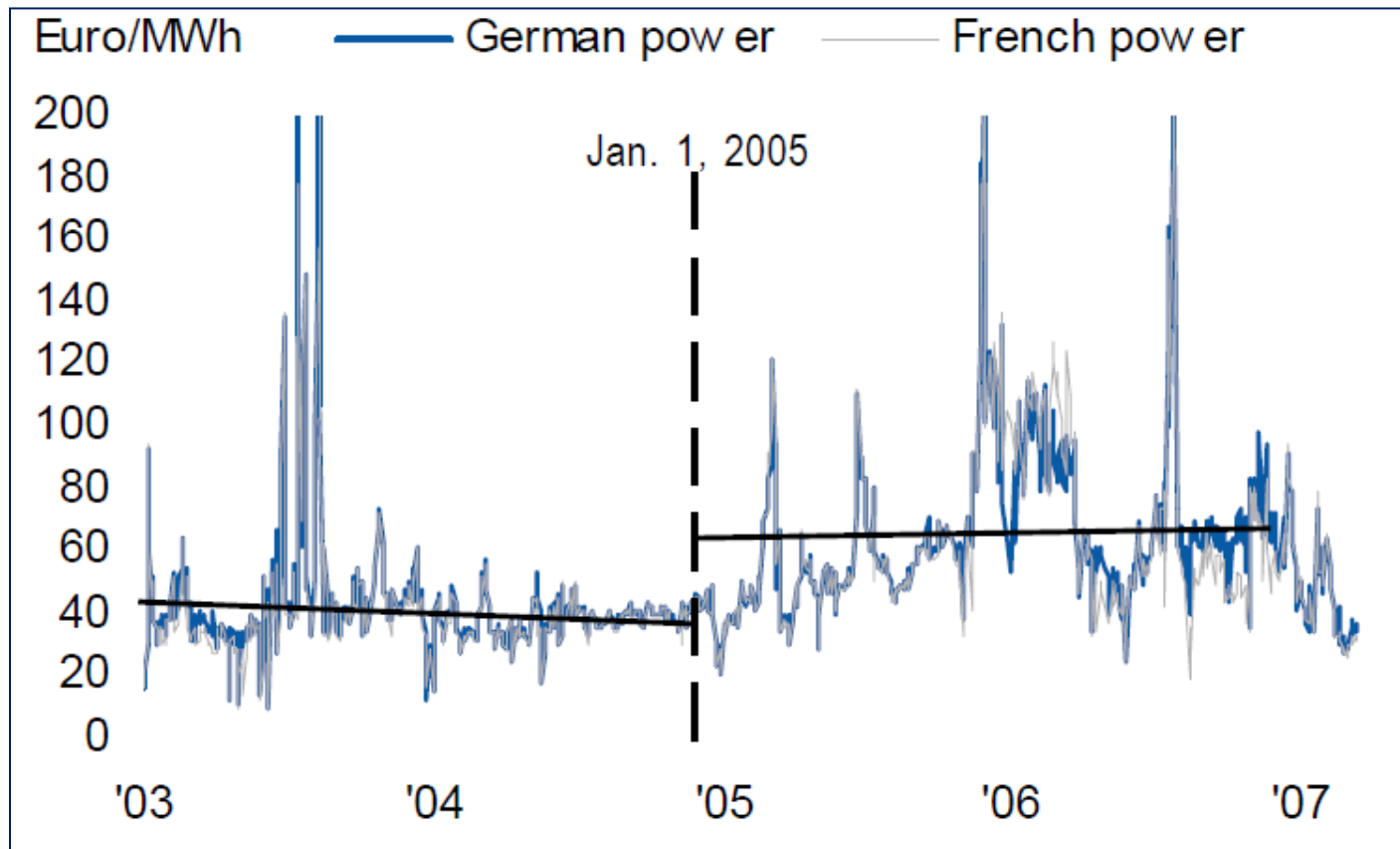
Greenhouse Gas (GHG)

Annual Greenhouse Gas Emissions by Sector



Motivation

European Power Prices Pre- and Post-CO₂ Regulation



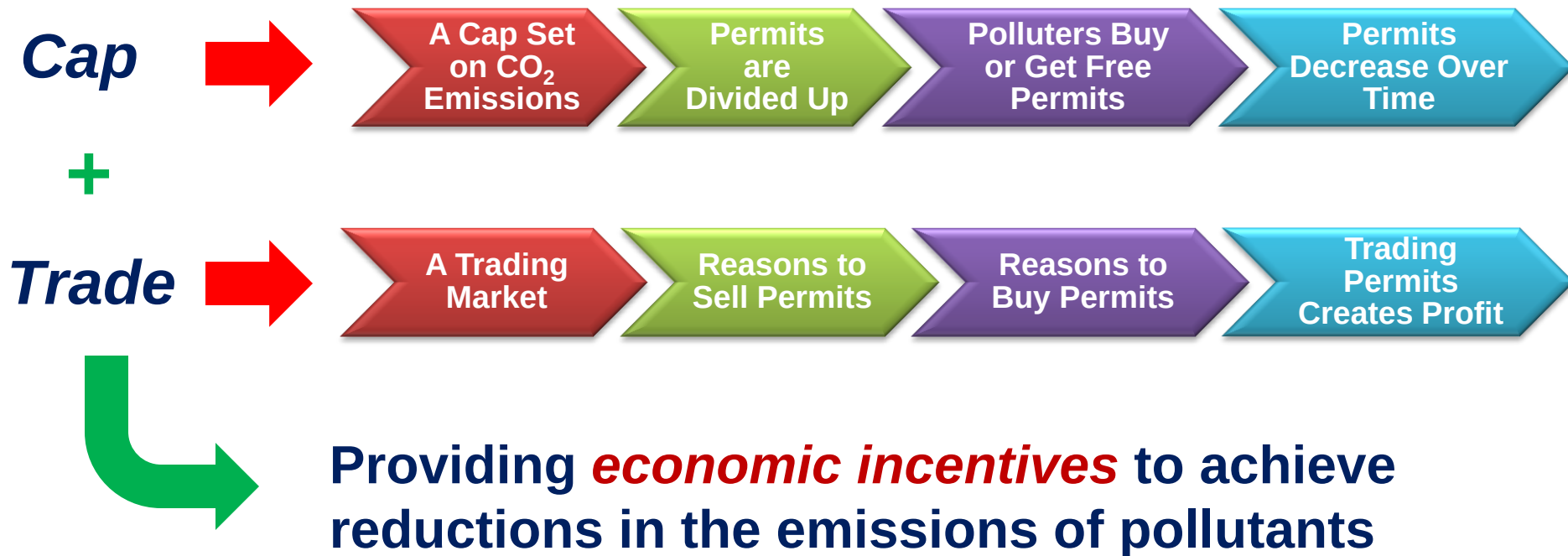
CO₂ Emission Regulation

- Carbon Capture and Storage /Sequestration (CCS)
- Non-CO₂ or Low-CO₂ Emission Power Sources (hydroelectric, nuclear, renewable energy resources)
- **Market-based and least-cost Mechanisms: Emission Trading**



CO₂ Emission Cap-and-Trade

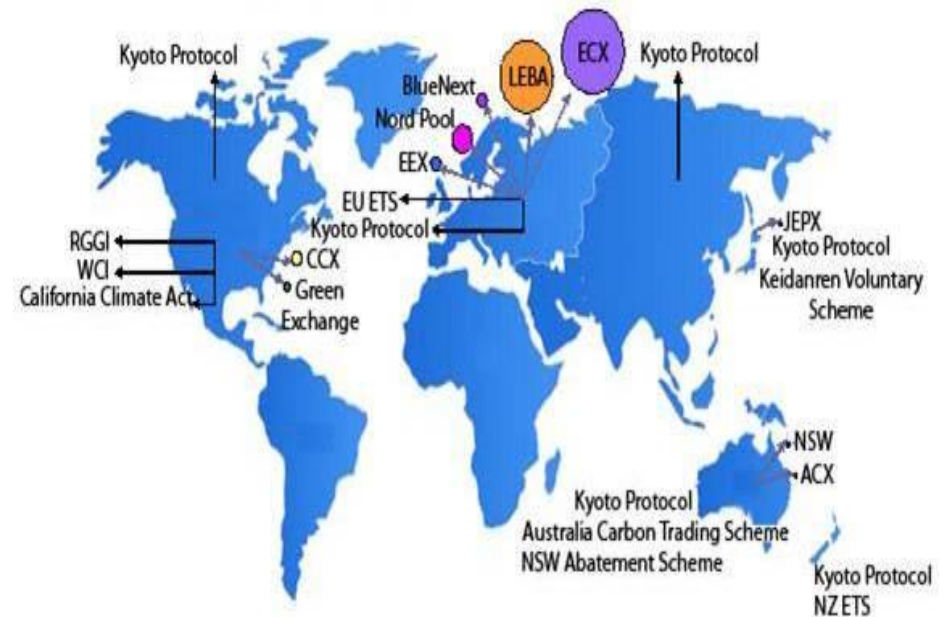
CO₂ Emission Cap-And-Trade



- The **buyer** is paying a charge for polluting, while the **seller** is being rewarded for having reduced emissions
- To encourage polluters to shift away from CO₂-emitting **fossil fuels** and toward **clean, renewable energy** sources

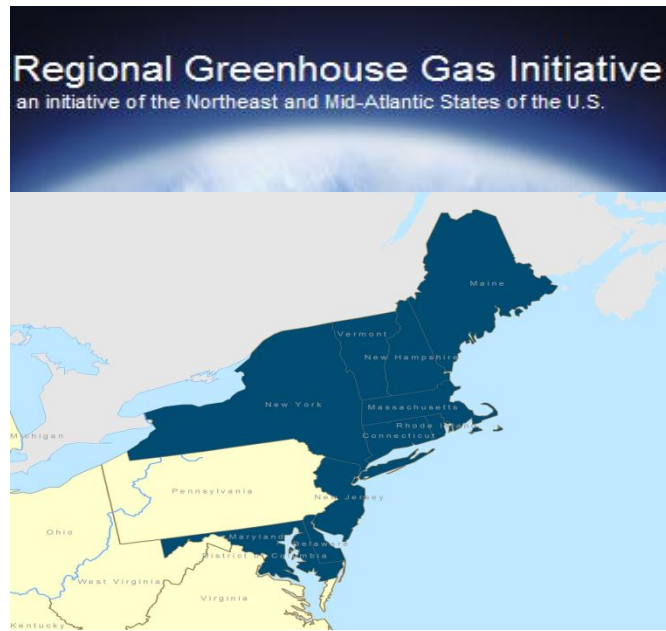
Carbon Trading Markets

1. Kyoto Protocol
2. New Zealand Emissions Trading Scheme (NZ ETS)
3. European Union Emission Trading Scheme (EU ETS)
4. United States

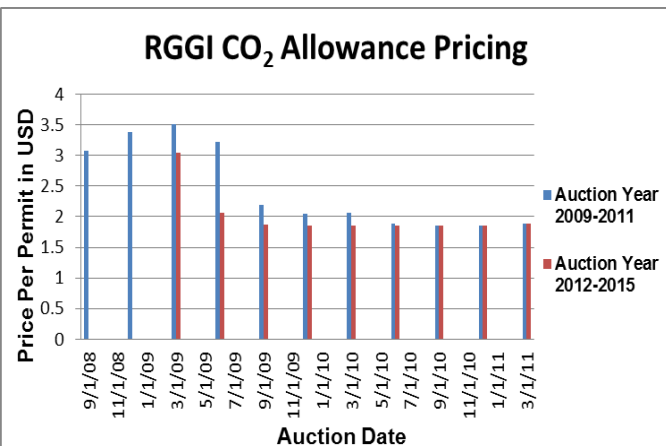


- **Chicago Climate Exchange (CCX)** starting from 2003;
- **Western Climate Initiative (WCI)** starting from 2007;
- **Regional Greenhouse Gas Initiative (RGGI)** starting from 2009.

RGGI CO₂ Allowance Market



- Ten Northeastern and Mid-Atlantic states, starting from Jan. 1, 2009
- Reduce 10% of CO₂ emissions by 2018
- Primary and secondary market
- **Quarterly auction** in the format of single-round, uniform-price, sealed-bid
- **Three-year** compliance period
- Reserved price
- Using offsets
- Cost-effective emission reductions

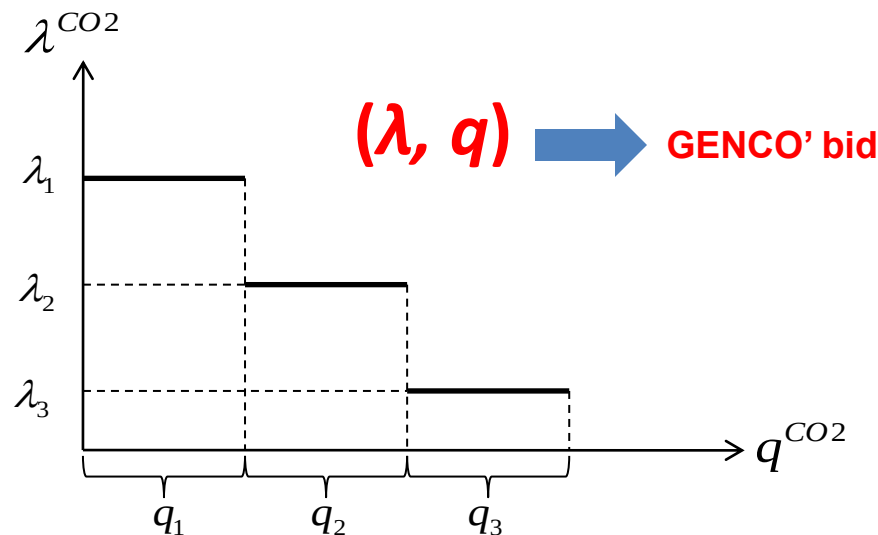


Market Equilibrium Model

- To investigate the ability of generation companies (GENCOs) to manipulate prices (*market power*)
- Derived a nonlinear complementarity problem (NCP) formulation based on the equivalence between the *KKT conditions* and *strong stationarity*
- Transformed to a nonlinear programming problem (NLP) and solve it by AMPL/MINOS commercial solver

GENCO Bidding Model

$$\begin{aligned}
 & \max_{P_i, q_i, OS_i, \lambda^{CO2*}, A_i} && \lambda^e \cdot P_i - \left(a_i \cdot P_i + b_i \cdot P_i^2 \right) - \lambda^{CO2*} \cdot A_i - h_i \cdot OS_i \\
 & s.t. && 0 \leq k_i \cdot P_i \leq A_i + OS_i \\
 & && OS_i \leq 0.033 \cdot A_i \\
 & && 0 \leq P_i \leq P_i^{\max}
 \end{aligned}$$

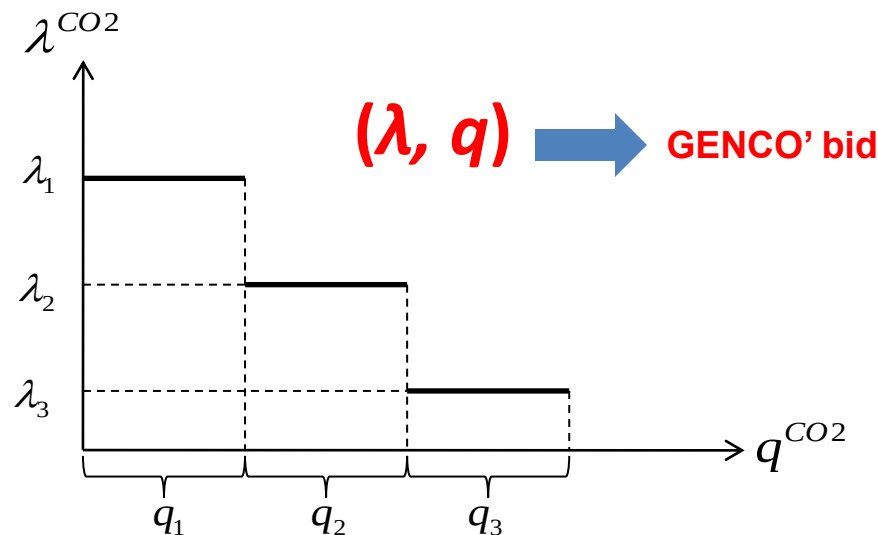


GENCO Bidding Model

$$\begin{aligned}
 & \max_{P_i, q_i, OS_i, \lambda^{CO2*}, A_i} \\
 & \text{s.t.} \quad \lambda^e \cdot P_i - \left(a_i \cdot P_i + b_i \cdot P_i^2 \right) - \lambda^{CO2*} \cdot A_i - h_i \cdot OS_i
 \end{aligned}$$

Revenue from electricity market Generation cost Emission allowance cost Offset cost

$$\begin{aligned}
 & 0 \leq k_i \cdot P_i \leq A_i + OS_i \quad \rightarrow \text{Emission regulation constraints} \\
 & OS_i \leq 0.033 \cdot A_i \quad \rightarrow \text{Offset usage constraints} \\
 & 0 \leq P_i \leq P_i^{\max} \quad \rightarrow \text{Generation capacity constraints}
 \end{aligned}$$



Market Clearing Model

$$\max_{A_j} \sum_{j=1}^n \lambda_j \cdot A_j$$

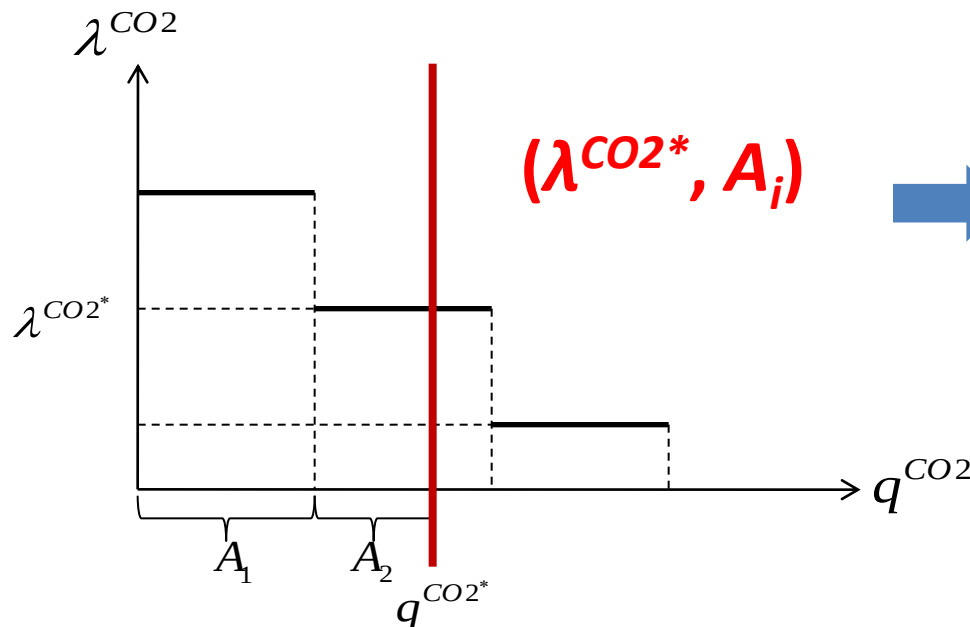
$$s.t. \quad \sum_{j=1}^n A_j = CAP^{CO_2}$$

RGGI's rule $\leftarrow A_j \leq 0.25 \cdot CAP^{CO_2}$

$$0 \leq A_j \leq q_j$$

$$\sum_{j=1}^n A_j - CAP^{CO_2} = 0$$

$$\left. \begin{array}{ll} 0 \leq A_j & \perp \quad -\lambda_j + \lambda^{CO_2*} + w_j^1 - w_j^2 \geq 0 \\ 0 \leq w_j^1 & \perp \quad q_j - A_j \geq 0 \\ 0 \leq w_j^2 & \perp \quad A_j \geq 0 \\ 0 \leq w_j^3 & \perp \quad 0.25 \cdot CAP^{CO_2} - A_j \geq 0 \end{array} \right\} j = 1, \dots, n$$



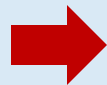
**Allowance price and
cleared demand**

CO₂ Allowance Market Model

$$\begin{aligned}
 & \max_{P_i, q_i, OS_i, \lambda^{CO_2^*}, A_i, w_i^1, w_i^2, w_i^3} \quad \lambda^e \cdot P_i - (a_i \cdot P_i + b_i \cdot P_i^2) - \lambda^{CO_2^*} \cdot A_i - h_i \cdot OS_i \\
 & \text{s.t.} \quad 0 \leq k_i \cdot P_i \leq A_i + OS_i \\
 & \quad OS_i \leq 0.033 \cdot A_i \\
 & \quad 0 \leq P_i \leq P_i^{\max} \\
 & \quad \sum_{j=1}^n A_j - CAP^{CO_2} = 0
 \end{aligned}$$

$$\left. \begin{aligned}
 0 \leq A_j & \quad \perp \quad -\lambda_j + \lambda^{CO_2^*} + w_j^1 - w_j^2 \geq 0 \\
 0 \leq w_j^1 & \quad \perp \quad q_j - A_j \geq 0 \\
 0 \leq w_j^2 & \quad \perp \quad A_j \geq 0 \\
 0 \leq w_j^3 & \quad \perp \quad 0.25 \cdot CAP^{CO_2} - A_j \geq 0
 \end{aligned} \right\} j = 1, \dots, n$$

GENCO' bid
(λ, q)



**Allowance price &
cleared demand**
($\lambda^{CO_2^*}, A_j$)

Mathematical
Programs
with
Equilibrium
Constraints
(**MPEC**)



Equilibrium
Problems
with
Equilibrium
Constraints
(**EPEC**)

EPEC Formulation

$$\max_{P_i, q_i, OS_i, \lambda^{CO2*}, A_i, w_i^1, w_i^2, w_i^3}$$

s.t.

$$\lambda^e \cdot P_i - (a_i \cdot P_i + b_i \cdot P_i^2) - \lambda^{CO2*} \cdot A_i - h_i \cdot OS_i$$

$$0 \leq k_i \cdot P_i \leq A_i + OS_i$$

$$OS_i \leq 0.03 \cdot A_i$$

$$0 \leq P_i \leq P_i^{\max}$$

$$\sum_{j=1}^n A_j - CAP^{CO2} = 0$$

$$0 \leq A_j \perp -\lambda_j + \lambda^{CO2*} + w_j^1 - w_j^2 \geq 0$$

$$0 \leq w_j^1 \perp q_j - A_j \geq 0$$

$$0 \leq w_j^2 \perp A_j \geq 0$$

$$0 \leq w_j^3 \perp 0.25 \cdot CAP^{CO2} - A_j \geq 0$$

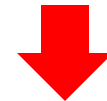
$j = 1, \dots, n$

$$\max_{x_i \geq 0, y, s} f(x_i, y)$$

$$s.t. \quad g(x_i, y) \leq 0$$

$$H_j - s_j = 0$$

$$0 \leq y_j \perp s_j \geq 0 \quad \left. \vphantom{0 \leq y_j} \right\} j = 1, \dots, n$$



Equilibrium Point

$$(x^*, y^*, s^*)$$

NCP Formulation

$$\left\{ \begin{array}{l} \nabla_{x_i} f(x_i, y) + \nabla_{x_i} g(x_i, y) \mu_i + \nabla_{x_i} h(x_i, y) \xi_i - \chi_i = 0 \\ \nabla_y f(x_i, y) + \nabla_y g(x_i, y) \mu_i + \nabla_y h(x_i, y) \xi_i + s_i \eta_i = 0 \\ \xi_i - \sigma_i + y \xi_i = 0 \\ 0 \leq g(x_i, y) \perp \mu_i \geq 0 \\ h(x_i, y) - s_i = 0 \\ 0 \leq x_i \perp \chi_i \geq 0 \\ 0 \leq \psi_i + s_i \perp y \geq 0 \\ 0 \leq \sigma_i + y \perp s \geq 0 \\ 0 \leq \psi_i + \sigma_i \perp \eta_i \geq 0 \end{array} \right.$$



Strongly Stationary Point

$$(x^*, y^*, s^*, \chi^*, \underbrace{\mu^*, \xi^*, \psi^*, \sigma^*, \eta^*}_{\text{multipliers}})$$

multipliers

Theorem 1: If there is an equilibrium point of *EPEC* and every *MPEC* satisfies an *MPEC-LICQ*, then there exist multipliers to get a strongly stationary point of the *NCP*.

NLP Formulation

$$\begin{aligned}
 & \min_{x,y,s,\mu,\xi,\psi,\sigma,\eta} && C_{pen} := \sum_{i=1}^n \left(x_i^T \chi_i + t_i^T \mu_i + y^T \psi_i + s^T \sigma_i \right) + y^T s \\
 & s.t. && \nabla_{x_i} f(x_i, y) + \nabla_{x_i} g(x_i, y) \mu_i + \nabla_{x_i} h(x_i, y) \xi_i - \chi_i = 0 \\
 & && \nabla_y f(x_i, y) + \nabla_y g(x_i, y) \mu_i + \nabla_y h(x_i, y) \xi_i - \psi_i + s_i \eta_i = 0 \\
 & && \xi_i - \sigma_i + y \xi_i = 0 \\
 & && g(x_i, y) = t_i \\
 & && h(x_i, y) = s_i \\
 & && y \geq 0, \quad s \geq 0 \\
 & && \chi_i \geq 0, \quad \mu_i \geq 0, \quad \psi_i \geq 0, \quad \sigma_i \geq 0, \quad \eta_i \geq 0 \\
 & && x_i \geq 0, \quad t_i \geq 0
 \end{aligned}$$

Theorem 2: If there is an local solution $(x^*, y^*, s^*, t^*, \chi^*, \mu^*, \xi^*, \psi^*, \sigma^*, \eta^*)$, with $C_{pen}=0$, then (x^*, y^*, s^*) is a strongly stationary point of the EPEC.

Sensitivity Analysis

GENCO	a	b	λ^e (\$/MW)	P^{max} (MW)	Bidding Price λ (\$/p.u.)	k (ton/MW)	h (\$/p.u.)
1	15	0.005	20	500	2	1	10
2	18	0.004	20	800	1.5	1	10
3	10	0.005	20	800	2.5	1	10
4	15	0.004	20	800	2.3	1	10



Base case

GEN.	P (MW)	A (p.u.)	q (p.u.)	$Profit$ (\$)	λ^{CO2} (\$/p.u.)
1	262.5	262.5	262.5	574.2	1.5
2	0	0	594	0	
3	800	800	800	3600	
4	437.5	437.5	437.5	765.6	

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$\lambda_2=1.9$

GEN.	P (MW)	A (p.u.)	q (p.u.)	Profit (\$)	λ^{CO_2} (\$/p.u.)
1	310	310	310	480.5	1.9
2	2.5	2.5	313.3	0.225	
3	800	800	800	3280	
4	387.5	387.5	387.5	600.625	

Sensitivity Analysis

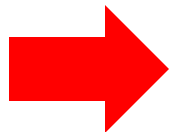
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 **Base case**

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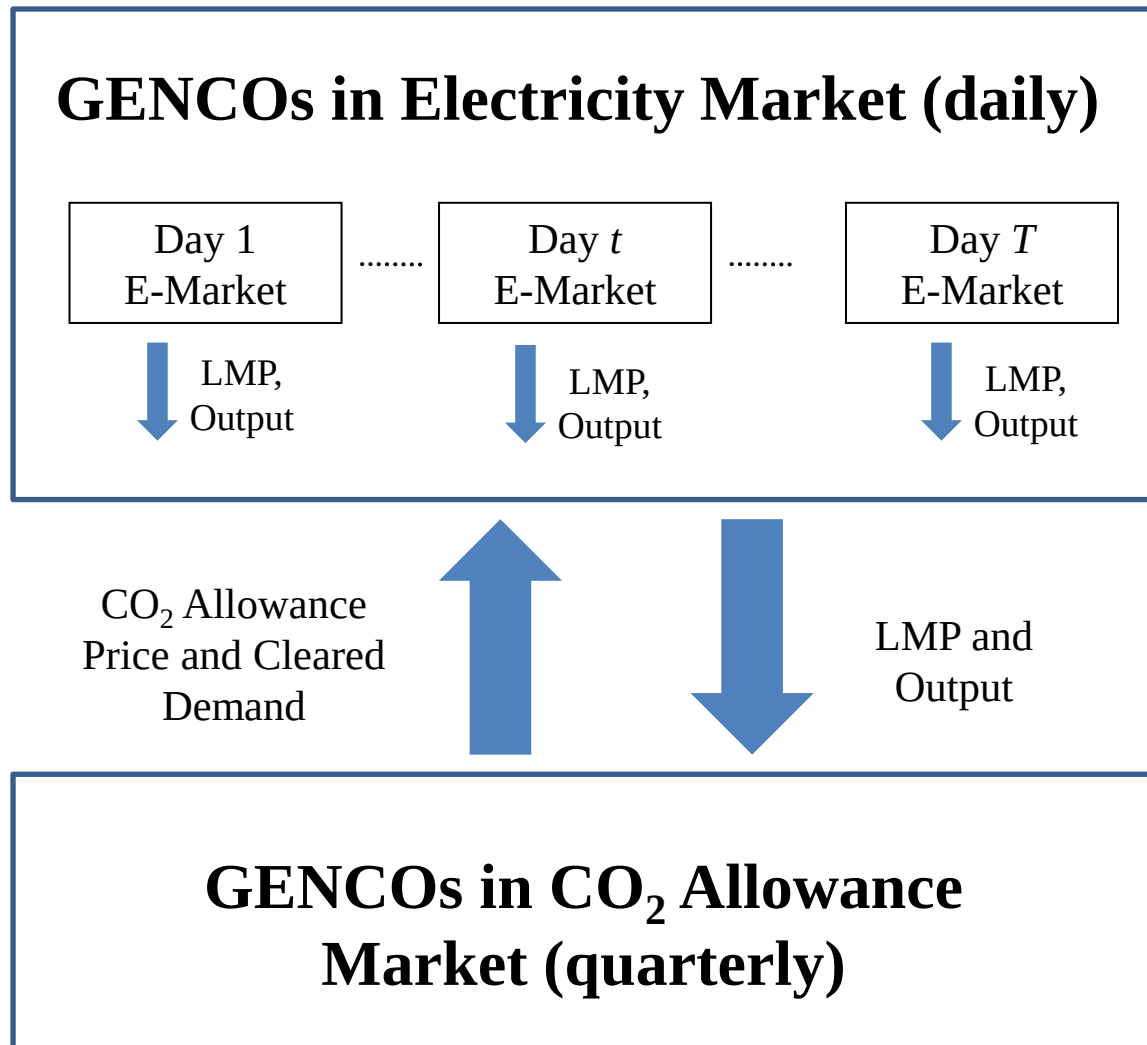
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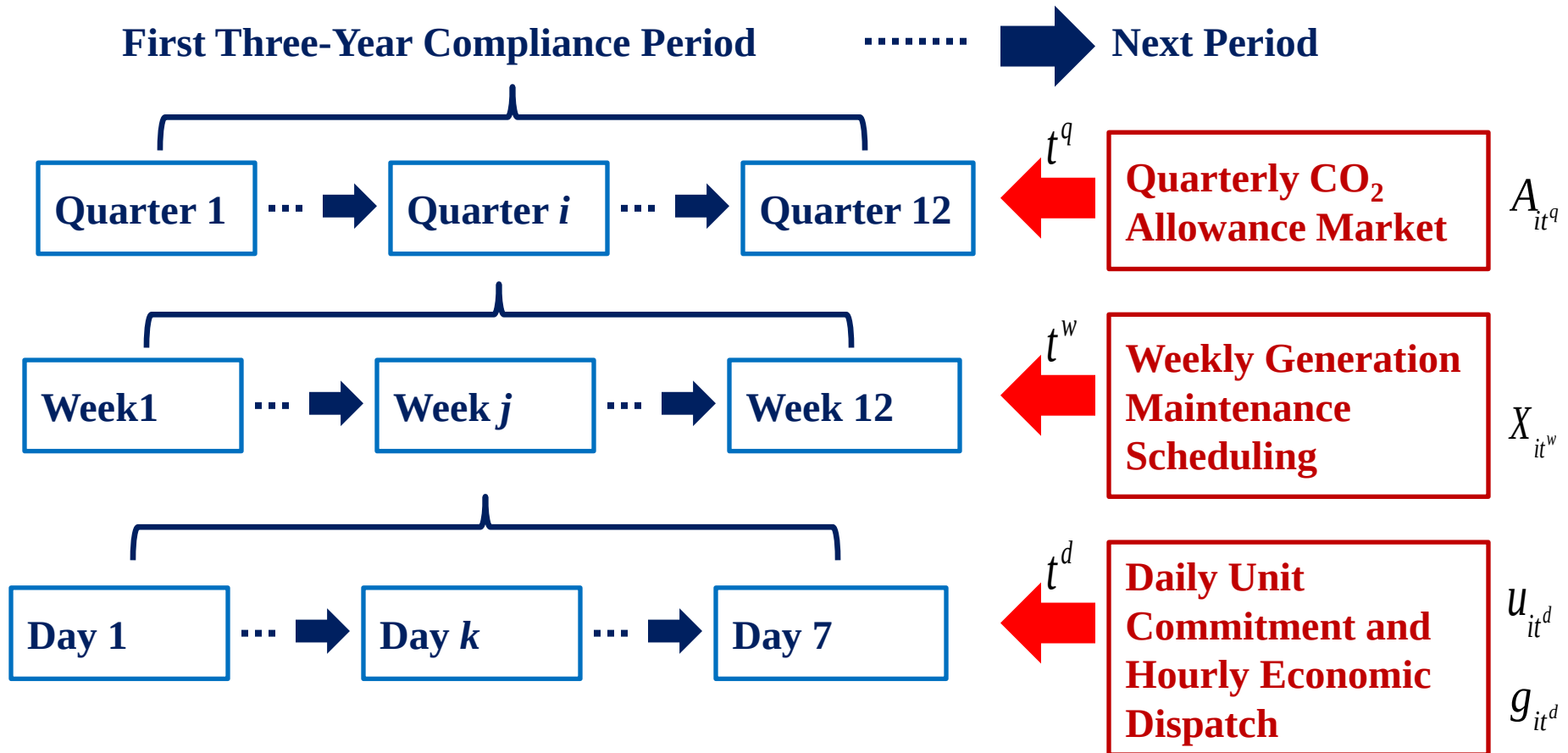


**Need to consider both electricity
market and CO₂ allowance market**

GENCOs Interactions in Two Markets



Time Horizon of New GSP



GENCO's Maximization Problem

Max **Total Profit during Time Period T**

subject to

Generation Maintenance Scheduling Constraints

UC and OPF Operation Constraints

CO₂ Allowance Market Constraints

where

Profit = Revenue - Cost

**selling power to the
electricity market**

**maintenance, fuel production,
startup, shutdown and CO₂ allowance**

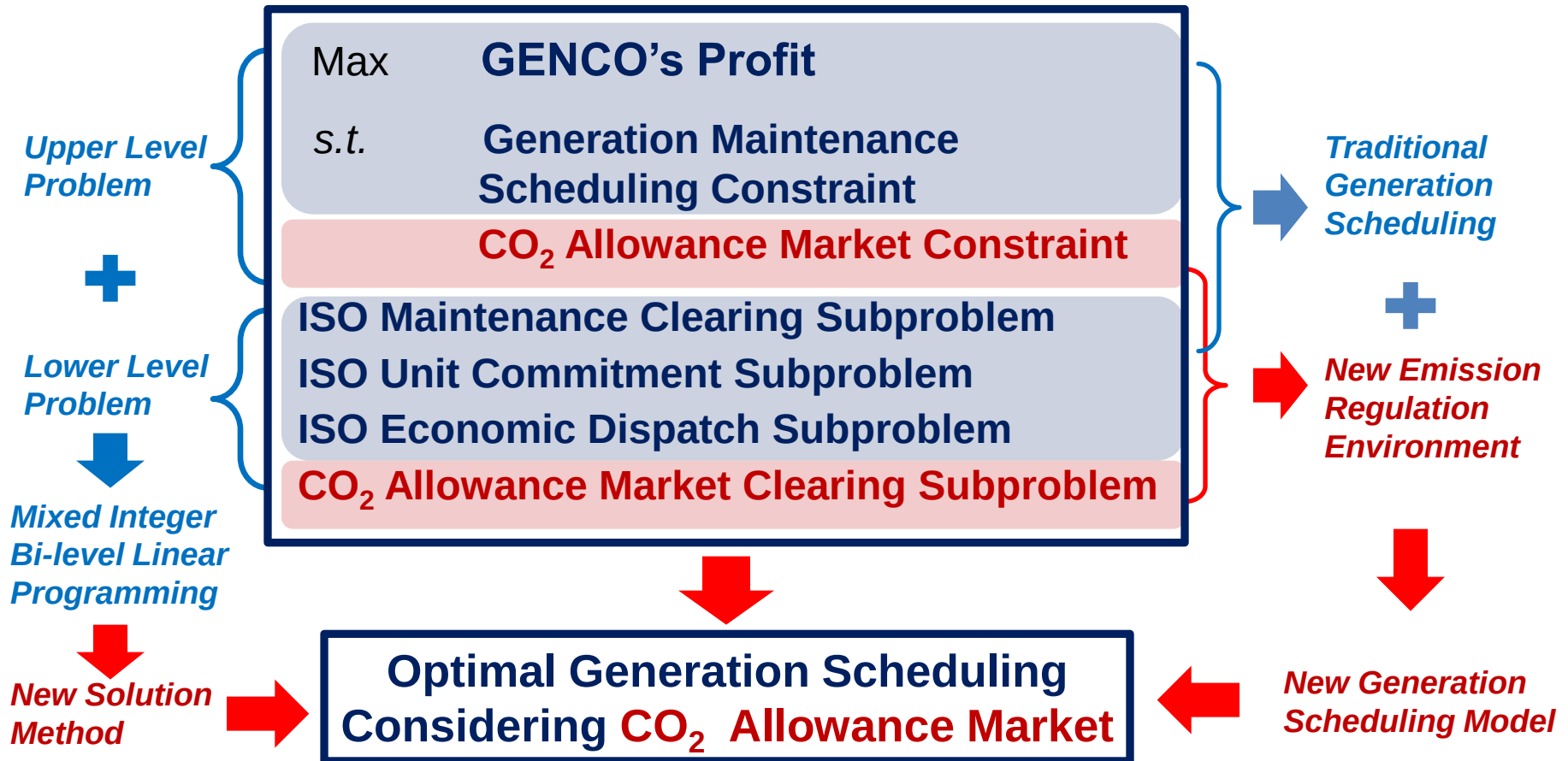
**GENCO's
Decision
Variables:**

$q_{ft'}$ *Allowances bid by firm f in interval t'*

$OS_{ft'}$ *Offsets used by firm f in interval t'*

X_{it} *Maintenance schedule of generation i in period t*

Structure of New GSP



Upper-Level Optimization Problem

$$\max_{g_{it^d}, x_{it^w}, q_{it^q}, OS_{it^q}} \quad \sum_{t^d} \left\{ \overset{\text{Revenue}}{p_{it^d}^E \times g_{it^d}} - C_{it^d}^P(g_{it^d}) - C_{it^d}^{SU} - C_{it^d}^{SD} \right\} - \sum_{t^w} C_{it^w}^M - \sum_{t^q} \left\{ \overset{\text{Cost}}{p_{t^q}^{CO2} \times A_{it^q} + C_i^{OS} \times OS_{it^q}} \right\}$$

s.t.

$$u_{it^d} - u_{it^d-1} \leq x_{it^w}, \quad \forall i, t^d \in \{t^w\}$$

$$x_{it^w} + u_{it^d} \leq 1, \quad \forall i, t^d \in \{t^w\}$$

$$\sum_{t^w} x_{it^w} = T1_i, \quad \forall i$$

$$x_{it^w} - x_{it^w-1} \leq x_{it^w+(T1_i-1)}, \quad \forall i, t^w$$

$$\sum_i x_{it^w} \leq NM_{t^w}, \quad \forall t^w$$

$$\sum_{t^d} g_{it^d} \leq \sum_{t^d} (G_i^{MAX} \times HE_{it^d}), \quad \forall i \in \{\text{hydroelectric}\}$$

$$G_i^{MIN} \times (1 - x_{it^w}) \leq g_{it^d}, \quad \forall i, t^d \in \{t^w\}$$

$$g_{it^d} \leq G_i^{MAX} \times (1 - x_{it^w}), \quad \forall i, t^d \in \{t^w\}$$

$$\sum_{i, t^d \in t^q} R_i^{CO2} \times g_{it^d} \leq A_{it^q} + OS_{it^q} + A_{it^q}^{IA}, \quad \forall t^q$$

$$OS_{it^q} \leq \sum_{i, t^d \in t^q} 0.033 \times R_i^{CO2} \times g_{it^d}, \quad \forall t^q$$

$$\forall g_{it^d}, x_{it^w}, q_{it^q}, OS_{it^q} \geq 0$$

**Generation
Maintenance
Scheduling**

**CO₂
Allowance
Market**

Lower-Level Optimization Problem

$$\begin{aligned} \min_{g_{it^d},} \quad & \sum_{t^w} \sum_i (C_{it^w}^M + C^{UE} \times UE_{it^w}) \\ \text{s.t.} \quad & \sum_{i, t^d \in t^w} g_{it^d} + UE_{it^w} = \sum_i D_{it^w}, \quad \forall t^w \end{aligned} \quad \begin{array}{l} \text{I. ISO Maintenance} \\ \text{Clearing} \\ \text{Subproblem} \end{array}$$

$$\begin{aligned} \min_{g_{it^d}} \quad & \sum_i \left(\alpha_i \times g_{it^d} + \frac{1}{2} \times \beta_i \times g_{it^d}^2 \right) \\ \text{s.t.} \quad & \sum_i g_{it^d} - \sum_i D_{it^d} = 0, \quad (\lambda_{t^d}) \\ & \sum_i GSF_{k-i} \times (g_{it^d} - D_{it^d}) \leq F_k^{\max}, \quad \forall k \quad (\mu_{kt^d}) \\ & G_i^{\min} \times u_{it^d} \leq g_{it^d} \leq G_i^{\max} \times u_{it^d} \\ & \forall g_{it^d} \geq 0 \end{aligned} \quad \begin{array}{l} \text{III. ISO Economic} \\ \text{Dispatch} \\ \text{Subproblem} \end{array}$$

where: $p_{it^d}^E = LMP_{it^d} = LMP_{it^d}^{\text{energy}} + LMP_{it^d}^{\text{cong}}$
 $= \lambda_{t^d} + \sum_i GSF_{k-i} \cdot \mu_{kt^d}$

$$\begin{aligned} \max_{A_{it^q}} \quad & \sum_i B_{it^q}^{CO_2} \cdot A_{it^q} \\ \text{s.t.} \quad & \sum_i A_{it^q} - CAP_{t^q}^{CO_2} = 0, \quad \forall t^q \quad (p_{t^q}^{CO_2}) \\ & A_{it^q} \leq 0.25 \cdot CAP_{t^q}^{CO_2}, \quad \forall i, t^q \\ & 0 \leq A_{it^q} \leq q_{it^q}, \quad \forall i, t^q \end{aligned} \quad \begin{array}{l} \text{IV. CO}_2 \text{ Allowance} \\ \text{Market Clearing} \\ \text{Subproblem} \end{array}$$

$$\begin{aligned} \min_{g_{it^d}} \quad & \sum_i \sum_{t^d} \{ C_{it^d}^P (g_{it^d}) + C_{it^d}^{SU} + C_{it^d}^{SD} \} \\ \text{s.t.} \quad & \sum_i g_{it^d} = \sum_i D_{it^d}, \quad \forall t^d \\ & \sum_i r_{it^d}^S \geq R_{t^d}^S, \quad \forall t^d \\ & \sum_i r_{it^d}^O \geq R_{t^d}^O, \quad \forall t^d \\ & G_i^{\min} \times u_{it^d} \leq g_{it^d}, \quad \forall i, t^d \\ & g_{it^d} + r_{it^d}^S + r_{it^d}^O \leq G_i^{\max} \times u_{it^d}, \quad \forall i, t^d \\ & r_{it^d}^S \leq R_{t^d}^S \times u_{it^d}, \quad \forall i, t^d \\ & r_{it^d}^O \leq R_{t^d}^O \times u_{it^d}, \quad \forall i, t^d \\ & g_{it^d} - g_{it^d-1} \leq \text{MaxInc}_i, \quad \forall i, t^d \\ & g_{it^d} - g_{it^d-1} \geq -\text{MaxDec}_i, \quad \forall i, t^d \\ & (Y_{it^d-1}^{ON} - T_i^{ON}) \times (u_{it^d-1} - u_{it^d}) \geq 0, \quad \forall i, t^d \\ & (Y_{it^d-1}^{OFF} - T_i^{OFF}) \times (u_{it^d} - u_{it^d-1}) \geq 0, \quad \forall i, t^d \\ & \sum_i PTDF_{ki} \times (g_{it^d} - D_{it^d}) \leq \text{MaxFlow}_k, \quad \forall i, t^d \end{aligned} \quad \begin{array}{l} \text{II. ISO Unit} \\ \text{Commitment} \\ \text{Subproblem} \end{array}$$

Mixed Integer Bilevel Linear Programming Problem (MIBLP)

$$\max_{x,y} \quad C1 * x + d1 * y$$

$$s.t. \quad A1 * x + B1 * y \leq b1$$

**Upper Level
Problem**

$$y \in \arg \max_w \quad C2 * x + d2 * w$$

$$s.t. \quad A2 * x + B2 * w \leq b2$$

$$w \geq 0 \quad w_I \text{ integer}$$

$$x \geq 0 \quad x_J \text{ integer}$$

**Lower Level
Problem**

- Benders Decomposition
- Linear Problem with Complementarity Constraints (LPCC)
- Branch-and-Cut

Solution Methodology

- Step 1: Decompose MIBLP to **slave problems** (SPs) and **restricted master problem** (RMP)

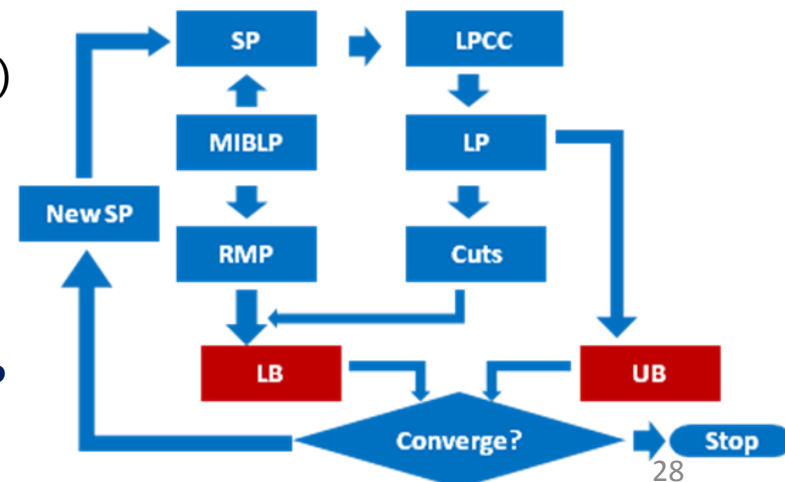
fix the binary variables
and get the BLP - **UB**

eliminate the constraints
and the lower objective
function - **LB**

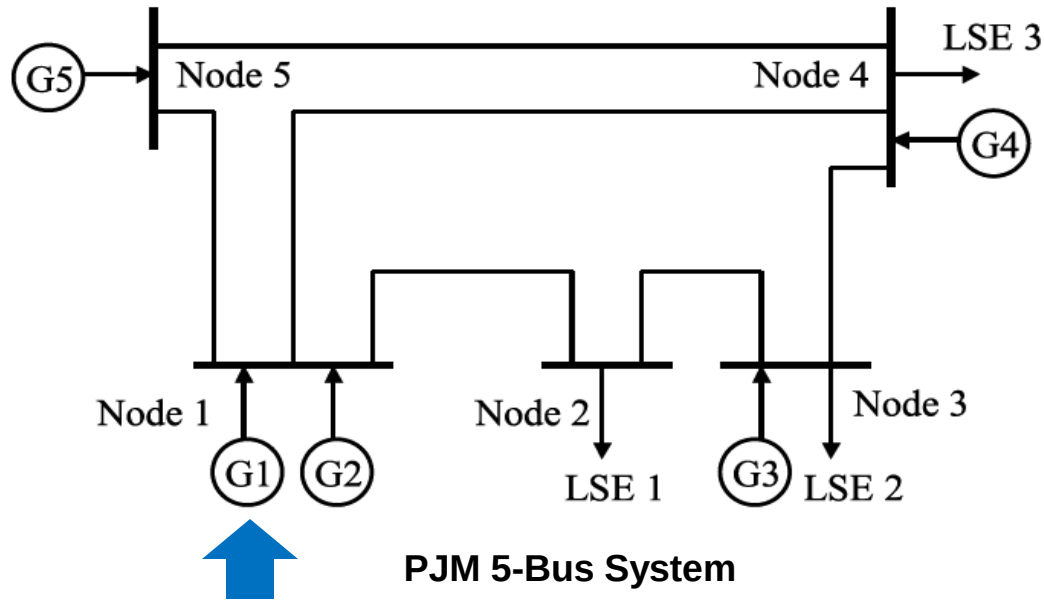
- Step 2: Transform **SP** to **LPCC**, and solve **LPCC** using " θ -free" algorithm
- Step 3: From the solution, construct the **LP**, which provides an **UB** (in Min problem)
- Step 4: Using the optimal dual values of **LP** to add a **cut** back to **RMP**

- Feasibility cut (dual LP unbounded)
- Optimality cut (dual LP bounded and restrict RMP)
- Integer Exclusion cut (dual LP bounded but not restrict RMP)

- Step 5: Solve the augmented RMP to get a new **LB**
- Step 6: If not satisfy convergence criterion, using **RMP** solutions to construct a new **SP** to iterate. Otherwise, Stop.



Numerical Example



**7-Week
Generation
Maintenance
Scheduling**

+

**Daily Unit
Commitment &
Hourly Economic
Dispatch**

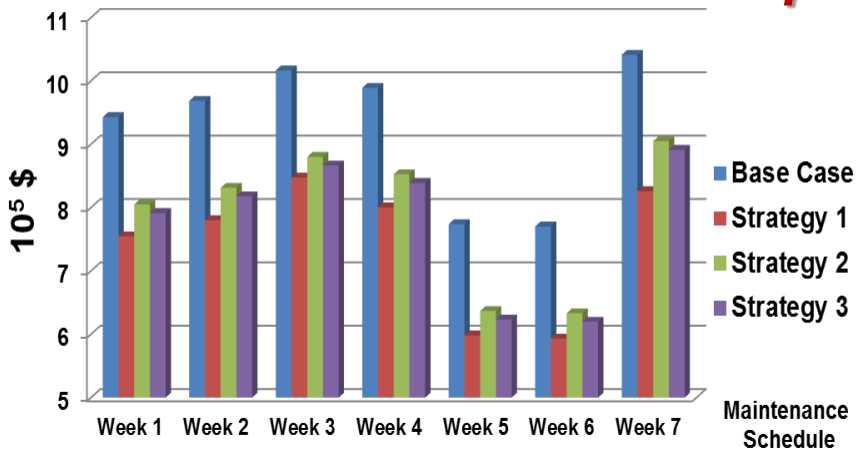
+

**1-Auction with
3 Bidding Strategies**

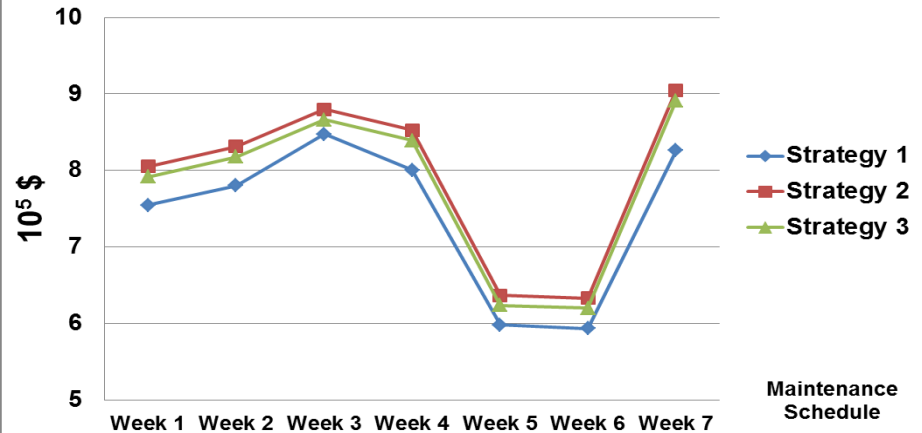
Strategy	Quantity	Price
1	Small	Low
2	Medium	Medium
3	Large	High

Simulation Results

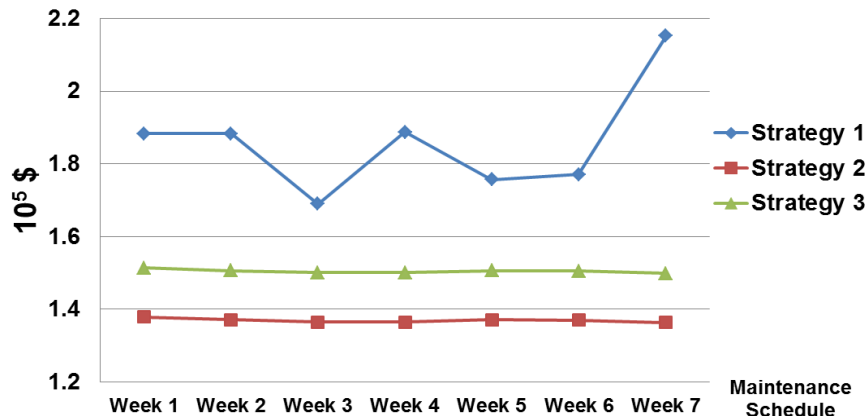
Profit of G1



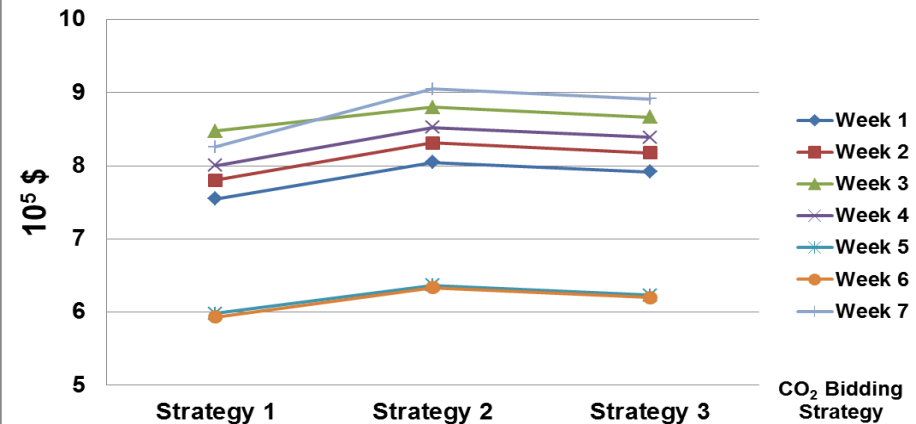
Comparison of the profit under different maintenance schedules



Comparison of the reduced profit under different CO₂ bidding strategies

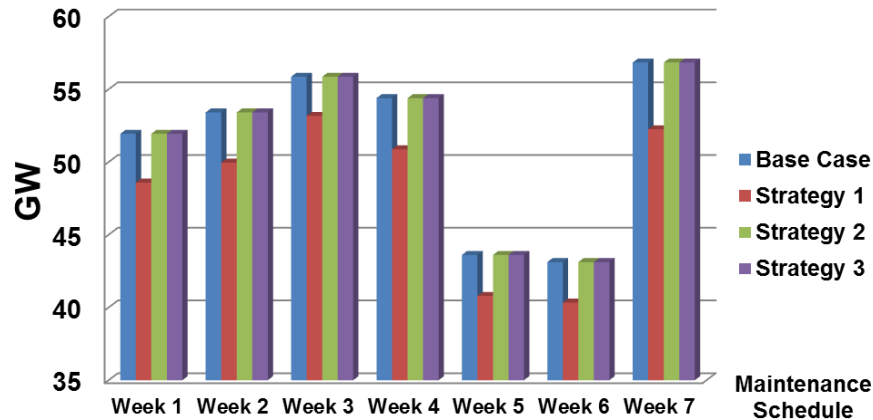


Comparison of the profit under different CO₂ bidding strategies



Simulation Results

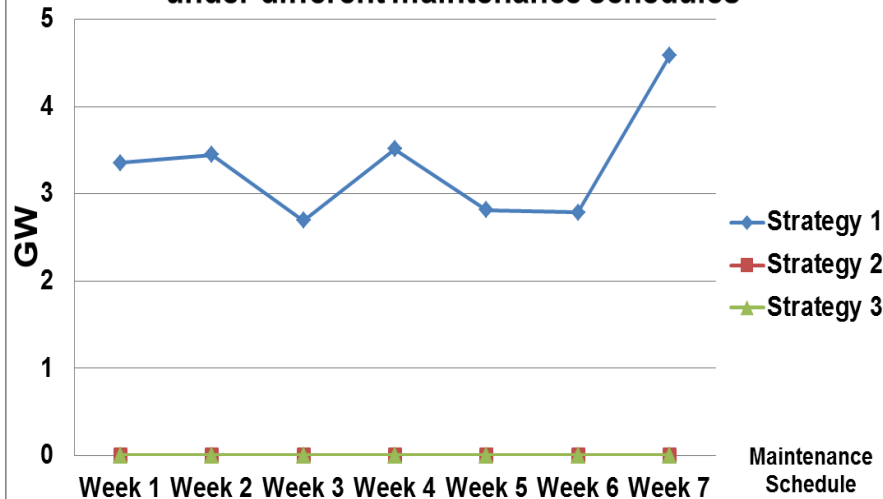
Generation Output of G1



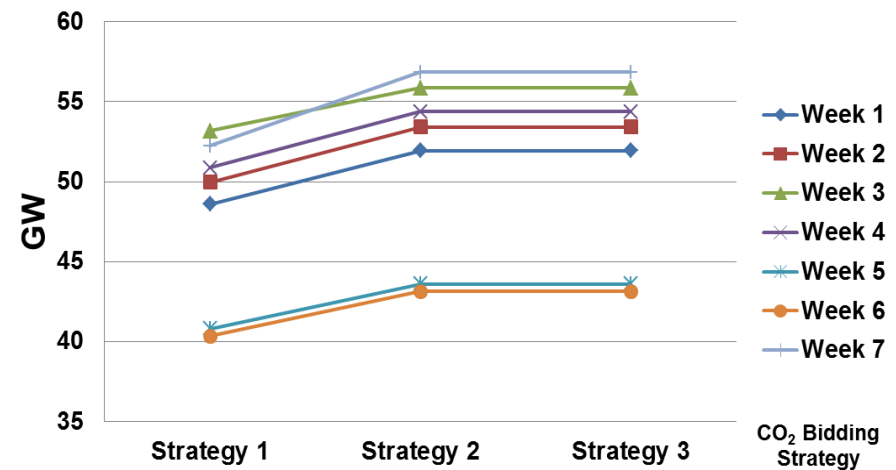
Comparison of the generation output under different maintenance schedules



Comparison of the reduced generation output under different maintenance schedules



Comparison of the generation output under different CO₂ bidding strategies



Simulation Results

The Profit under Optimal Maintenance Scheduling & CO₂ Allowance Bidding Strategy



Optimal
Maintenance
Scheduling

Bidding
Strategy

Conclusions

- Optimal generation maintenance scheduling will be changed when GENCOs participate in both electricity market and CO₂ allowance market.
- Neither the **conservative** (small quantity) nor the **aggressive** (large quantity) bidding strategy will bring the optimal profit.
- GENCOs need to consider the maintenance scheduling and CO₂ allowance bidding together in order to maximize their profits.
- Based on the proposed model, GENCOs will be able to determine their optimal **mid-term generation maintenance scheduling** and **CO₂ allowance bidding strategy** participating in both markets.

Questions

