Equilibrium models to analyze TSO-DSOs coordination architectures in two-stage energy markets under uncertainty of demand and renewable generation

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Advanced Decision-Making for

Net-Zero Energy Systems

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Research Motivation

Motivation: Flexibility in the Energy Transition

Renewables growth

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Flexibility needs

↓

TSO-DSOs interaction

- Increasing need of **flexibility**
  - Generation-demand balance
  - Congestion management.
- **Distributed resources** can contribute
  - Locally
  - To the transmission grid.
- **Challenge**: coordination & market design
  - TSO-DSO dispatch alignment
  - Exercise of market power.

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  - To the transmission grid.
- **Challenge**: coordination & market design
  - TSO-DSO dispatch alignment
  - Exercise of market power.

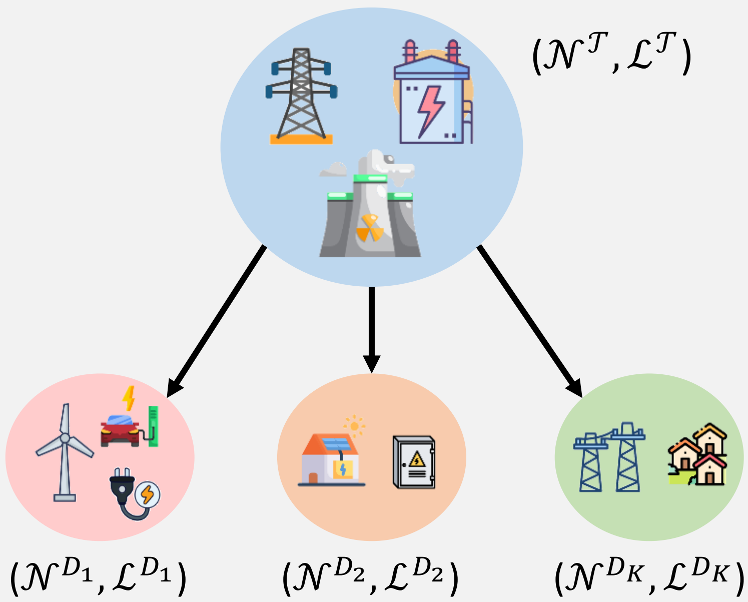
Research Goal

Define the best coordination scheme between TSO & DSOs for balancing and congestion management, accounting for market power.

Mathematical Formulation

Problem Overview

Power System Representation



Market Structure

1. **Day-Ahead Market (DAM)**
   - Forecasted net load covered by programmable generation units ($\mathcal{U}$).
2. **Ancillary services market (ASM)**
   - Balancing & congestion management
   - Actions:
     - ✓ Adjust programmable generation
     - ✓ Curtail RES generation
     - ✓ Curtail loads.

Uncertainty

- Applies to **realt-time** demand and RES generation
- Represented by a set $\mathcal{S}$ of **scenarios**.

Strategic Game

Market Players

- Each player $i \in I$ controls:

Programmable generators $\mathcal{U}_i \subset \mathcal{U}$

Curtailable loads $\mathcal{N}_i \subset \mathcal{N}$.

Strategic Behaviour

- Market players define **joint** price bidding strategies on DAM & ASM.
- The **maximum** available power capacity is offered.

Assessing Market Power

- Consider **each** market player separately
- Formulate its **bidding** optimization problem:
  - **Decision**: determine bid prices
  - **Objective**: maximize expected profits
  - **Constraints**: respect market clearing rules (DAM & ASM).

TSO-DSOs Coordination Schemes

We examine three coordination schemes:

A. Two-stage architecture
1. DAM
2. Common ASM for $\mathcal{T}$+$\mathcal{D}$

B. Three-stage architecture 1
1. DAM
2. ASM in each distribution network $\mathcal{D}_k$, with resources in $\mathcal{D}_k$
3. ASM in transmission $\mathcal{T}$, with resources in $\mathcal{T}$

C. Three-stage architecture 2
1. DAM
2. ASM in each distribution network $\mathcal{D}_k$, with resources in $\mathcal{D}_k$
3. ASM in transmission $\mathcal{T}$, with resources in $\mathcal{T}$ + residual resources in $\mathcal{D}$

Scheme A: Two-stage architecture

Stage 1 – DAM

- Players submit sell bids
- DAM cleared by DAM Operator.

Stage 2 – ASM

- Players submit adjustment bids
- ASM cleared by ASM Operator (coordinated TSO + DSO)

Decisions of player i

- On **DAM**

$u \in \mathcal{U}_i$	$b_u^{\mathcal{U}}$	Price of **sell** bid

- On **ASM**

$u \in \mathcal{U}_i$	$b_u^{\mathcal{U},\uparrow}$	Price of **upward** regulation bid
$u \in \mathcal{U}_i$	$b_u^{\mathcal{U},\downarrow}$	Price of **downward** regulation bid
$n \in \mathcal{N}_i$	$b_n^{\mathcal{N},\downarrow}$	Price of **load curtailment** bid

Scheme A: Mathematical formulation

$$\max \underbrace{\sum_{u\in\mathcal{U}_i} (\lambda - C_u)\, g_u}_{\text{Revenues on DAM}} + \underbrace{\sum_{s\in\mathcal{S}} \sigma_s \left\{ \sum_{u\in\mathcal{U}_i} \left[(b_u^{\mathcal{U},\uparrow} - C_u^{\uparrow})\, g_{u,s}^{\uparrow} + (C_u^{\downarrow} - b_u^{\mathcal{U},\downarrow})\, g_{u,s}^{\downarrow} \right] + \sum_{n\in\mathcal{N}_i} b_n^{\mathcal{N},\downarrow}\, d_{n,s}^{\downarrow} \right\}}_{\text{Expected revenues on ASM}},$$

$$\text{s. t.} \quad g_u \in \arg\min \sum_{u\in\mathcal{U}} b_u^{\mathcal{U}}\, g_u$$

DAM

$$\text{s. t.} \quad \sum_{u\in\mathcal{U}} g_u = \sum_{n\in\mathcal{N}} D_n - \sum_{n\in\mathcal{N}} W_n \quad : \quad [\lambda]$$

$$0 \le g_u \le G_u, \quad u \in \mathcal{U}$$

$$\left(g_{u,s}^{\uparrow}, g_{u,s}^{\downarrow}, d_{n,s}^{\downarrow}, w_{n,s}^{\downarrow}\right) \in \arg\min \underbrace{\sum_{u\in\mathcal{U}} b_u^{\mathcal{U},\uparrow}\, g_{u,s}^{\uparrow} + \sum_{n\in\mathcal{N}} b_n^{\mathcal{N},\downarrow}\, d_{n,s}^{\downarrow}}_{\text{Upward regulation costs}} - \underbrace{\sum_{u\in\mathcal{U}} b_u^{\mathcal{U},\downarrow}\, g_{u,s}^{\downarrow}}_{\text{Downward regulation revenues}}$$

ASM

$$\text{s. t.} \quad \sum_{u\in\mathcal{U}} g_{u,s}^{\uparrow} + \sum_{n\in\mathcal{N}} d_{n,s}^{\downarrow} - \sum_{u\in\mathcal{U}} g_{u,s}^{\downarrow} - \sum_{n\in\mathcal{N}} w_{n,s}^{\downarrow} = \underbrace{\Delta_s}_{\text{Total Imbalance}}$$

$$\sum_{n\in\mathcal{N}} H_{l,n} \underbrace{\left[\sum_{u\in\mathcal{U}_n} (g_u + g_{u,s}^{\uparrow} - g_{u,s}^{\downarrow}) + (\tilde{W}_{n,s} - w_{n,s}^{\downarrow}) - (\tilde{D}_{n,s} - d_{n,s}^{\downarrow}) \right]}_{\text{Net injection in node } n} \le \overline{F}_l, \quad l \in \mathcal{L}$$

$$0 \le g_{u,s}^{\uparrow} \le G_u - g_u, \qquad u \in \mathcal{U}$$

$$0 \le g_{u,s}^{\downarrow} \le g_u, \qquad u \in \mathcal{U}$$

$$0 \le d_{n,s}^{\downarrow} \le \delta_n\, \tilde{D}_{n,s}, \qquad n \in \mathcal{N}$$

$$0 \le w_{n,s}^{\downarrow} \le \tilde{W}_{n,s}, \qquad n \in \mathcal{N}$$

Scheme B: Three-stage architecture 1

Stage 1 – DAM

- Players submit sell bids
- DAM cleared by DAM Operator.

Stage 2 – Local ASMs

- Players submit adjustment bids for $\mathcal{D}$ resources
- Every local ASM is cleared by the correspondent DSO

Stage 3 – $\mathcal{T}$ ASM

- Players submit adjustment bids for $\mathcal{T}$ resources
- $\mathcal{T}$ ASM is cleared by the TSO

Decisions of player i

- On **DAM**

$u \in \mathcal{U}_i$	$b_u^{\mathcal{U}}$	Price of **sell** bid

- On the corresponding **ASM**

$u \in \mathcal{U}_i$	$b_u^{\mathcal{U},\uparrow}$	Price of **upward** regulation bid
$u \in \mathcal{U}_i$	$b_u^{\mathcal{U},\downarrow}$	Price of **downward** regulation bid
$n \in \mathcal{N}_i$	$b_n^{\mathcal{N},\downarrow}$	Price of **load curtailment** bid

Scheme B: Mathematical formulation (1/2)

$$\max \underbrace{\sum_{u\in\mathcal{U}_i} (\lambda - C_u)\, g_u}_{\text{Revenues on DAM}} + \underbrace{\sum_{s\in\mathcal{S}} \sigma_s \Big\{ \sum_{u\in\mathcal{U}_i} \Big[(b_u^{\mathcal{U},\uparrow} - C_u^{\uparrow})\, g_{u,s}^{\uparrow} + (C_u^{\downarrow} - b_u^{\mathcal{U},\downarrow})\, g_{u,s}^{\downarrow} \Big] + \sum_{n\in\mathcal{N}_i} b_n^{\mathcal{N},\downarrow}\, d_{n,s}^{\downarrow} \Big\}}_{\text{Expected revenues on ASM}},$$

DAM

$$\text{s. t.} \quad g_u \in \arg\min \sum_{u\in\mathcal{U}} b_u^{\mathcal{U}}\, g_u$$

$$\text{s. t.} \quad \sum_{u\in\mathcal{U}} g_u = \sum_{n\in\mathcal{N}} D_n - \sum_{n\in\mathcal{N}} W_n \quad : \quad [\lambda]$$

$$0 \le g_u \le G_u, \quad u \in \mathcal{U}$$

Local ASMs

$$\left(g_{u,s}^{\uparrow}, g_{u,s}^{\downarrow}, d_{n,s}^{\downarrow}, w_{n,s}^{\downarrow}\right) \in \arg\min \underbrace{\sum_{u\in\mathcal{U}^{\mathcal{D}}} b_u^{\mathcal{U},\uparrow}\, g_{u,s}^{\uparrow} + \sum_{n\in\mathcal{N}^{\mathcal{D}}} b_n^{\mathcal{N},\downarrow}\, d_{n,s}^{\downarrow}}_{\text{Upward regulation costs}} - \underbrace{\sum_{u\in\mathcal{U}^{\mathcal{D}}} b_u^{\mathcal{U},\downarrow}\, g_{u,s}^{\downarrow}}_{\text{Downward regulation revenues}}$$

$$\text{s. t.} \quad \sum_{u\in\mathcal{U}^{\mathcal{D}_k}} g_{u,s}^{\uparrow} + \sum_{n\in\mathcal{N}^{\mathcal{D}_k}} d_{n,s}^{\downarrow} - \sum_{u\in\mathcal{U}^{\mathcal{D}_k}} g_{u,s}^{\downarrow} - \sum_{n\in\mathcal{N}^{\mathcal{D}_k}} w_{n,s}^{\downarrow} = \underbrace{\Delta_s^{\mathcal{D}_k}}_{\text{Imbalance in network } \mathcal{D}_k} \qquad 1 \le k \le K$$

$$\sum_{n\in\mathcal{N}^{\mathcal{D}_k}} H_{l,n} \underbrace{\Big[\sum_{u\in\mathcal{U}_n} (g_u + g_{u,s}^{\uparrow} - g_{u,s}^{\downarrow}) + (\tilde{W}_{n,s} - w_{n,s}^{\downarrow}) - (\tilde{D}_{n,s} - d_{n,s}^{\downarrow}) \Big]}_{\text{Net injection in node } n} \le \overline{F}_l, \quad l \in \mathcal{L}^{\mathcal{D}_k},\ 1 \le k \le K$$

$$0 \le g_{u,s}^{\uparrow} \le G_u - g_u, \qquad u \in \mathcal{U}^{\mathcal{D}_k}, 1 \le k \le K$$

$$0 \le g_{u,s}^{\downarrow} \le g_u, \qquad u \in \mathcal{U}^{\mathcal{D}_k}, 1 \le k \le K$$

$$0 \le d_{n,s}^{\downarrow} \le \delta_n\, \tilde{D}_{n,s}, \qquad n \in \mathcal{N}^{\mathcal{D}_k}, 1 \le k \le K$$

$$0 \le w_{n,s}^{\downarrow} \le \tilde{W}_{n,s}, \qquad n \in \mathcal{N}^{\mathcal{D}_k}, 1 \le k \le K$$

Scheme B: Mathematical formulation (2/2)

$$\max \underbrace{\sum_{u\in\mathcal{U}_i} (\lambda - C_u)\, g_u}_{\text{Revenues on DAM}} + \underbrace{\sum_{s\in\mathcal{S}} \sigma_s \Big\{ \sum_{u\in\mathcal{U}_i} \Big[(b_u^{\mathcal{U},\uparrow} - C_u^{\uparrow})\, g_{u,s}^{\uparrow} + (C_u^{\downarrow} - b_u^{\mathcal{U},\downarrow})\, g_{u,s}^{\downarrow} \Big] + \sum_{n\in\mathcal{N}_i} b_n^{\mathcal{N},\downarrow}\, d_{n,s}^{\downarrow} \Big\}}_{\text{Expected revenues on ASM}},$$

s. t.

$\mathcal{T}$ ASM

$$\left(g_{u,s}^{\uparrow}, g_{u,s}^{\downarrow}, d_{n,s}^{\downarrow}, w_{n,s}^{\downarrow}\right) \in \arg\min \underbrace{\sum_{u\in\mathcal{U}^{\mathcal{T}}} b_u^{\mathcal{U},\uparrow}\, g_{u,s}^{\uparrow} + \sum_{n\in\mathcal{N}^{\mathcal{T}}} b_n^{\mathcal{N},\downarrow}\, d_{n,s}^{\downarrow}}_{\text{Upward regulation costs}} - \underbrace{\sum_{u\in\mathcal{U}^{\mathcal{T}}} b_u^{\mathcal{U},\downarrow}\, g_{u,s}^{\downarrow}}_{\text{Downward regulation revenues}}$$

$$\text{s. t.} \sum_{u\in\mathcal{U}^{\mathcal{T}}} g_{u,s}^{\uparrow} + \sum_{n\in\mathcal{N}^{\mathcal{T}}} d_{n,s}^{\downarrow} - \sum_{u\in\mathcal{U}^{\mathcal{T}}} g_{u,s}^{\downarrow} - \sum_{n\in\mathcal{N}^{\mathcal{T}}} w_{n,s}^{\downarrow} = \underbrace{\Delta_s^{\mathcal{T}}}_{\text{Transmission imbalance}}$$

$$\sum_{n\in\mathcal{N}} H_{l,n} \underbrace{\Big[\sum_{u\in\mathcal{U}_n} (g_u + g_{u,s}^{\uparrow} - g_{u,s}^{\downarrow}) + (\tilde{W}_{n,s} - w_{n,s}^{\downarrow}) - (\tilde{D}_{n,s} - d_{n,s}^{\downarrow}) \Big]}_{\text{Net injection in node } n} \le \overline{F}_l, \quad l \in \mathcal{L}^{\mathcal{T}}$$

$$0 \le g_{u,s}^{\uparrow} \le G_u - g_u, \qquad u \in \mathcal{U}^{\mathcal{T}}$$

$$0 \le g_{u,s}^{\downarrow} \le g_u, \qquad u \in \mathcal{U}^{\mathcal{T}}$$

$$0 \le d_{n,s}^{\downarrow} \le \delta_n\, \tilde{D}_{n,s}, \qquad n \in \mathcal{N}^{\mathcal{T}}$$

$$0 \le w_{n,s}^{\downarrow} \le \tilde{W}_{n,s}, \qquad n \in \mathcal{N}^{\mathcal{T}}$$

Scheme C: Three-stage architecture 2

Stage 1 – DAM

- Players submit sell bids
- DAM cleared by DAM Operator.

Stage 2 – Local ASMs

- Players submit adjustment bids for $\mathcal{D}$ resources
- Every local ASM is cleared by the correspondent DSO

Stage 3 – $\mathcal{T}$ ASM

- Players submit adjustment bids for $\mathcal{T}$ and $\mathcal{D}$ resources
- $\mathcal{T}$ ASM is cleared by the TSO

Decisions of player i

- On **DAM**

  $u \in \mathcal{U}_i$ $\quad b_u^{\mathcal{U}}$

- On **ASM**

  - Local ASM

    $u \in \mathcal{U}_i^{\mathcal{D}}$ $\quad b_u^{\mathcal{U},\mathcal{D},\uparrow}$

    $u \in \mathcal{U}_i^{\mathcal{D}}$ $\quad b_u^{\mathcal{U},\mathcal{D},\downarrow}$

    $n \in \mathcal{N}_i^{\mathcal{D}}$ $\quad b_n^{\mathcal{N},\mathcal{D},\downarrow}$

  - $\mathcal{T}$ ASM

    $u \in \mathcal{U}_i$ $\quad b_u^{\mathcal{U},\mathcal{T},\uparrow}$

    $u \in \mathcal{U}_i$ $\quad b_u^{\mathcal{U},\mathcal{T},\downarrow}$

    $n \in \mathcal{N}_i$ $\quad b_n^{\mathcal{N},\mathcal{T},\downarrow}$

Scheme C: Mathematical formulation (1/2)

$$\max \underbrace{\sum_{u\in\mathcal{U}_i}(\lambda - C_u)\, g_u}_{\text{Profit on DAM}} + \sum_{s\in\mathcal{S}} \sigma_s \Big\{ \underbrace{\sum_{u\in\mathcal{U}_i^{\mathcal{D}}} \Big[(b_u^{\mathcal{U},\mathcal{D},\uparrow} - C_u^{\uparrow})\, g_{u,s}^{\mathcal{D},\uparrow} + (C_u^{\downarrow} - b_u^{\mathcal{U},\mathcal{D},\downarrow})\, g_{u,s}^{\mathcal{D},\downarrow}\Big] + \sum_{n\in\mathcal{N}_i^{\mathcal{D}}} b_n^{\mathcal{N},\mathcal{D},\downarrow}\, d_{n,s}^{\mathcal{D},\downarrow}}_{\text{Profit on } \mathcal{D}-\text{ASM in scenario } s} +$$

$$\underbrace{\sum_{u\in\mathcal{U}_i} \Big[(b_u^{\mathcal{U},\mathcal{T},\uparrow} - C_u^{\uparrow})\, g_{u,s}^{\mathcal{T},\uparrow} + (C_u^{\downarrow} - b_u^{\mathcal{U},\mathcal{T},\downarrow})\, g_{u,s}^{\mathcal{T},\downarrow}\Big] + \sum_{n\in\mathcal{N}_i} b_n^{\mathcal{N},\mathcal{T},\downarrow}\, d_{n,s}^{\mathcal{T},\downarrow}}_{\text{Profit on } \mathcal{T}-\text{ASM in scenario } s} \Big\},$$

s. t.

DAM

$$g_u \in \arg\min \sum_{u\in\mathcal{U}} b_u^{\mathcal{U}}\, g_u$$

$$\text{s. t.} \quad \sum_{u\in\mathcal{U}} g_u = \sum_{n\in\mathcal{N}} D_n - \sum_{n\in\mathcal{N}} W_n \quad : \quad [\lambda]$$

$$0 \le g_u \le G_u, \quad u \in \mathcal{U}$$

Local ASMs

$$\begin{pmatrix} g_{u,s}^{\mathcal{D},\uparrow},\ g_{u,s}^{\mathcal{D},\downarrow} \\ d_{n,s}^{\mathcal{D},\downarrow},\ w_{n,s}^{\mathcal{D},\downarrow} \end{pmatrix} \in \arg\min \sum_{u\in\mathcal{U}^{\mathcal{D}_k}} b_u^{\mathcal{U},\mathcal{D},\uparrow}\, g_{u,s}^{\mathcal{D},\uparrow} + \sum_{n\in\mathcal{N}^{\mathcal{D}_k}} b_n^{\mathcal{N},\mathcal{D},\downarrow}\, d_{n,s}^{\mathcal{D},\downarrow} - \sum_{u\in\mathcal{U}^{\mathcal{D}_k}} b_u^{\mathcal{U},\mathcal{D},\downarrow}\, g_{u,s}^{\mathcal{D},\downarrow}$$

$$\text{s. t.} \quad \sum_{u\in\mathcal{U}^{\mathcal{D}_k}} g_{u,s}^{\mathcal{D},\uparrow} + \sum_{n\in\mathcal{N}^{\mathcal{D}_k}} d_{n,s}^{\mathcal{D},\downarrow} - \sum_{u\in\mathcal{U}^{\mathcal{D}_k}} g_{u,s}^{\mathcal{D},\downarrow} - \sum_{n\in\mathcal{N}^{\mathcal{D}_k}} w_{n,s}^{\mathcal{D},\downarrow} = \Delta_s^{\mathcal{D}_k}, \quad 1 \le k \le K$$

$$\sum_{n\in\mathcal{N}^{\mathcal{D}_k}} H_{l,n}\Big[\sum_{u\in\mathcal{U}_n}(g_u + g_{u,s}^{\mathcal{D},\uparrow} - g_{u,s}^{\mathcal{D},\downarrow}) + (\tilde{W}_{n,s} - w_{n,s}^{\mathcal{D},\downarrow}) +$$

$$- (\tilde{D}_{n,s} - d_{n,s}^{\mathcal{D},\downarrow})\Big] \le \overline{F}_l, \qquad l \in \mathcal{L}^{\mathcal{D}_k}, 1 \le k \le K$$

$$0 \le g_{u,s}^{\mathcal{D},\uparrow} \le G_u - g_u, \qquad u \in \mathcal{U}^{\mathcal{D}_k}, 1 \le k \le K$$

$$0 \le g_{u,s}^{\mathcal{D},\downarrow} \le g_u, \qquad u \in \mathcal{U}^{\mathcal{D}_k}, 1 \le k \le K$$

$$0 \le d_{n,s}^{\mathcal{D},\downarrow} \le \delta_n\, \tilde{D}_{n,s}, \qquad n \in \mathcal{N}^{\mathcal{D}_k}, 1 \le k \le K$$

$$0 \le w_{n,s}^{\mathcal{D},\downarrow} \le \tilde{W}_{n,s}, \qquad n \in \mathcal{N}^{\mathcal{D}_k}, 1 \le k \le K$$

Scheme C: Mathematical formulation (2/2)

$\mathcal{T}$ ASM

$$
\text{s. t.} \quad \begin{pmatrix} g_{u,s}^{\mathcal{T},\uparrow}, \ g_{u,s}^{\mathcal{T},\downarrow} \\ d_{n,s}^{\mathcal{T},\downarrow}, \ w_{n,s}^{\mathcal{T},\downarrow} \end{pmatrix} \in \arg\min \sum_{u\in\mathcal{U}} b_u^{\mathcal{U},\mathcal{T},\uparrow} \ g_{u,s}^{\mathcal{T},\uparrow} + \sum_{n\in\mathcal{N}} b_n^{\mathcal{N},\mathcal{T},\downarrow} \ d_{n,s}^{\mathcal{T},\downarrow} - \sum_{u\in\mathcal{U}} b_u^{\mathcal{U},\mathcal{T},\downarrow} \ g_{u,s}^{\mathcal{T},\downarrow}
$$

$$
\text{s. t.} \quad \sum_{u\in\mathcal{U}} g_{u,s}^{\mathcal{T},\uparrow} + \sum_{n\in\mathcal{N}} d_{n,s}^{\mathcal{T},\downarrow} - \sum_{u\in\mathcal{U}} g_{u,s}^{\mathcal{T},\downarrow} - \sum_{n\in\mathcal{N}} w_{n,s}^{\mathcal{T},\downarrow} = \Delta_s^{\mathcal{T}}
$$

$$
\sum_{n\in\mathcal{N}^{\mathcal{T}}} H_{l,n} \Big[\sum_{u\in\mathcal{U}_n} (g_u + g_{u,s}^{\mathcal{T},\uparrow} - g_{u,s}^{\mathcal{T},\downarrow}) + (\tilde{W}_{n,s} - w_{n,s}^{\mathcal{T},\downarrow}) - (\tilde{D}_{n,s} - d_{n,s}^{\mathcal{T},\downarrow}) \Big] +
$$

$$
+ \sum_{k=1}^{K} \sum_{n\in\mathcal{N}^{\mathcal{D}_k}} H_{l,n} \Big[\sum_{u\in\mathcal{U}_n} (g_u + g_{u,s}^{\mathcal{T},\uparrow} - g_{u,s}^{\mathcal{T},\downarrow} + g_{u,s}^{\mathcal{D},\uparrow} - g_{u,s}^{\mathcal{D},\downarrow}) + (\tilde{W}_{n,s} +
$$

$$
- w_{n,s}^{\mathcal{T},\downarrow} - w_{n,s}^{\mathcal{D},\downarrow}) - (\tilde{D}_{n,s} - d_{n,s}^{\mathcal{T},\downarrow} - d_{n,s}^{\mathcal{D},\downarrow}) \Big] \le \overline{F}_l, \qquad l \in \mathcal{L}^{\mathcal{T}}
$$

$$
0 \le g_{u,s}^{\mathcal{T},\uparrow} \le G_u - g_u, \qquad u \in \mathcal{U}^{\mathcal{T}}
$$

$$
0 \le g_{u,s}^{\mathcal{T},\uparrow} \le G_u - g_u - g_{u,s}^{\mathcal{D},\uparrow} + g_{u,s}^{\mathcal{D},\downarrow}, \qquad u \in \mathcal{U}^{\mathcal{D}}
$$

$$
0 \le g_{u,s}^{\mathcal{T},\downarrow} \le g_u, \qquad u \in \mathcal{U}^{\mathcal{T}}
$$

$$
0 \le g_{u,s}^{\mathcal{T},\downarrow} \le g_u + g_{u,s}^{\mathcal{D},\uparrow} - g_{u,s}^{\mathcal{D},\downarrow}, \qquad u \in \mathcal{U}^{\mathcal{D}}
$$

$$
0 \le d_{n,s}^{\mathcal{T},\downarrow} \le \delta_n \ \tilde{D}_{n,s}, \qquad n \in \mathcal{N}^{\mathcal{T}}
$$

$$
0 \le d_{n,s}^{\mathcal{T},\downarrow} \le \delta_n \ \tilde{D}_{n,s} - d_{n,s}^{\mathcal{D},\downarrow}, \qquad n \in \mathcal{N}^{\mathcal{D}}
$$

$$
0 \le w_{n,s}^{\mathcal{T},\downarrow} \le \tilde{W}_{n,s}, \qquad n \in \mathcal{N}^{\mathcal{T}}
$$

$$
0 \le w_{n,s}^{\mathcal{T},\downarrow} \le \tilde{W}_{n,s} - w_{n,s}^{\mathcal{D},\downarrow}, \qquad n \in \mathcal{N}^{\mathcal{D}}
$$

From Bilevel to MILP Formulation

- The bidding problem of market player i is a **nonlinear bilevel** program. We reformulate it as an equivalent **MILP** through the following steps:

Step 1: KKT Reformulation

- Replace the lower-level problems by their **KKT** conditions
- Obtain a **single-level** optimization problem.

Step 2: Linearizing Complementarity

- Introduce **SOS1 variables**
- Enforce complementarity constraints **linearly**

Step 3: Discrete Bid Prices

- Assume bid prices are chosen from **discrete sets**
- Apply McCormick reformulation to **binary x continuous** terms

Finding a Nash Equilibrium

Bid prices are suitably initialized

Finding a Nash Equilibrium

Bid prices are suitably initialized

↓

Consider the first player $i = 1$

Finding a Nash Equilibrium

Bid prices are suitably initialized

↓

Consider the first player $i = 1$

↓

Problem solution

- Compute the best response of player i to competitors
- Update bid prices for resources $u \in \mathcal{U}_i$ and $n \in \mathcal{N}_i$ of player i

Finding a Nash Equilibrium

Bid prices are suitably initialized

↓

Consider the first player $i = 1$

↓

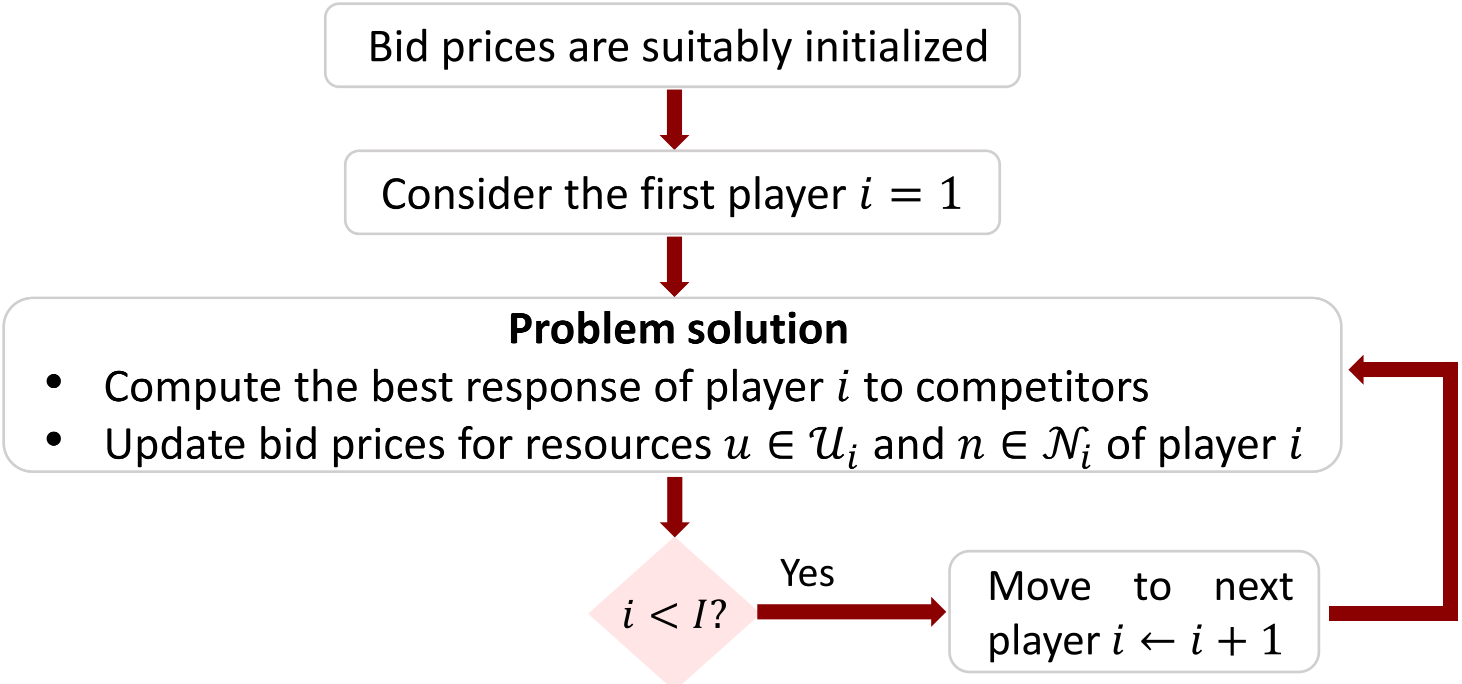
Problem solution

- Compute the best response of player i to competitors
- Update bid prices for resources $u \in \mathcal{U}_i$ and $n \in \mathcal{N}_i$ of player i

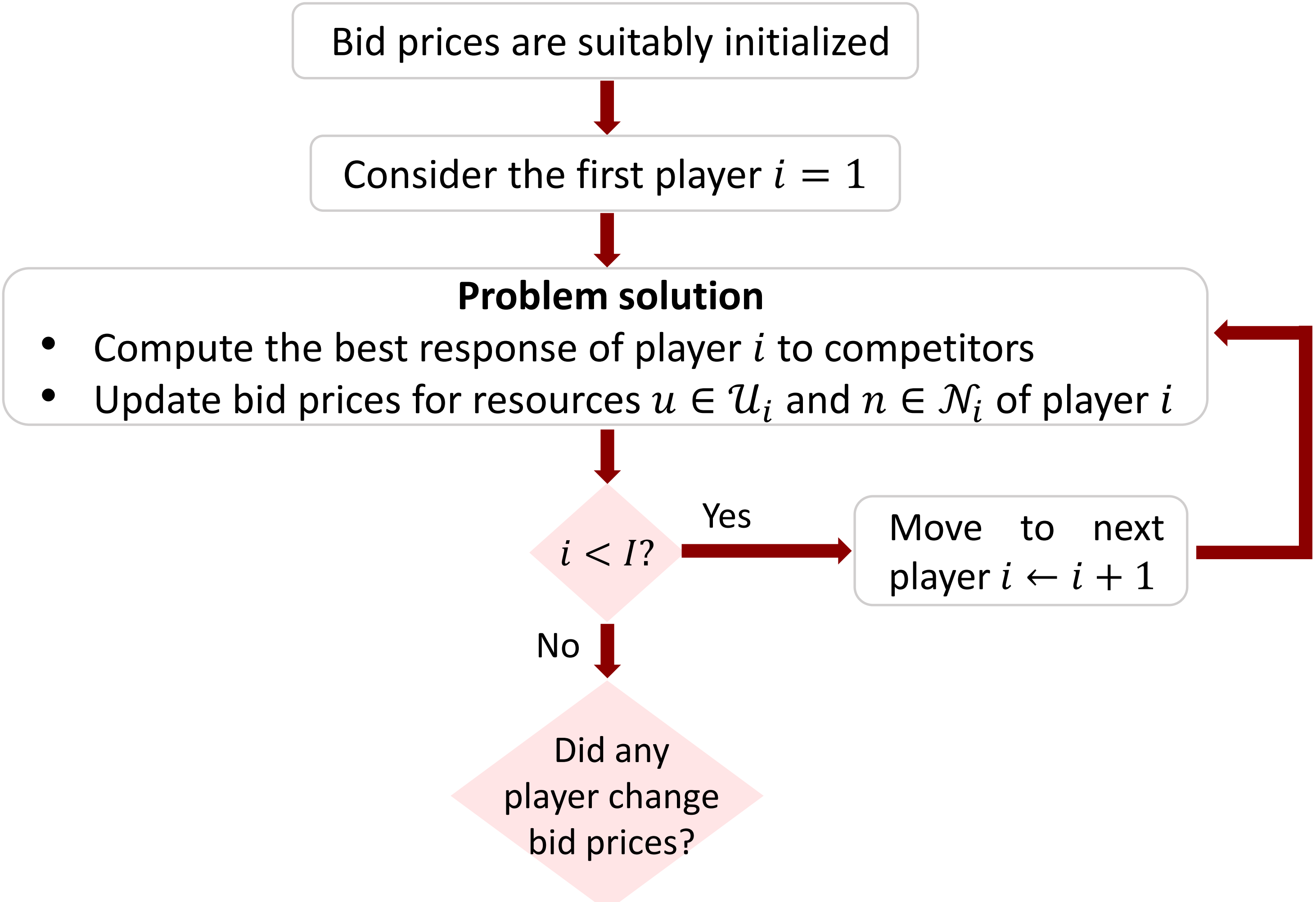
↓

$i < I$?

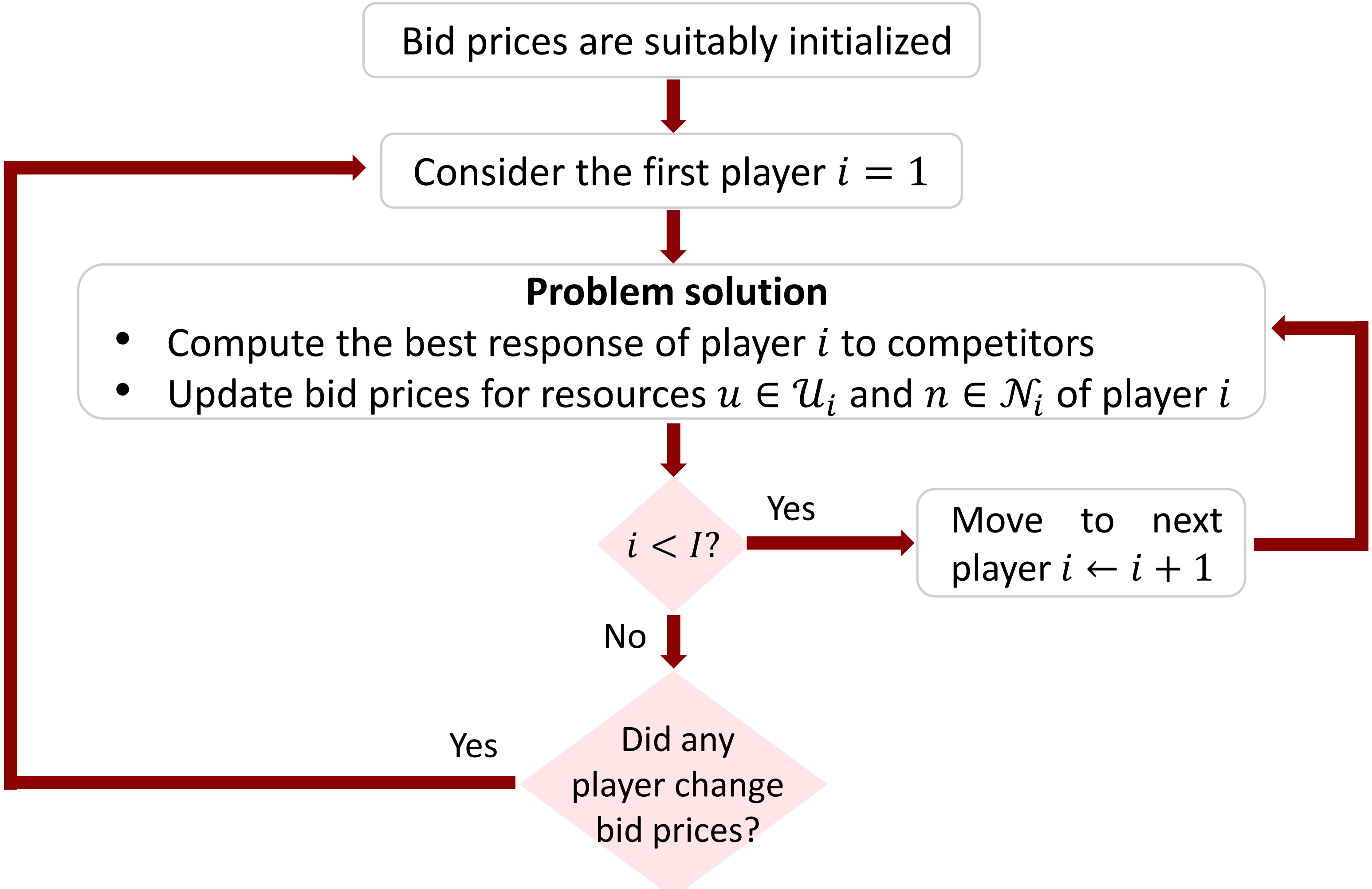
Finding a Nash Equilibrium



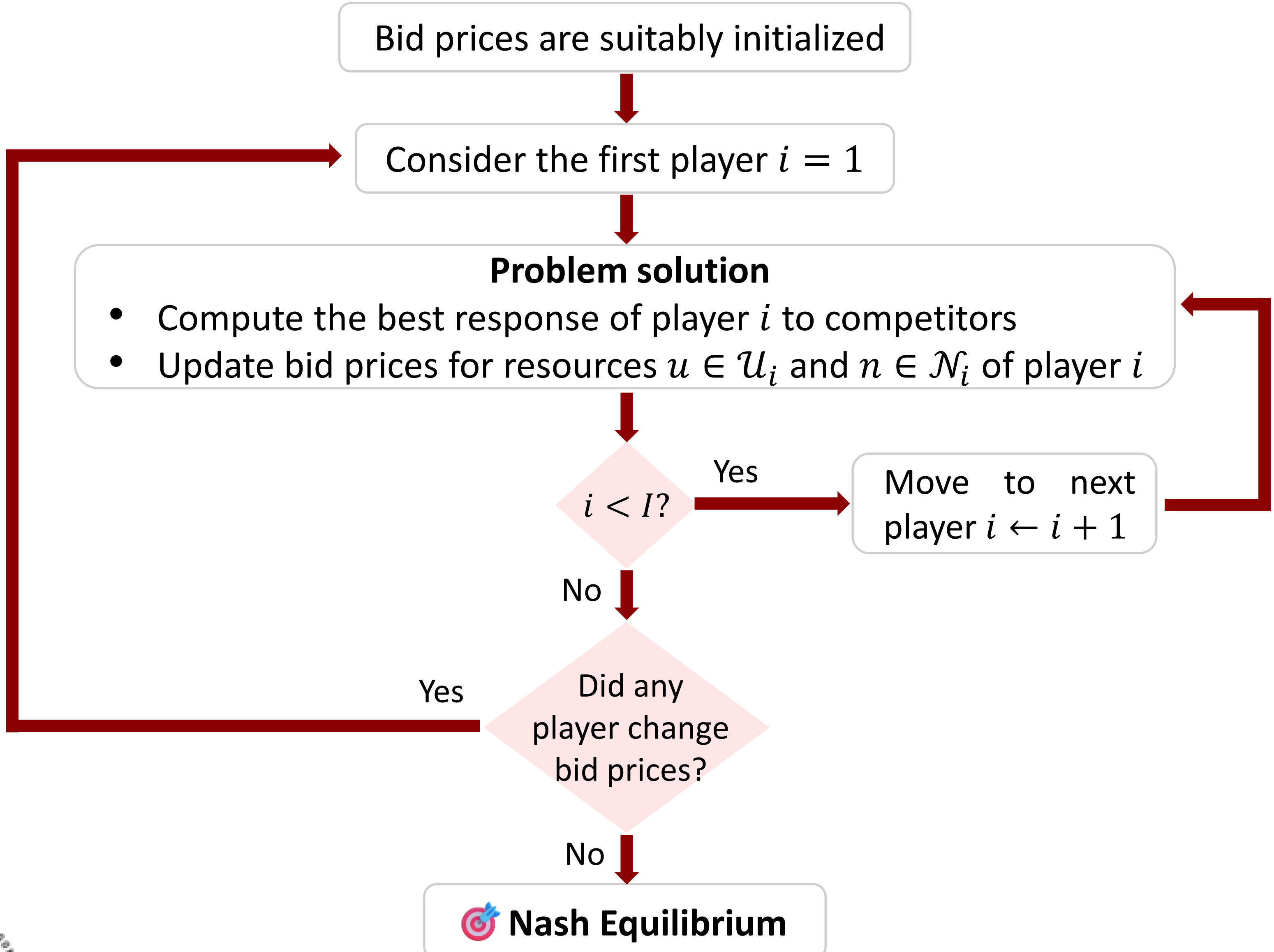
Finding a Nash Equilibrium



Finding a Nash Equilibrium



Finding a Nash Equilibrium

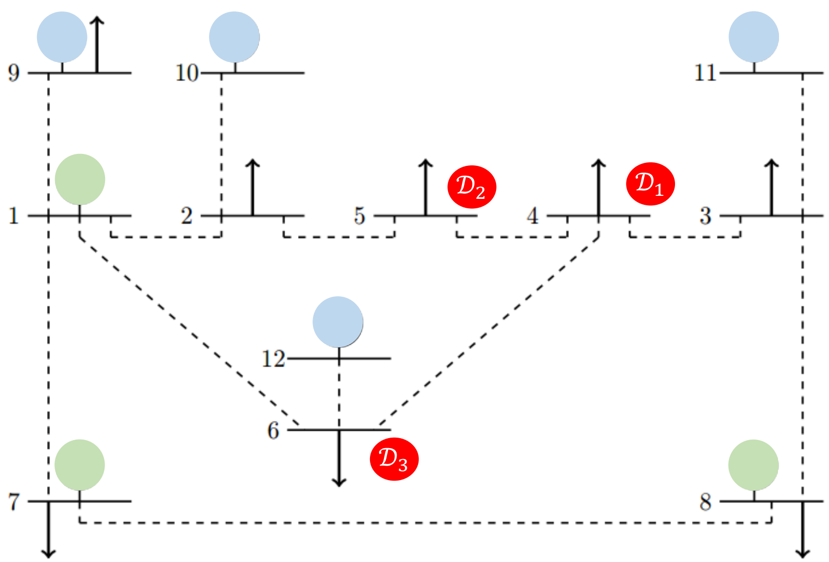


Numerical Results

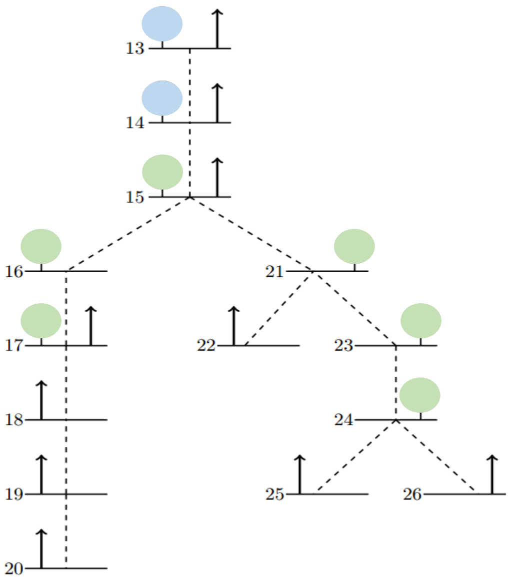
Case study

- A **CIGRE** transmission network connected to three distribution networks.

Transmission System



Distribution System $\mathcal{D}_k$



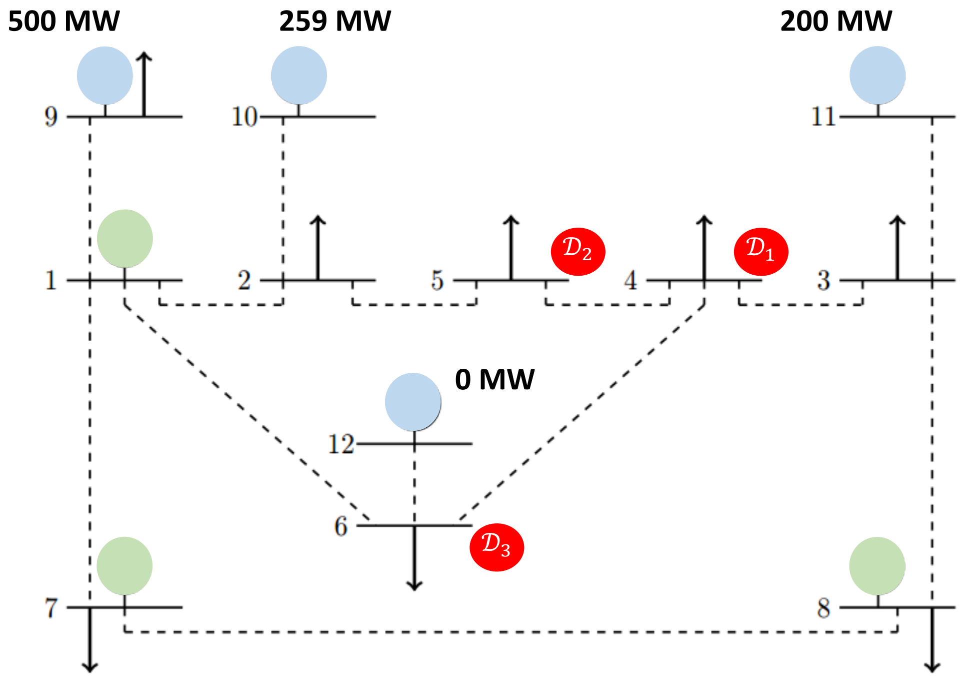
Imbalance Scenarios

- 7 scenarios
- Forecast error on load and RES: {+0.25 ; +0.15 ; +0.05 ; 0 ; –0.05 ; –0.15 ; –0.25}.

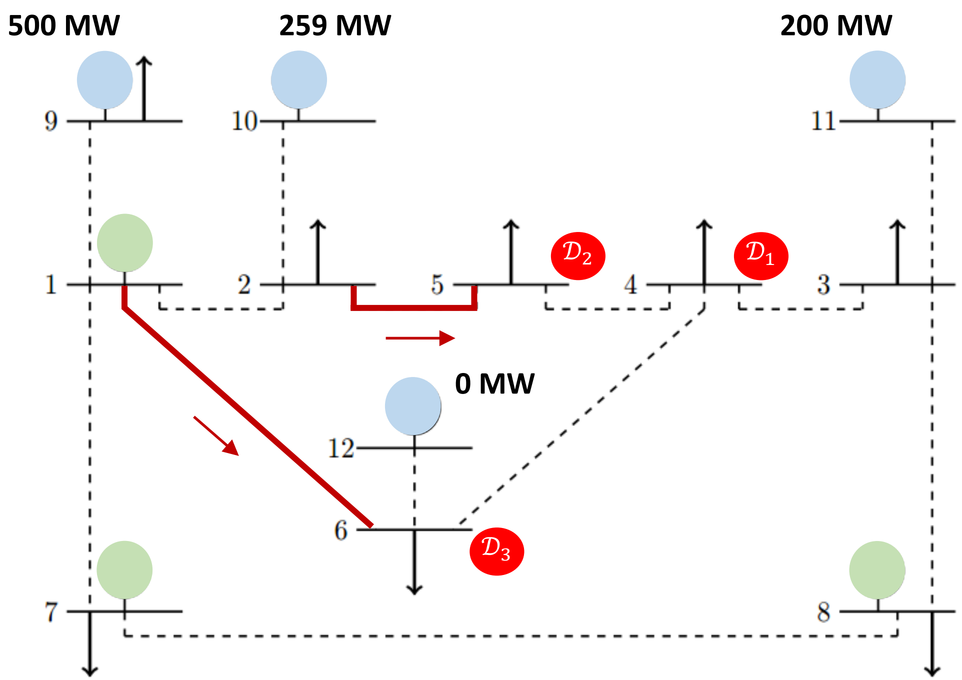
Bidding Strategies

- 9 market players
- 5 price strategies on the DAM
- 3 price strategies for upward and downward regulation on the ASM.

Optimal dispatching

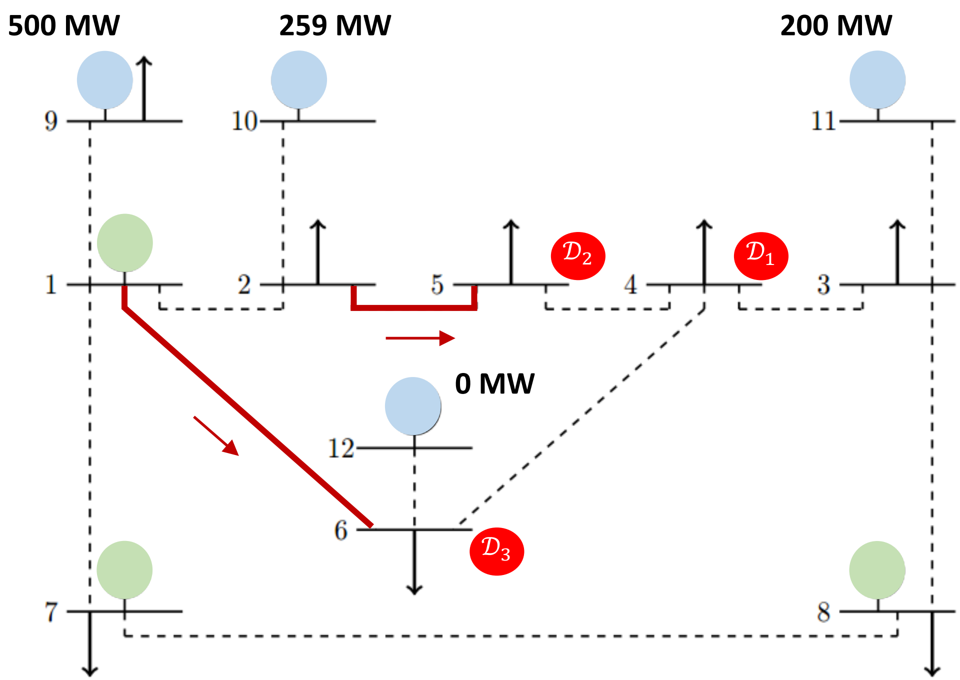


Optimal dispatching



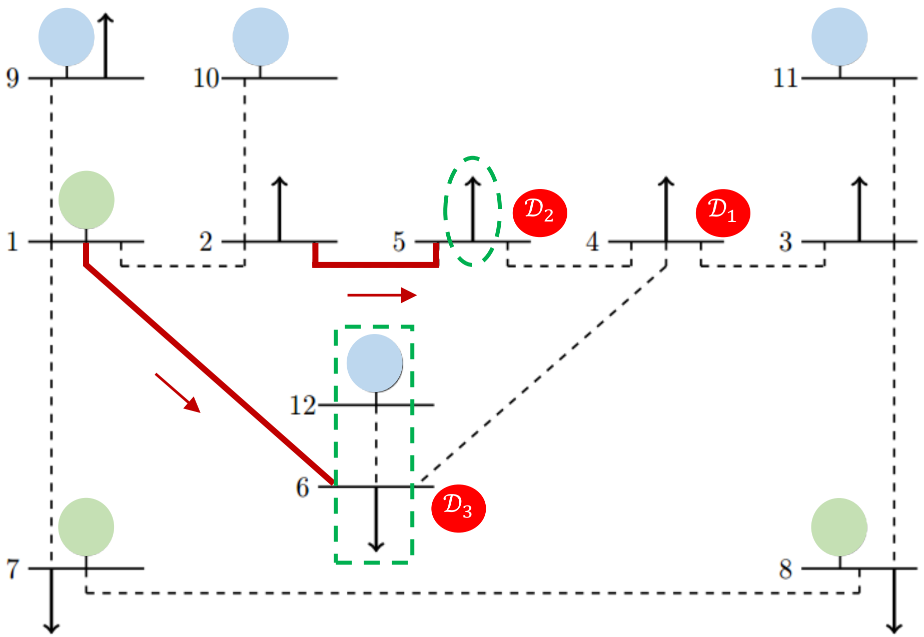
- DA plan **violates** transmission line limits.

Optimal dispatching



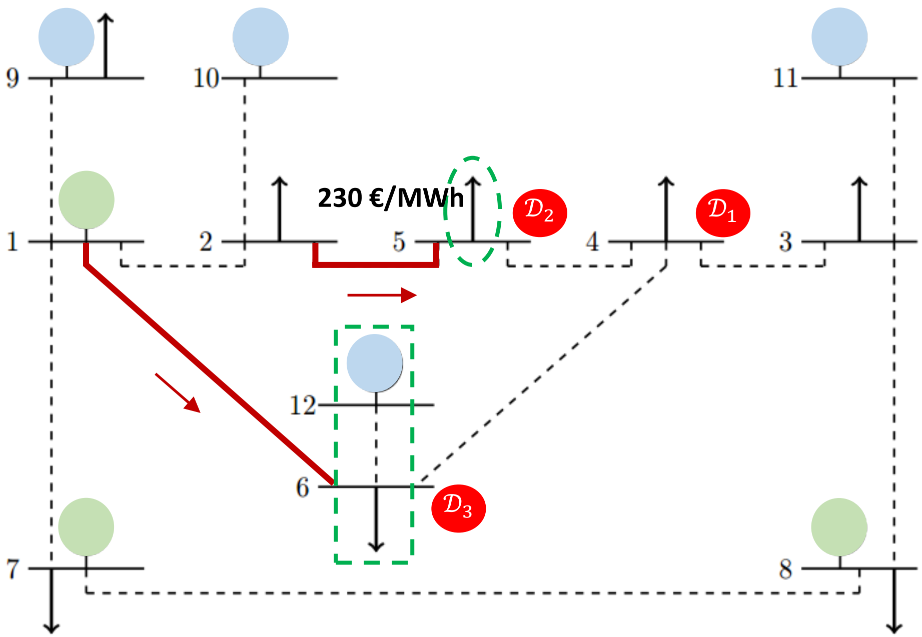
- DA plan **violates** transmission line limits.
- Congestion enables **market power exercise**.

Optimal dispatching



- DA plan **violates** transmission line limits.
- Congestion enables **market power exercise**.
- Critical buses:
  - **5**
  - 6 / 12

Optimal dispatching



- DA plan **violates** transmission line limits.
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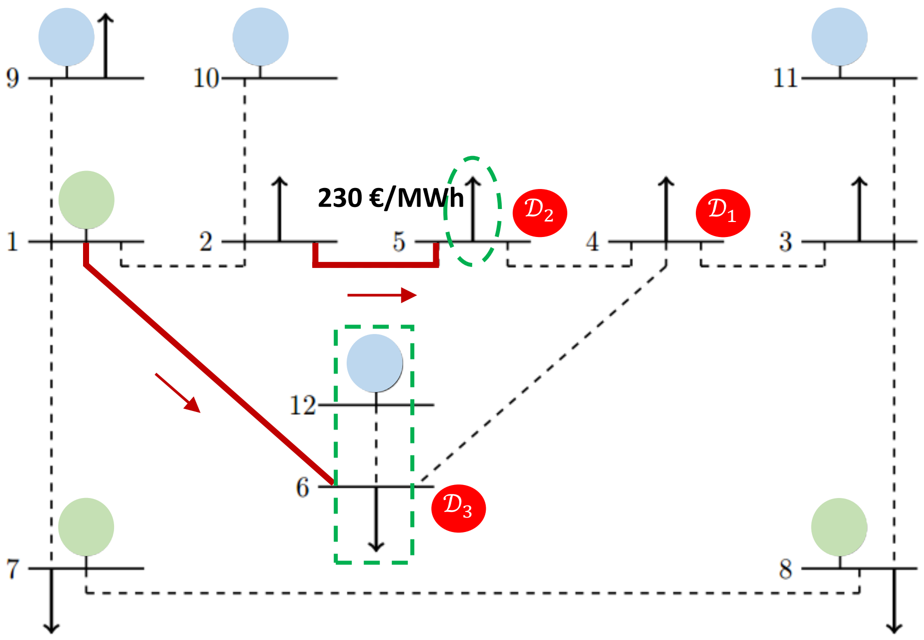
Optimal dispatching



- DA plan **violates** transmission line limits.
- Congestion enables **market power exercise**.
- Critical buses:
  - **5**
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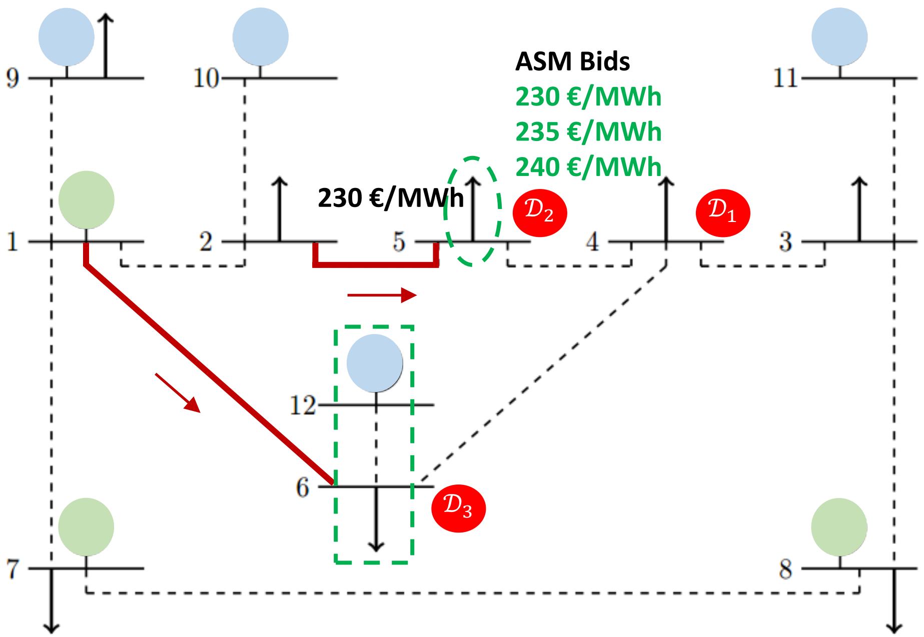
- Different ASM configurations lead to **different strategic behaviors.**

Optimal dispatching



- DA plan **violates** transmission line limits.
- Congestion enables **market power exercise**.
- Critical buses:
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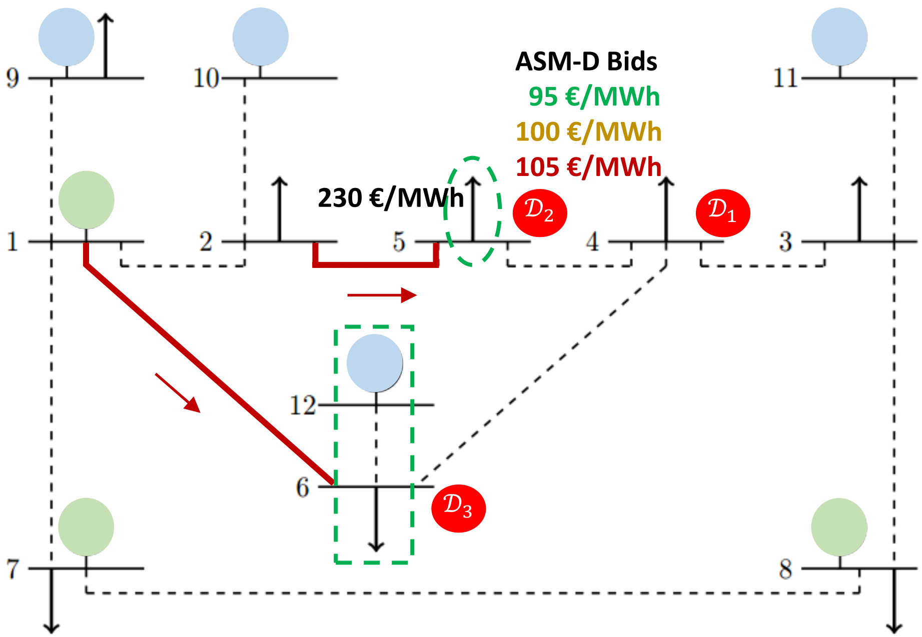
- Different ASM configurations lead to **different strategic behaviors.**

Scheme A

- Resources in distribution network 2 submit maximum-priced bids in the common ASM.
- All bids are accepted to relieve congestion of line 2-5.

Optimal dispatching

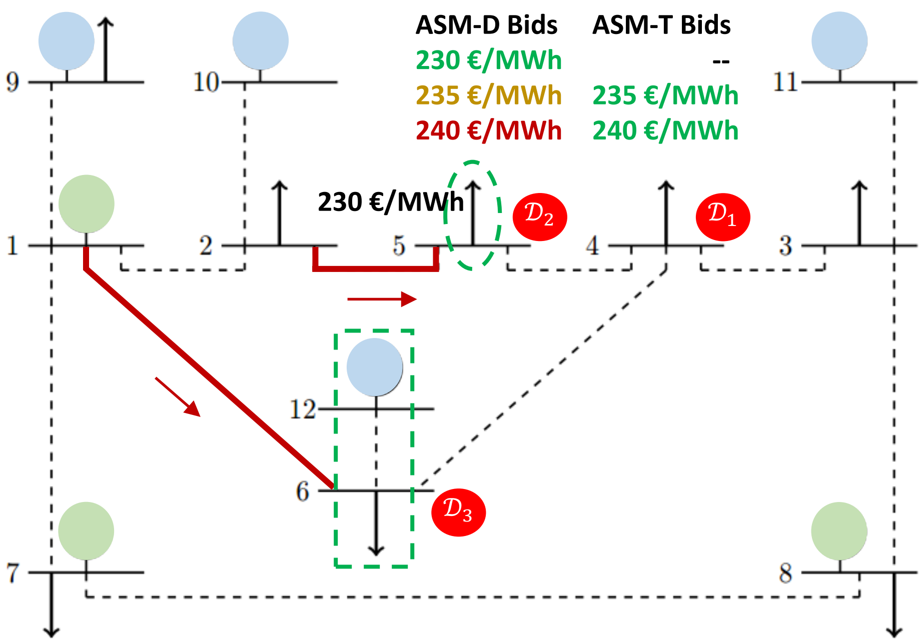


- DA plan **violates** transmission line limits.
- Congestion enables **market power exercise**.
- Critical buses:
  - **5**
  - **6 / 12**
- Different ASM configurations lead to **different strategic behaviors.**

Scheme B

- Distribution resources select the minimum-priced option to be dispatched on the local ASM.
- Only two bids are accepted.

Optimal dispatching



- DA plan **violates** transmission line limits.
- Congestion enables **market power exercise**.
- Critical buses:
  - **5**
  - **6 / 12**
- Different ASM configurations lead to **different strategic behaviors.**

Scheme C

- Distribution resources select the maximum-priced option.
- Only two bids are accepted on ASM-D.
- Resources not fully dispatched on ASM-D are fully dispatched on ASM-T.

Conclusions

- Numerical tests show **scheme B** is the most efficient, since local ASM are not affected by the high prices formed in the transmission ASM under congestion.

Scheme	A	B	C
Expected Cost (€)	6717.77	6390.01	7863.51

Micheli, G., Vespucci, M.T., Migliavacca, G. & Siface, D. (2025). Equilibrium models to analyse the impactof different coordination schemes between Transmission System Operator and Distribution System Operators on market power in sequentially-cleared energy and ancillary services markets underload and renewable generation uncertainty. *Under Review*. Preprint available at https://doi.org/10.48550/arXiv.2505.15168.

Thanks for your attention

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