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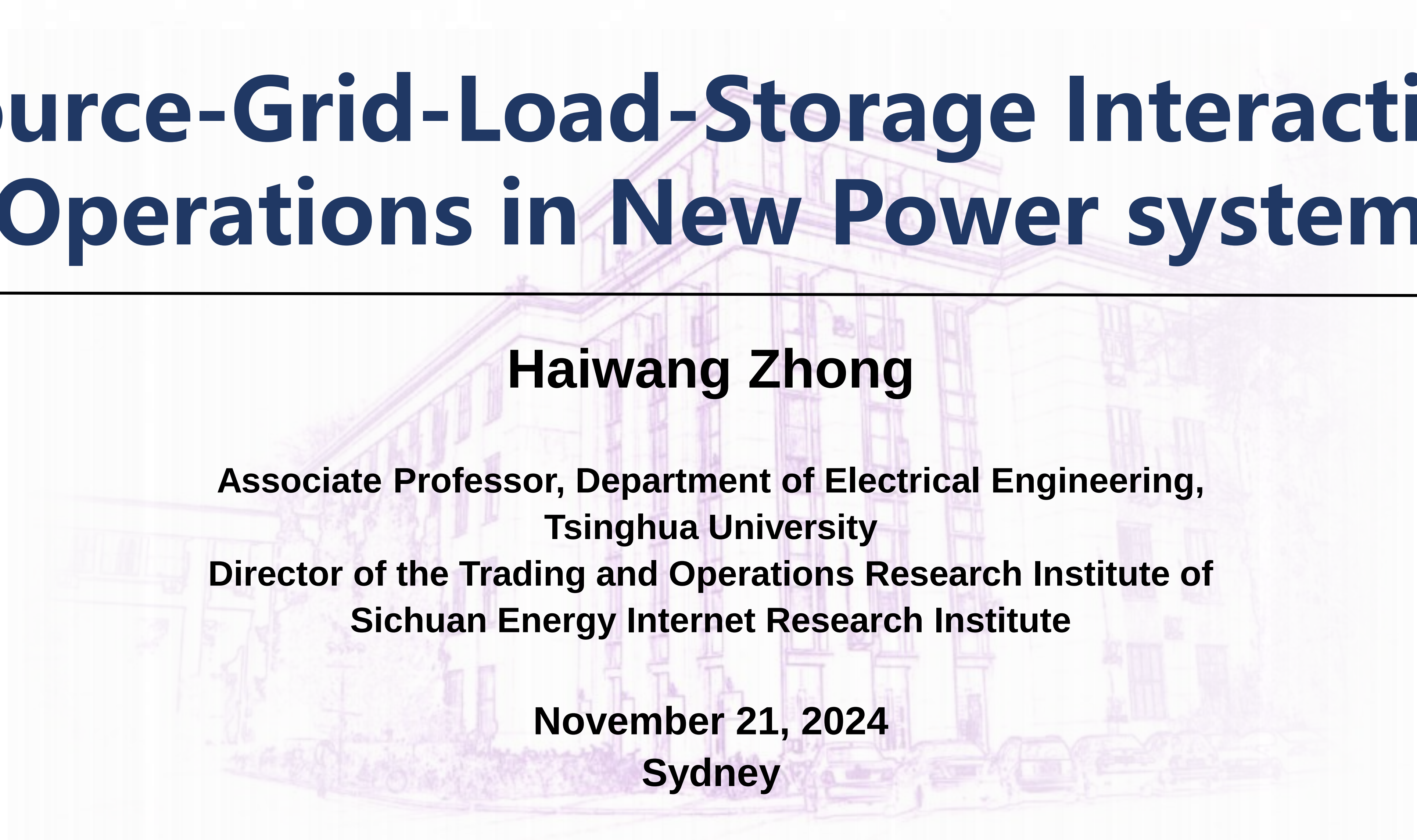
Department of Electrical Engineering, Tsinghua University

智慧能源课题组
Energy Intelligence Laboratory



Source-Grid-Load-Storage Interactive Operations in New Power system

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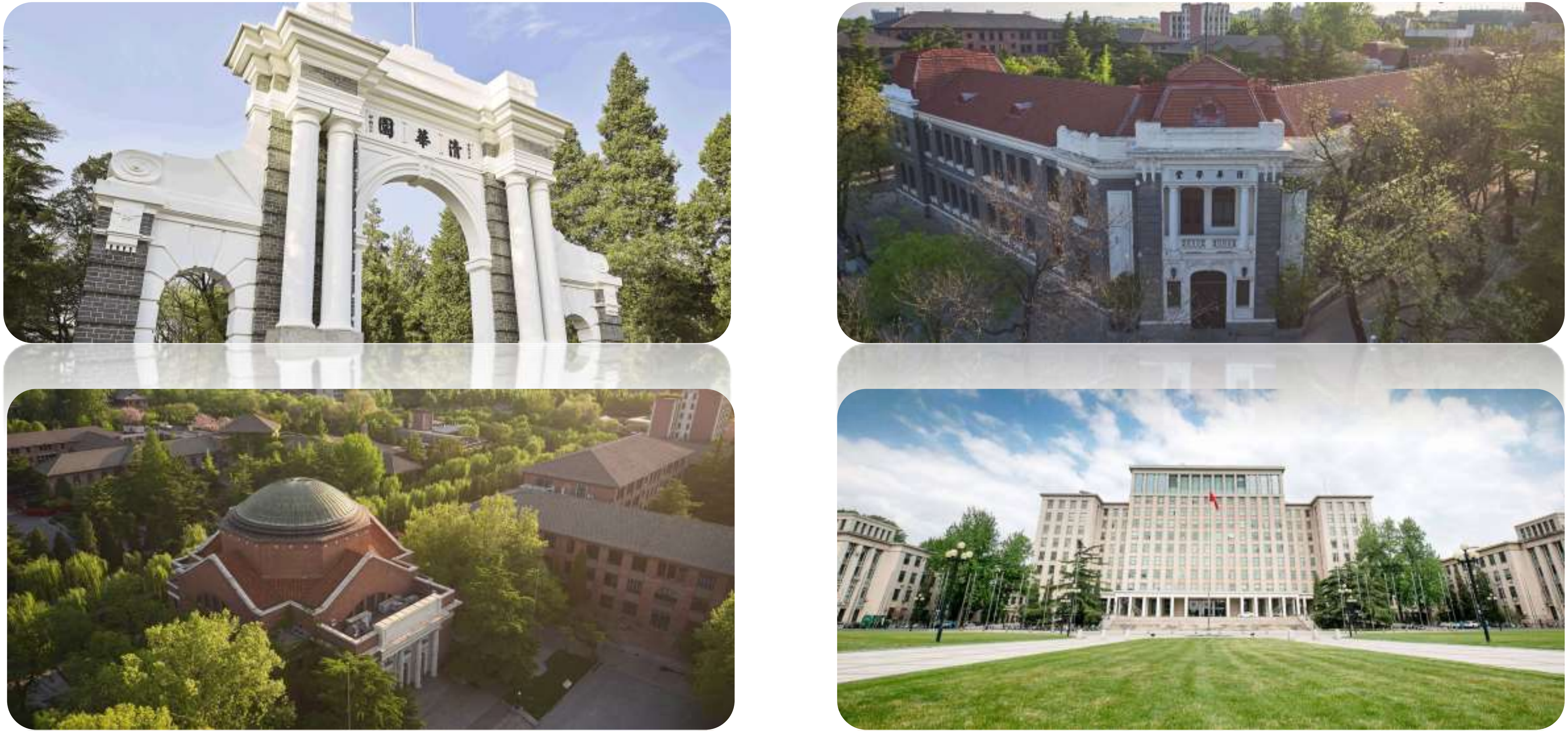
Sichuan Energy Internet Research Institute

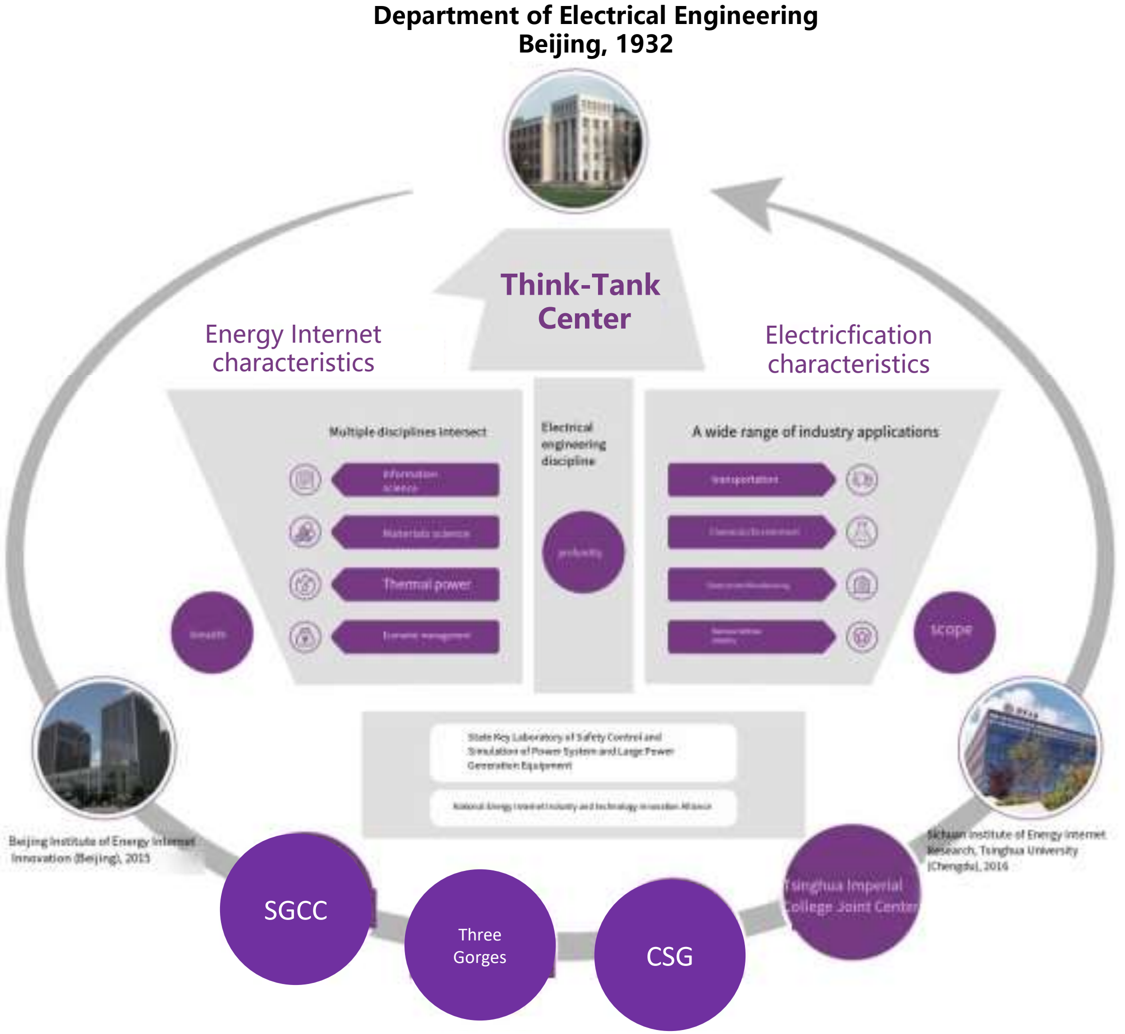
November 21, 2024
Sydney

Tsinghua University



Department of Electrical Engineering

The organizational structure of "one department and two institutes" & the discipline system of "one axis and two wings"



Collaboration between Tsinghua and UNSW

☐ UNSW-Tsinghua Collaborative Research Program

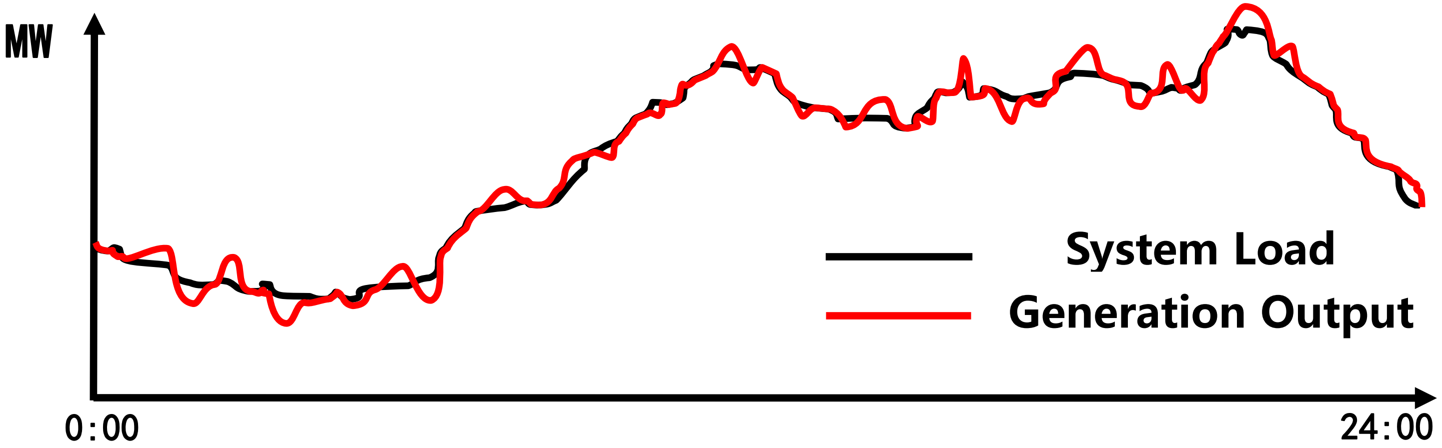
Virtual Power Plant with Electric Vehicles for Decarbonisation: Understanding the Design and Operation Mechanisms in Australia and China.

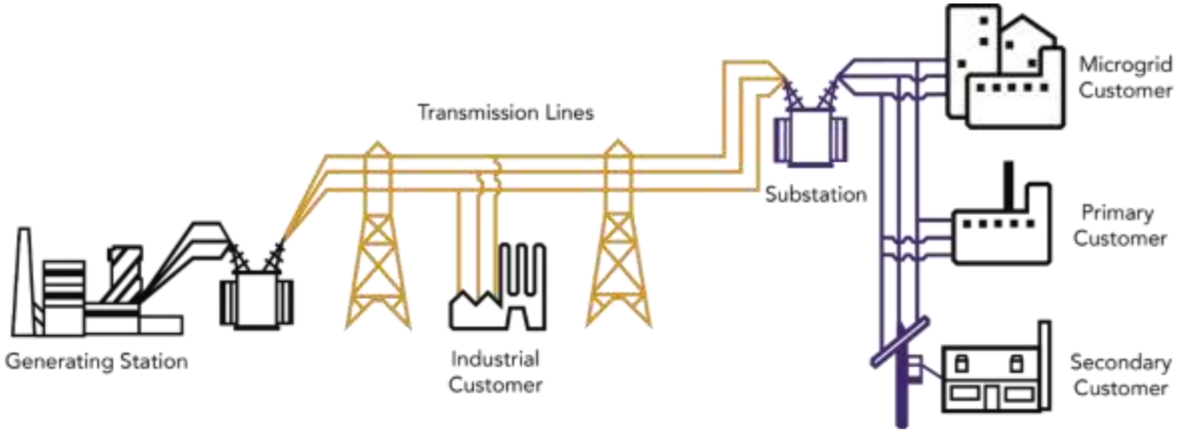
Fair and Efficient Profit Allocation for Collaborative Operation of Distributed Renewable Energy Operators and Electric Vehicle Charging Stations

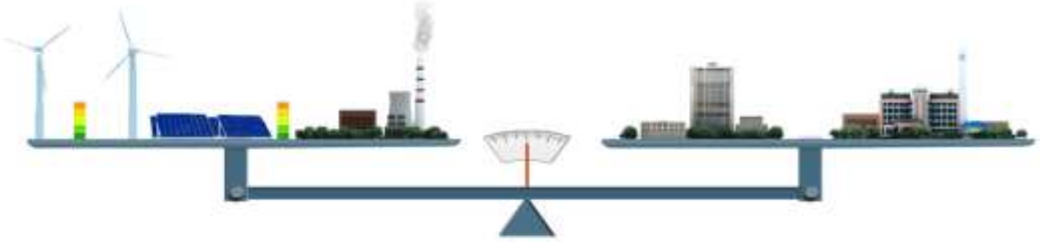
Contents

Conventional Operations

- **The power system maintains the instantaneous power balance via dispatching conventional generating units to follow the load.**



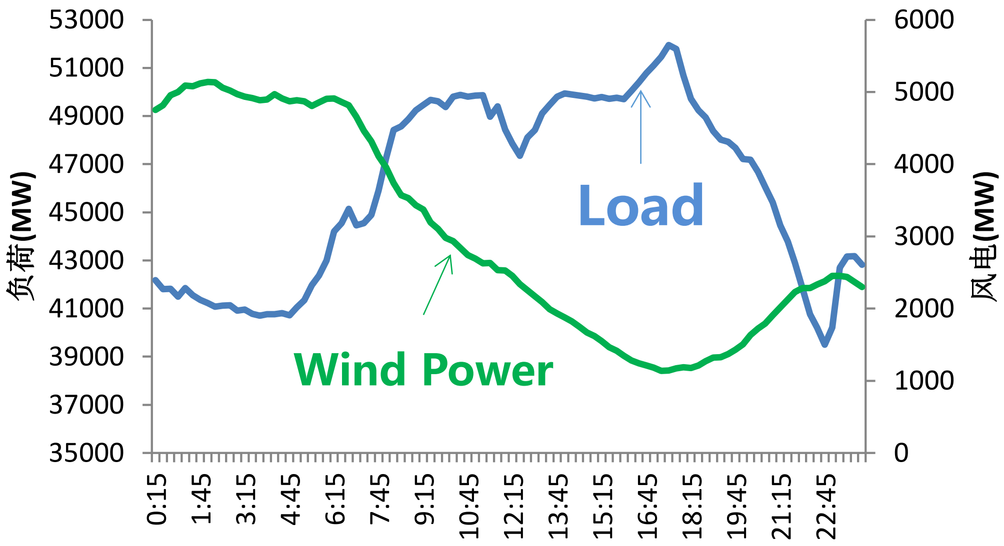


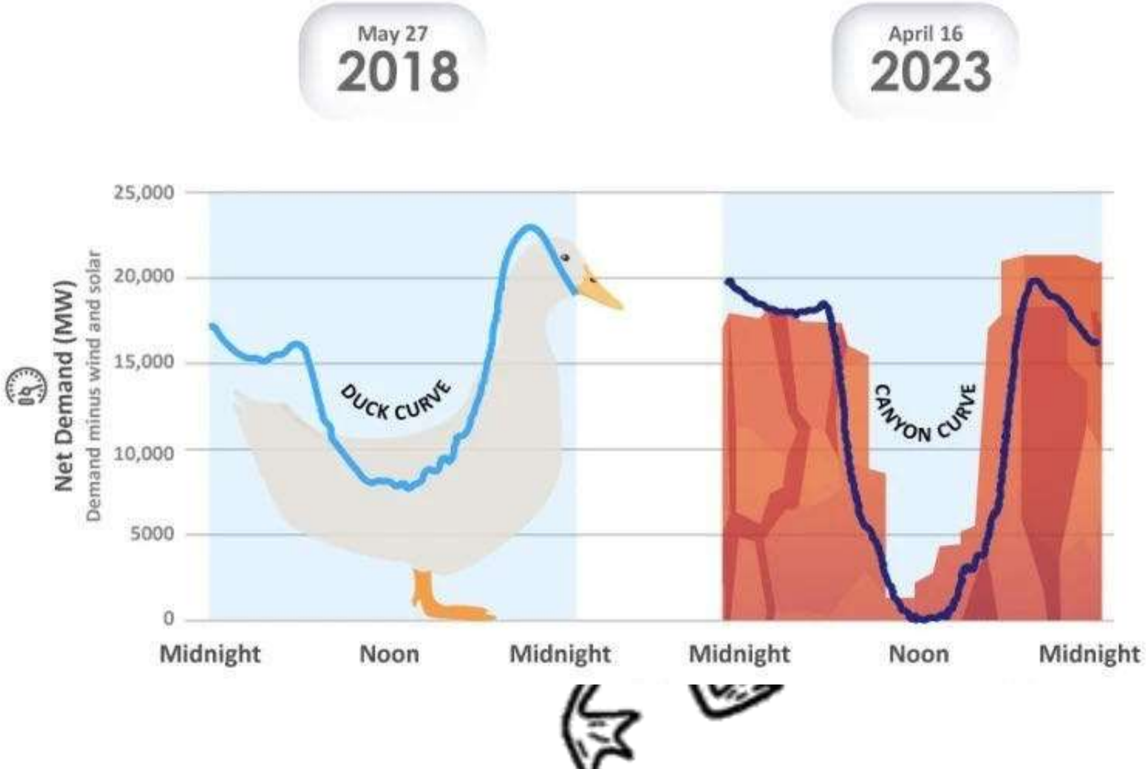


Renewable Energy

- Wind power is negative related with the load profile, the increase of PV will cause the Duck Curve (or Canyon Curve), and thermal units need to shut down during valley load periods.
- With the development of renewable energy, the conventional operation mode is unable to handle the challenges. There is an urgent need to improve the existing operation mode.

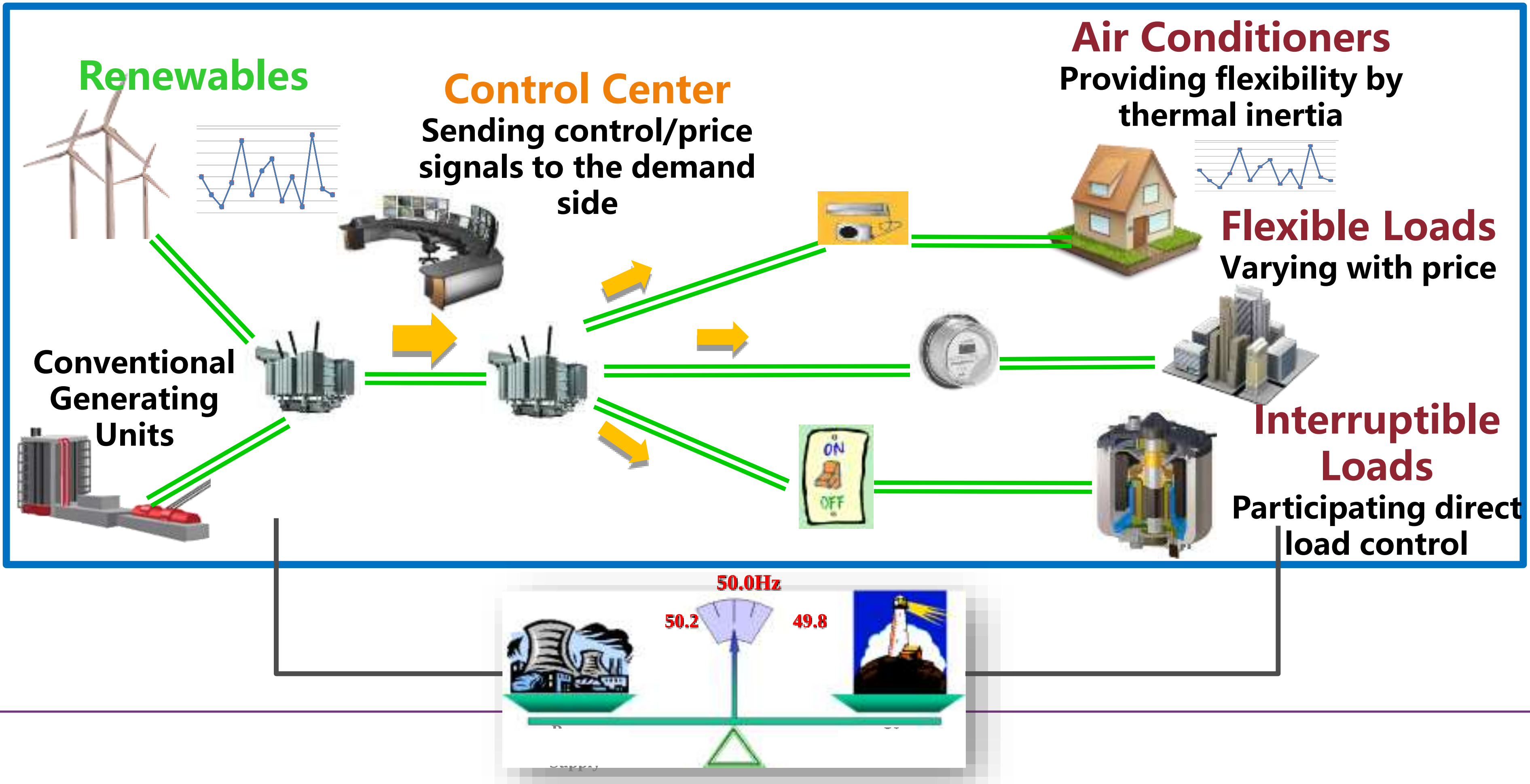
Negative Related with the Load Profile





Toward Interactive Operations

- There are a lot of flexible resources on the demand side, such as air conditioners, interruptible loads, centralized/distributed energy storage, and etc.
- Utilize the flexibility of demand-side resources and move towards source-grid-load-storage interactive operations.



Renewables

Conventional Generating Units

Control Center
Sending control/price signals to the demand side

Air Conditioners
Providing flexibility by thermal inertia

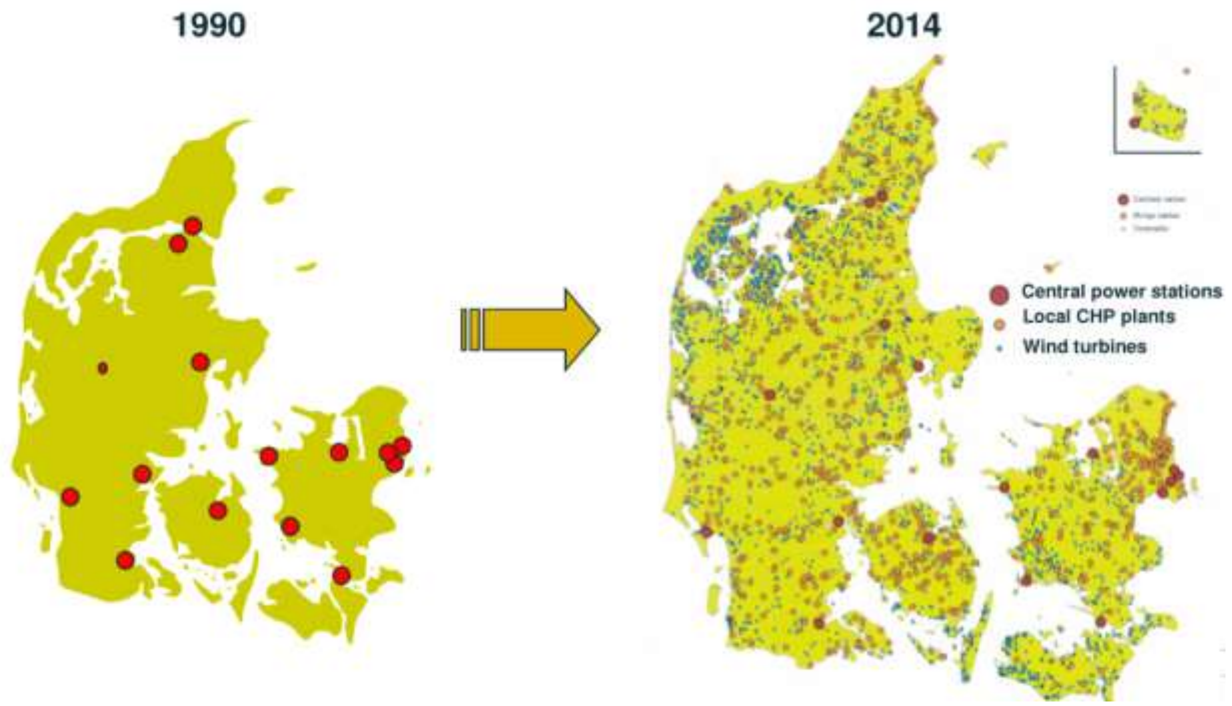
Flexible Loads
Varying with price

Interruptible Loads
Participating direct load control

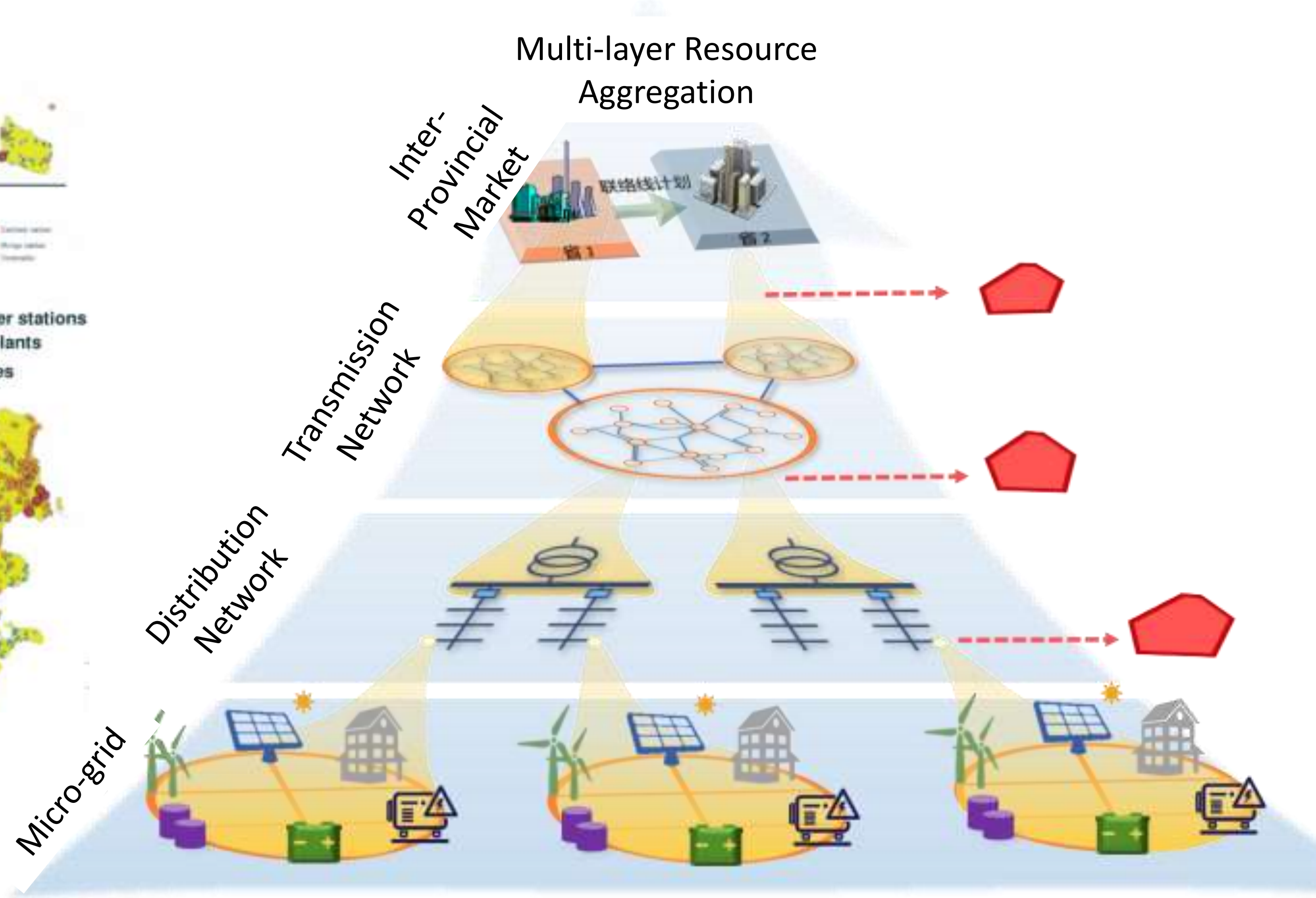
Contents

Aggregation Needed

- ☐ **Multi-layer aggregation**
- ☐ **Coordinative optimization**



Resource: Energinet.dk



Tan Z, **Zhong H**, Xia Q, et al. Non-Iterative Multi-Area Coordinated Dispatch via Condensed System Representation[J]. IEEE Transactions on Power Systems, 2020, 36(2): 1594-1604.

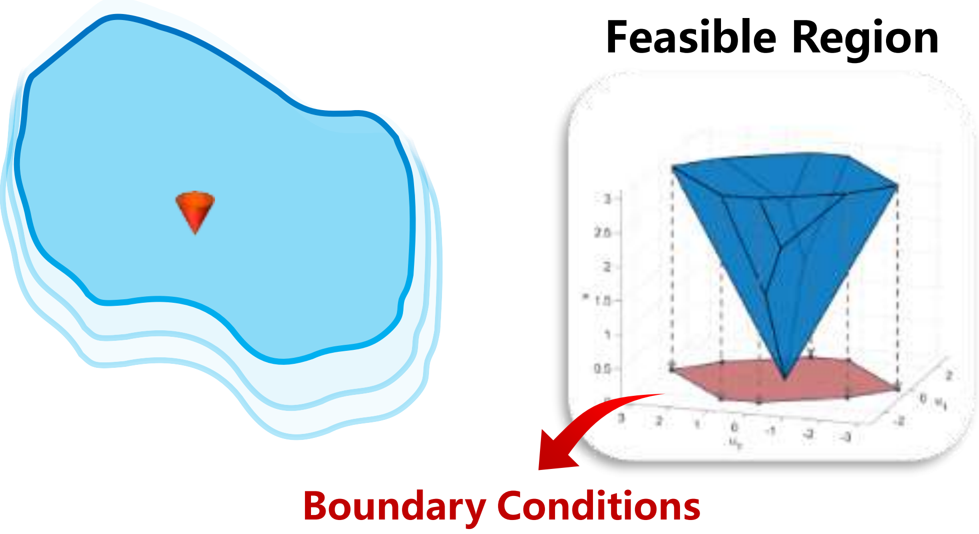
Feasible Region Projection

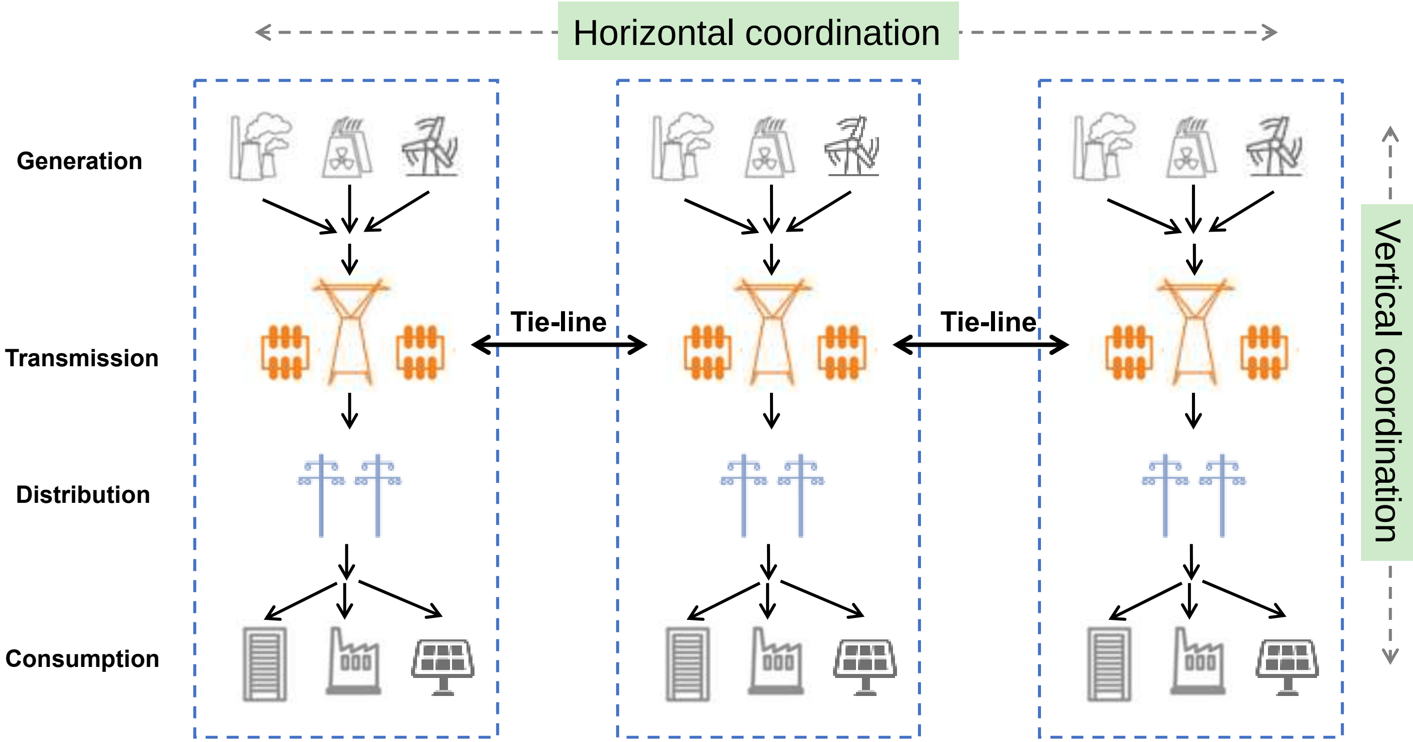
- □ **Multi-layer aggregation** and **coordinative optimization** of resources at multiple voltage levels based on **feasible region projection**

微信文章：基于可行域投影的电力系统分层分区协调优化

微信文章：基于等效投影的电力系统非迭代式协调优化调度

Constructing Feasible Region

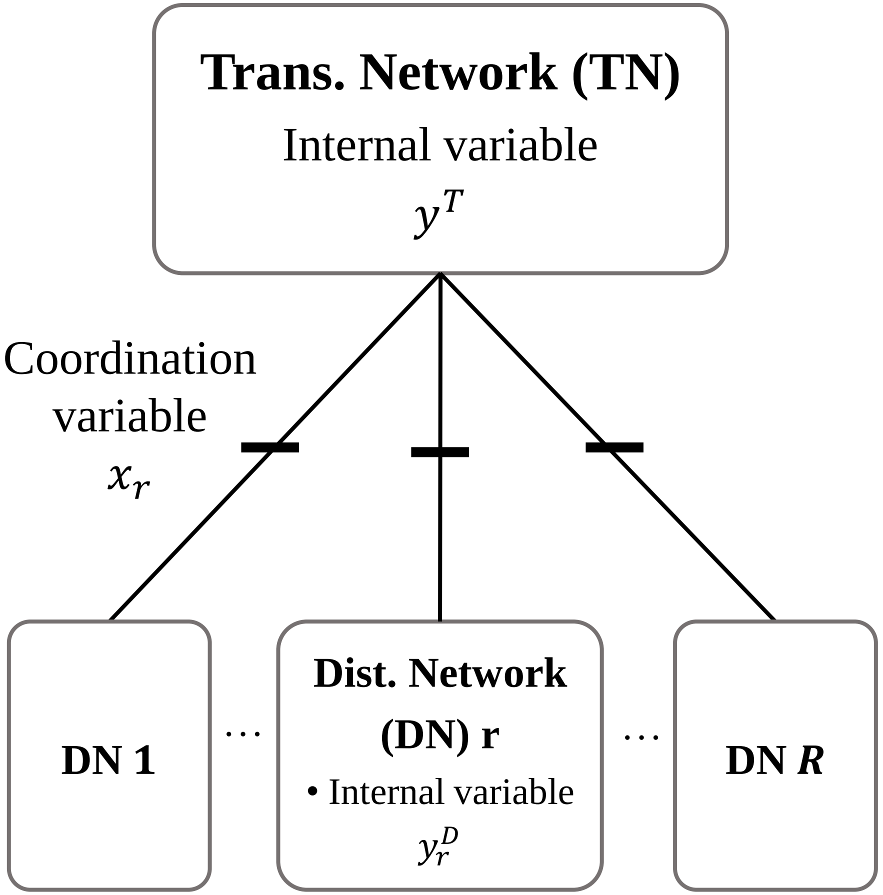




Tan Z, **Zhong H**, Xia Q, et al. Non-Iterative Multi-Area Coordinated Dispatch via Condensed System Representation[J]. IEEE Transactions on Power Systems, 2020, 36(2): 1594-1604.

Cheng T, Tan Z, **Zhong H**. Exploiting Flexibility of Integrated Demand Response to Alleviate Power Flow Violation during Line Tripping Contingency[J]. MPCE. 2022.

Problem Formulation



Trans. Network (TN)

Internal variable

y^T

Coordination variable

x_r

DN 1

…

Dist. Network (DN) r

- Internal variable

y_r^D

…

DN *R*

Joint Optimization

$$\min_{x,y} \sum_r C_r\left(y_r\right)$$

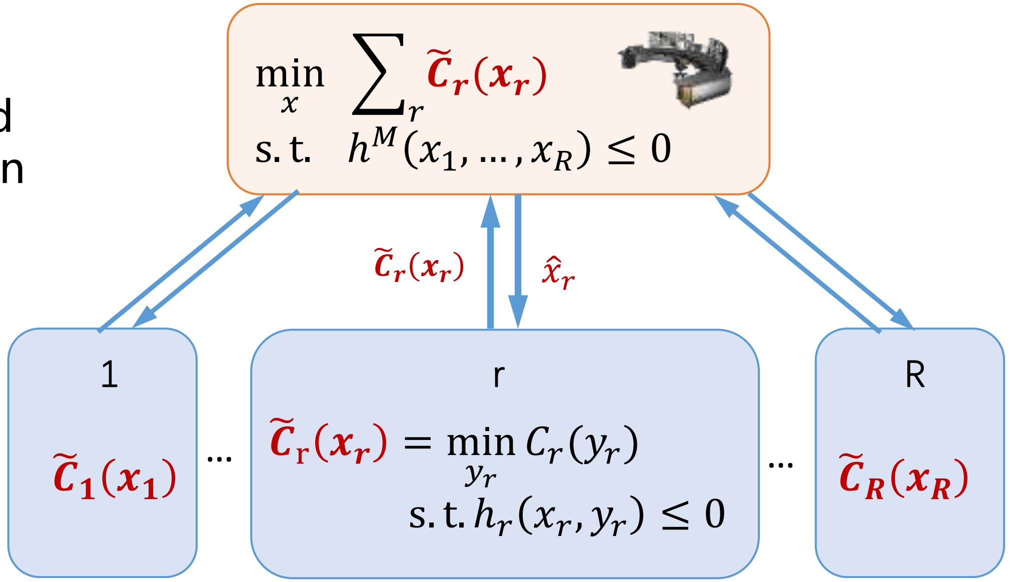
$$s.t.\ \ h^M(x_1,\dots,x_r,\dots,x_R) \le 0$$

Coupling constrains

$$h_r(x_r,y_r) \le 0, r = 1,\dots,N$$

Subsystem constraints

Primal Decomposition



Coordinated Optimization

$$\min_x \sum_r \tilde{C}_r(x_r)$$

$$\mathrm{s.t.}\ \ h^M(x_1,\dots,x_R) \le 0$$

$\tilde{C}_r(x_r)$

$\hat{x}_r$

1

$\tilde{C}_1(x_1)$

…

r

$$\tilde{C}_r(x_r) = \min_{y_r} C_r(y_r)$$

$$\mathrm{s.t.}\, h_r(x_r,y_r) \le 0$$

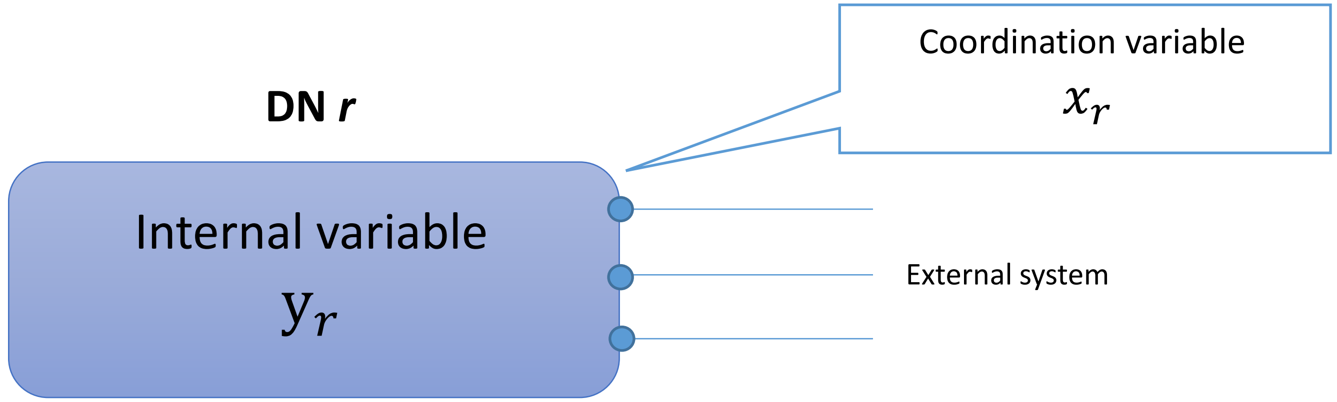
…

R

$\tilde{C}_R(x_R)$

Tan Z, Yan Z, **Zhong H,** et al. Non-Iterative Solution for Coordinated Optimal Dispatch Via Equivalent Projection—Part I: Theory[J]. IEEE Transactions on Power Systems, 2023.

Equivalent Projection



DN *r*

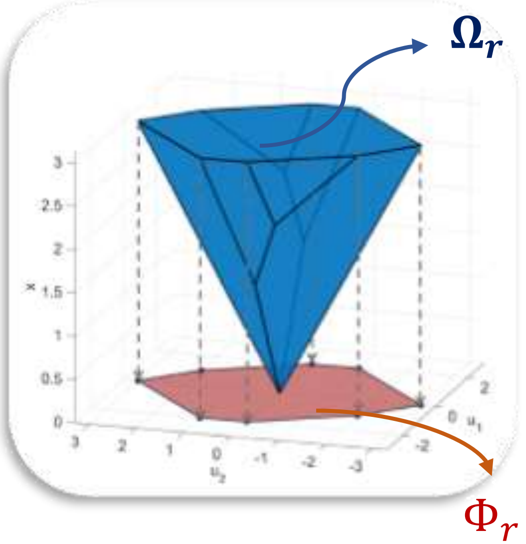
Coordination variable

x_r

Internal variable

y_r

External system



- **Operating feasible region** of DN *r*

$$\Omega_\mathrm{r} = \left\{ (x_r, \pi_r, y_r) \in R^{N_x+1} \times R^{N_y} \middle| \begin{matrix} \bar{\pi}_r \geq \pi_r \geq C_r\,(y_r) \\ h_r(x_r, y_r) \leq 0 \end{matrix} \right\}$$

→ Epigraph of cost function

→ Technical operation constraints

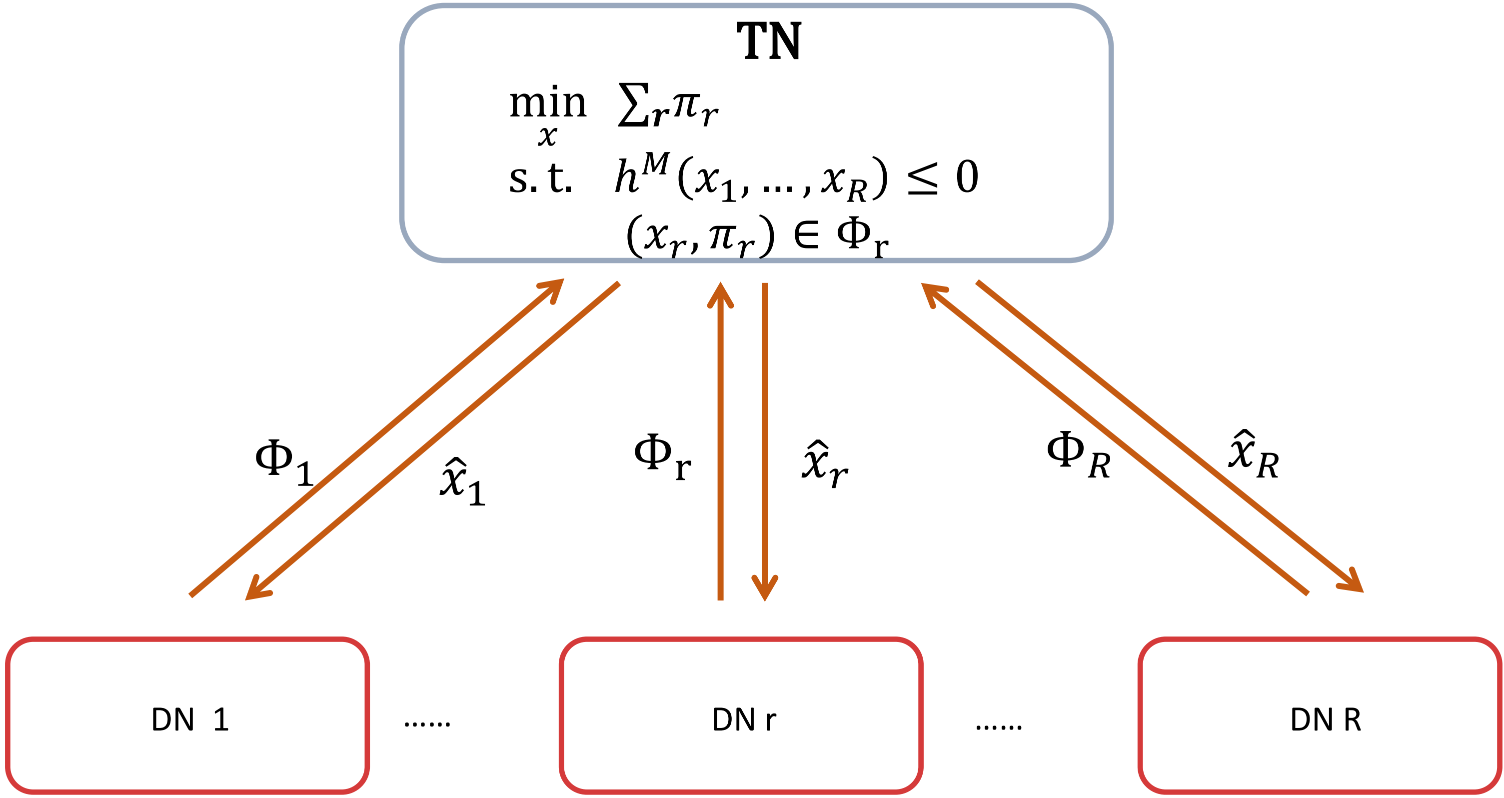
- **Equivalent projection: depicts economic and technical characteristics of DN at coordination boundary**

$$\Phi_r = proj(\Omega_\mathrm{r}) \triangleq \{(x_r, \pi_r) \in R^{N_x+1} \,|\, \exists y_r, \mathrm{s.t.}, (x_r, \pi_r, y_r) \in \Omega_\mathrm{r}\}$$

Tan Z, Yan Z, **Zhong H**, et al. Non-Iterative Solution for Coordinated Optimal Dispatch Via Equivalent Projection—Part I: Theory[J]. IEEE Transactions on Power Systems, 2023.

Non-Iterative Coordination

- **Stage 1:** Each DSO calculates its equivalent projection Φ_{r}.
- **Stage 2:** TSO optimally decides $\hat{x}_r$ with Φ_{r} as constraints.
- **Stage 3:** DSO optimally schedules the local system with $\hat{x}_r$ as boundary conditions.



TN

$$\begin{aligned} \min_{x} \quad & \textstyle\sum_{\boldsymbol{r}} \pi_r \\ \text{s.t.} \quad & h^M(x_1, \dots, x_R) \leq 0 \\ & (x_r, \pi_r) \in \Phi_{\mathrm{r}} \end{aligned}$$

Equivalent to the joint optimization and no iteration is required.

Tan Z, Yan Z, Zhong H, et al. Non-Iterative Solution for Coordinated Optimal Dispatch Via Equivalent Projection—Part I: Theory[J]. IEEE Transactions on Power Systems, 2023.

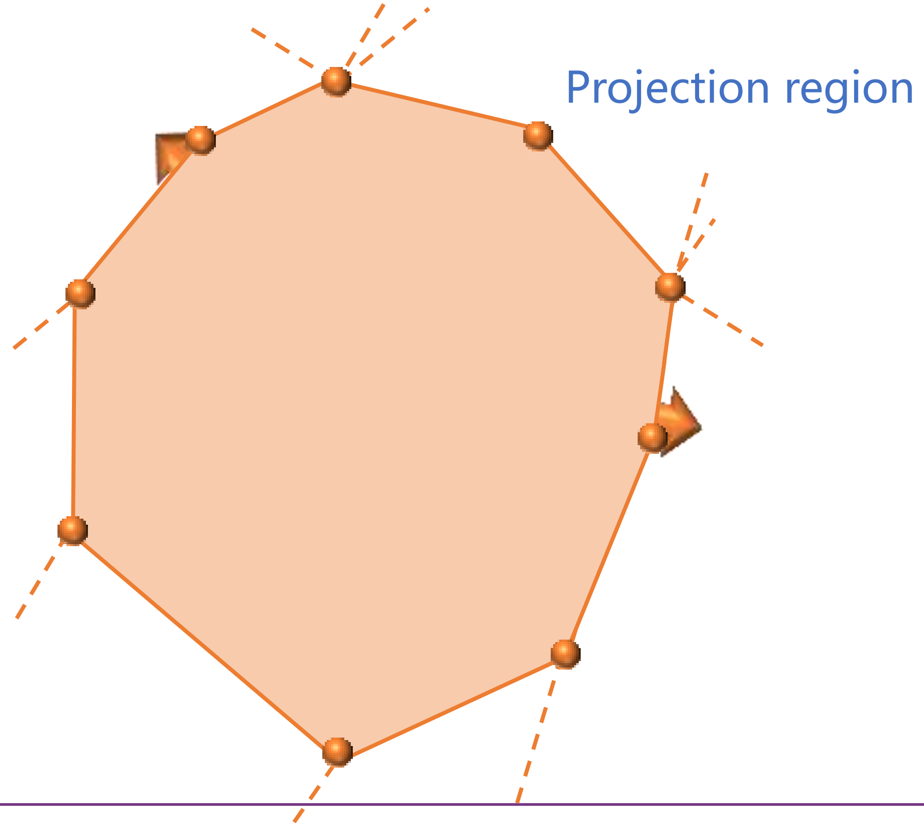
Calculation Method

Step 1：
Model linearization

Step 2：
Solve linear projection problem

Step 3：
Recovery to AC solution

- With linearization, Φ becomes a polytope

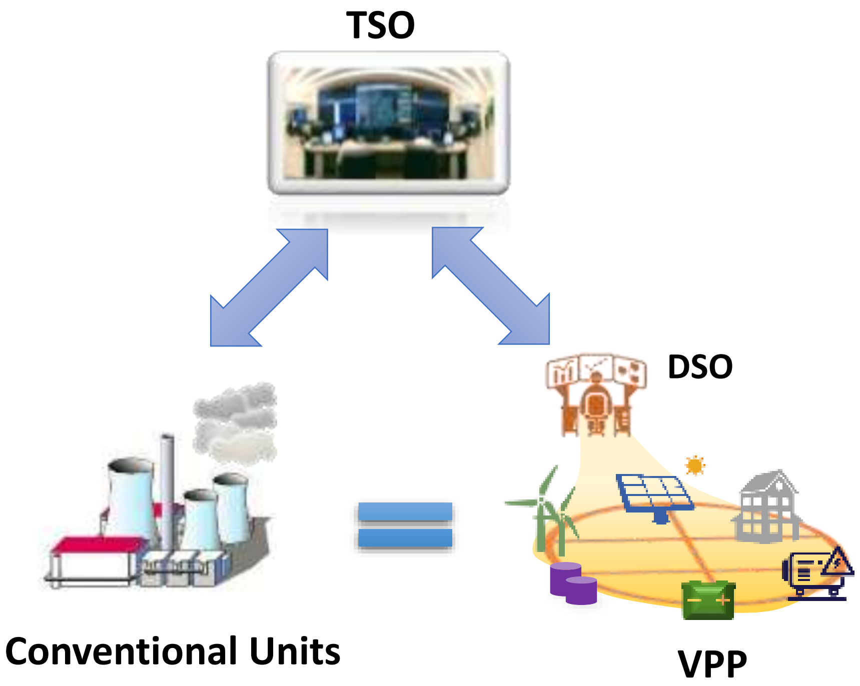


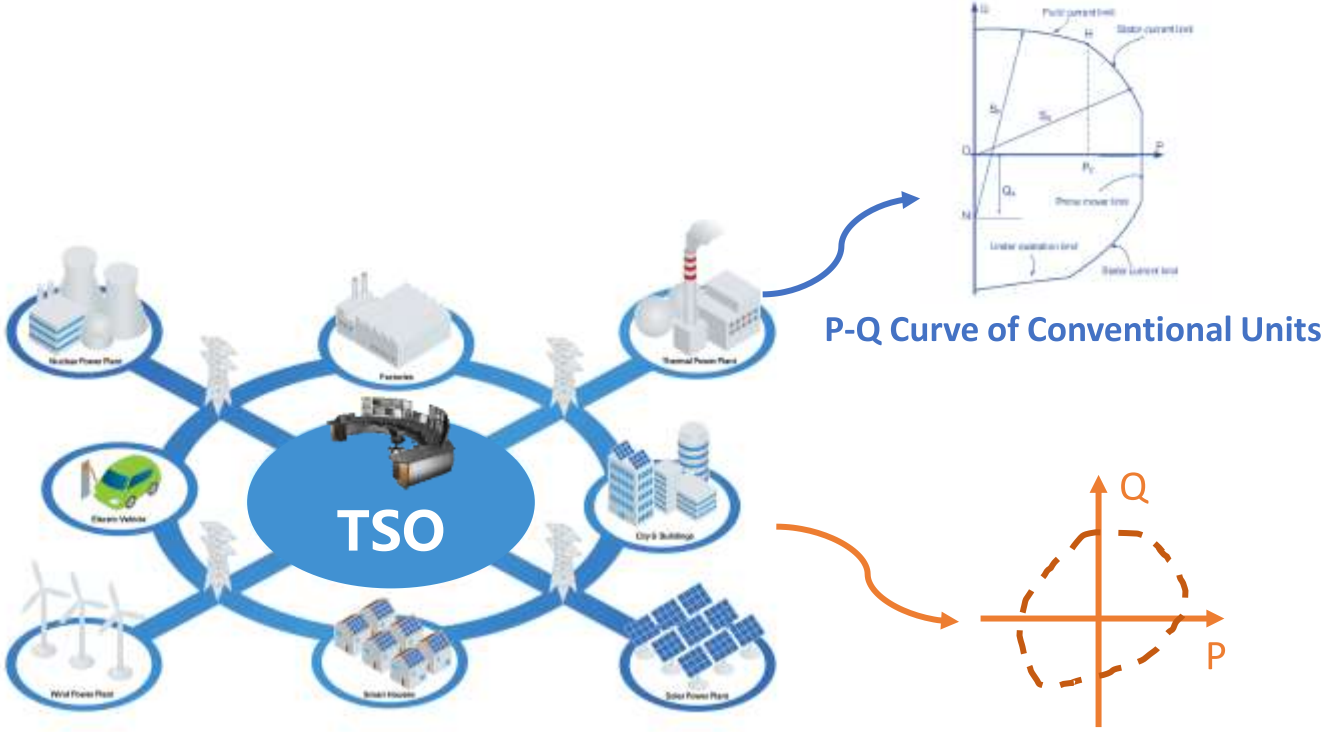
```
Algorithm 1： Progressive Vertex Enumeration
Initialize vertex set ： $\boldsymbol{V} \leftarrow \boldsymbol{V}_0$
repeat
    Convex hull of identified vertices： $P = conv(\boldsymbol{V})$
    Initialize improvement： $\boldsymbol{G} \leftarrow \emptyset$
    for $\boldsymbol{f}_k$ on $P$
        Vertex expansion： new vertex $\boldsymbol{v}_k$、 optimal value $g_k^{max}$
        if $\boldsymbol{v}_k \in R(\boldsymbol{f}_k)$ and $\Delta g_k > 0$
            Save new vertex： $\boldsymbol{V} \leftarrow \{\boldsymbol{v} \in \boldsymbol{V}, \boldsymbol{v}_k\}$
            Save improvement： $\boldsymbol{G} \leftarrow \{\Delta g \in \boldsymbol{G},\ \Delta g_k\}$
        end if
    end for
until max $\boldsymbol{G} < Tolerance$
return $\boldsymbol{V}$, $P = conv(\boldsymbol{V})$
```

Tan Z, Yan Z, Zhong H, et al. Non-Iterative Solution for Coordinated Optimal Dispatch Via Equivalent Projection—Part II: Method and Applications[J]. IEEE Transactions on Power Systems, 2023.

Application 1: Virtual Power Plant (VPP)

- Estimate the capability curve of a virtual power plant
  - A virtual power plant aggregates the economic and physical parameters of distributed resources into a standard form, improving the observability and controllability of DER as well as providing an interface for the coordination of transmission and distribution networks.
  - Estimating the capability curve of a VPP is necessary for the secure operation of distribution networks.



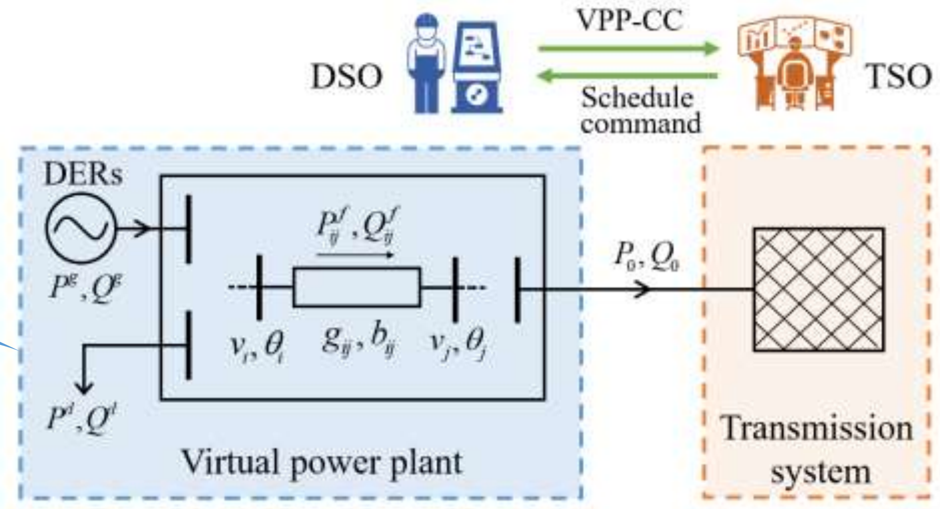


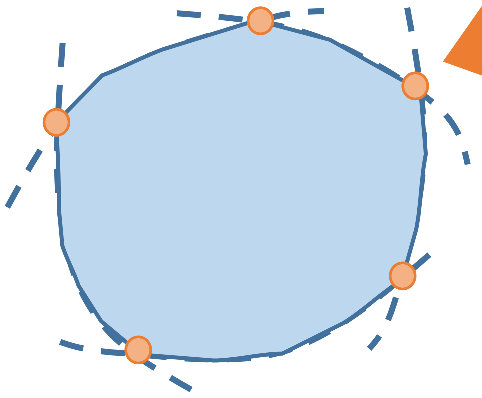
Tan Z, **Zhong H**, Wang X, et al. An efficient method for estimating the capability curve of a virtual power plant[J]. CSEE Journal of Power and Energy Systems, 2020.

Application 1: Virtual Power Plant (VPP)

Feasible Operating Region

- ☐ **Power Balance**
  - ■ $P_i^g - P_i^d = \sum_{j\in L_i} P_{ij}^f, P_0 = \sum_{j\in L_0} P_{j0}^f$
  - ■ $Q_i^g - Q_i^d = \sum_{j\in L_i} Q_{ij}^f, Q_0 = \sum_{j\in L_0} Q_{j0}^f$
- ☐ **Power Flow Equations**
  - ■ $P_{ij}^f = g_{ij}(v_i^2 - v_i v_j \cos\theta_{ij}) - b_{ij} v_i v_j \sin\theta_{ij}$
  - ■ $Q_{ij}^f = -b_{ij}(v_i^2 - v_i v_j \cos\theta_{ij}) - g_{ij} v_i v_j \sin\theta_{ij}$
- ☐ **Capability Constraints**
  - ■ $\left(P_{ij}^f\right)^2 + \left(Q_{ij}^f\right)^2 \le \left(S_{ij}^f\right)^2, (P_0)^2 + (Q_0)^2 \le (S_0)^2$
- ☐ **Bus Voltage Constraints**
  - ■ $\underline{v}_i \le v_i \le \overline{v}_i$
- ☐ **DER Operational Constraints**
  - ■ $(P_i^g, Q_i^g) \in X_i$





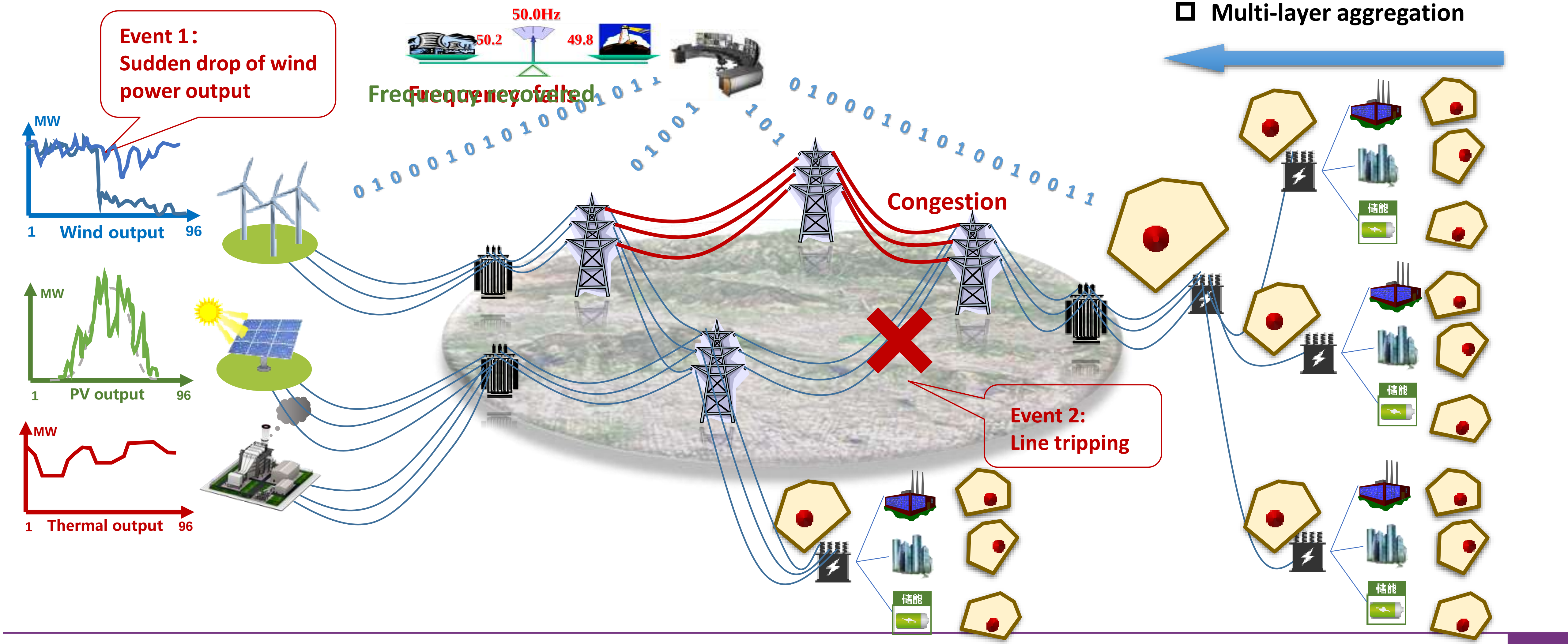
P-Q Capacity

- ☐ **A two-stage framework:**
  - ➢ **Stage 1: calculate the linearized capability curve.**
  - ➢ **Stage 2: recover the vertices to the points on the perimeter of the real capability curve.**

Tan Z, **Zhong H**, Xia Q, et al. Estimating the robust PQ capability of a technical virtual power plant under uncertainties[J]. IEEE Transactions on Power Systems, 2020, 35(6): 4285-4296.

Application 2: Secure Power System Operation

☐ **Optimal resource allocation by source-grid-load-storage interaction**



☐ **Multi-layer aggregation**

Event 1：
Sudden drop of wind power output

Event 2:
Line tripping

Congestion

Frequency falls

Frequency recovered

Application 3: Integrated Energy System

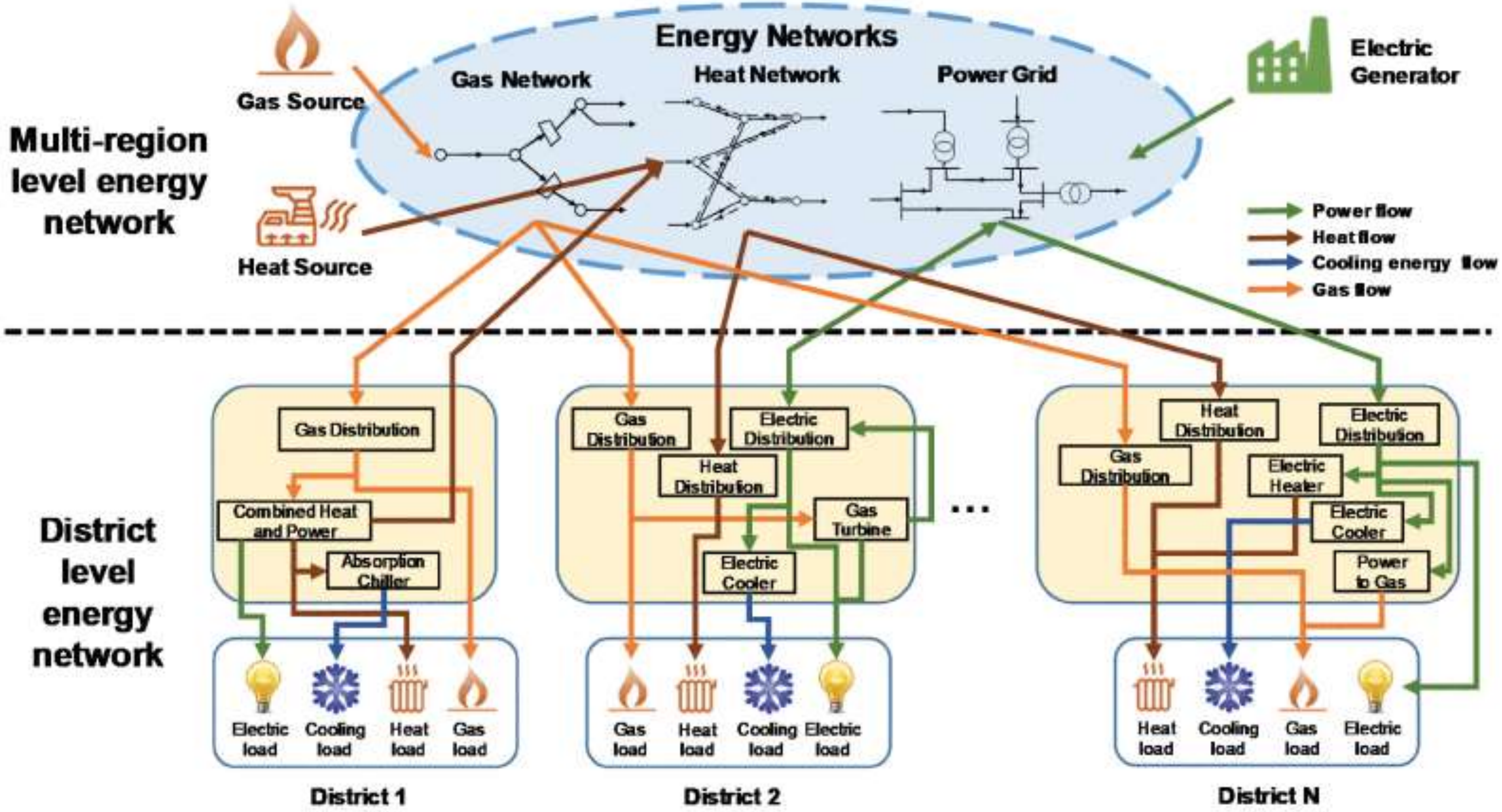


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*Figure from Huang W, Zhang N, Cheng Y, et al. Multienergy networks analytics: Standardized modeling, optimization, and low carbon analysis[J]. Proceedings of the IEEE, 2020, 108(9): 1411-1436.

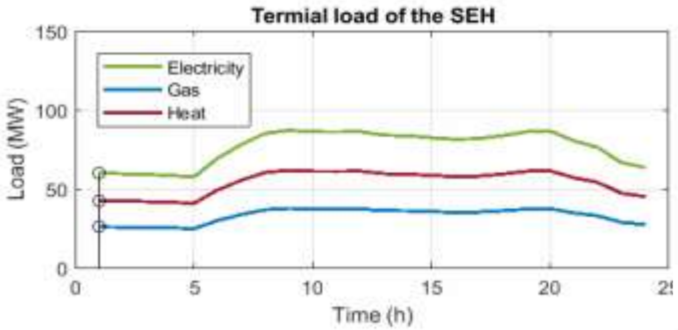
Application 3: Integrated Energy System

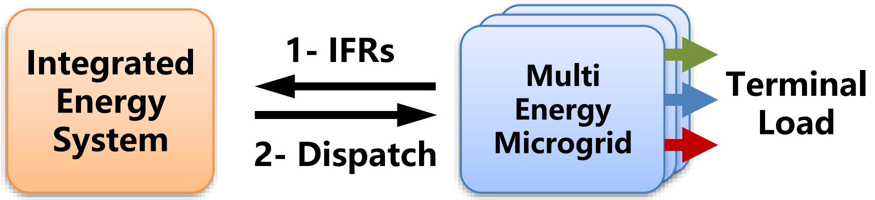
☐ Feasible region in integrated energy system

- ➢ **Turn fixed demand to flexible demand without affecting user comfort**
- ➢ **Expand optimization space to reduce renewable energy curtailment**

微信文章：电机系博士生谭振飞、钟海旺副教授论文获2020 IEEE PES General Meeting最佳论文奖

Integrated Flexibility Region (IFR)



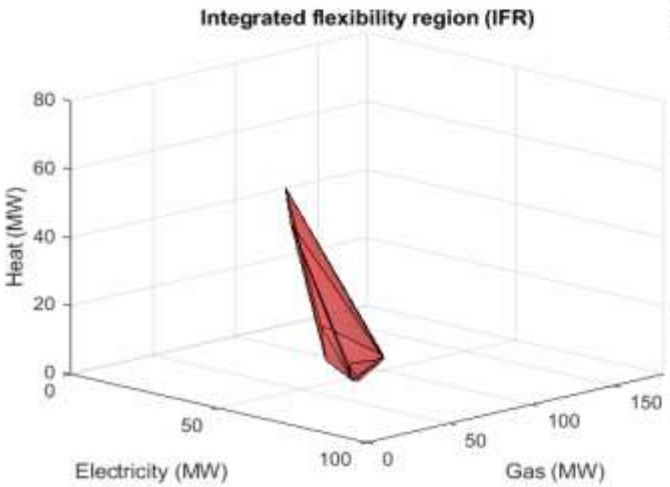

Integrated Energy System

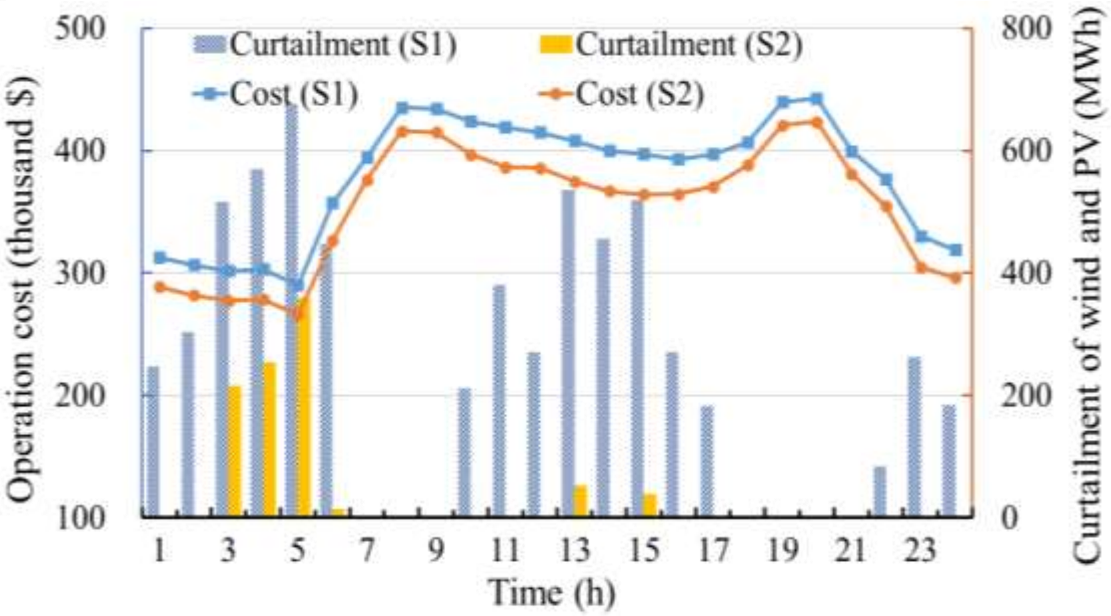
1- IFRs

2- Dispatch

Multi Energy Microgrid

Terminal Load

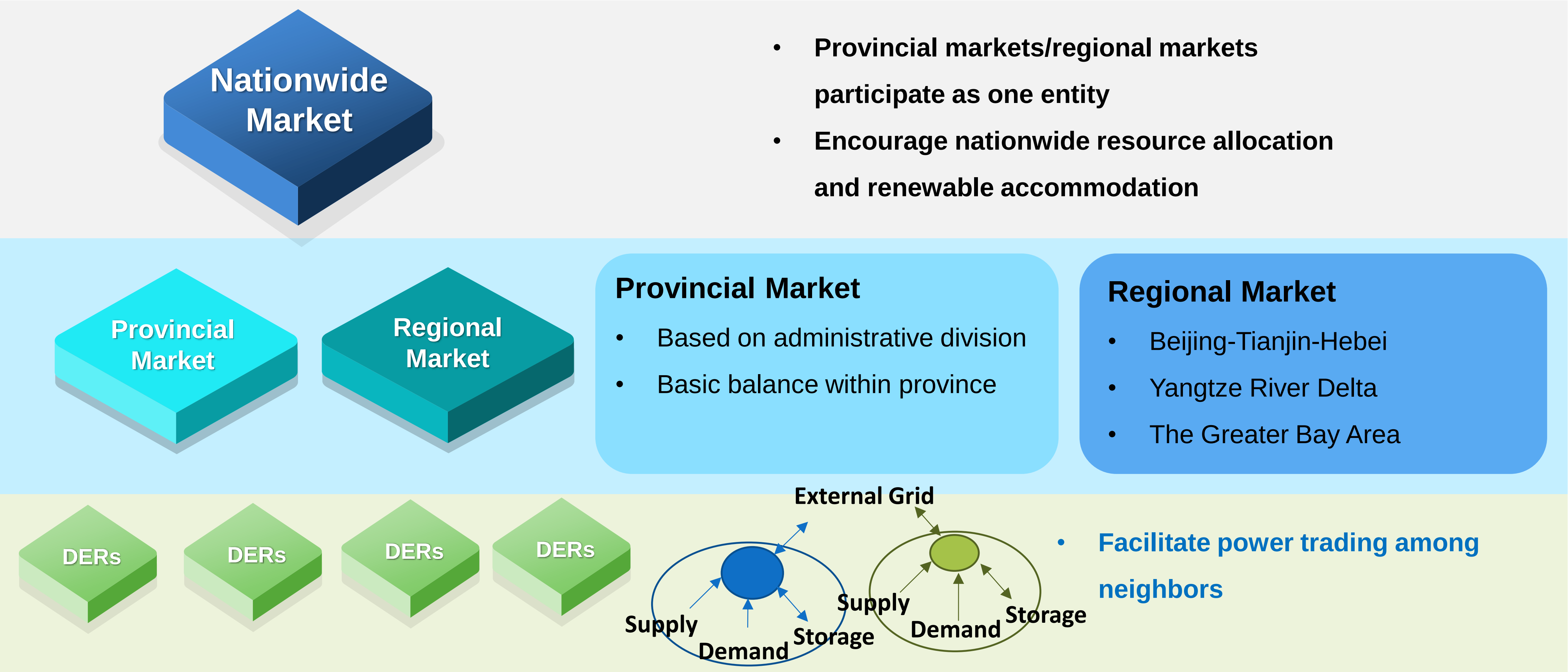




Tan Z, **Zhong H**, Xia Q, et al. Exploiting integrated flexibility from a local smart energy hub[C]//2020 IEEE Power & Energy Society General Meeting (PESGM). IEEE, 2020: 1-5.
2020 IEEE PES General Meeting Best-of-the-Best Paper Award， 4 out of 1300

Application 4: Support Nationwide Electricity Market

Architecture of nationwide electricity market in China



- **Provincial markets/regional markets participate as one entity**
- **Encourage nationwide resource allocation and renewable accommodation**

Provincial Market

- Based on administrative division
- Basic balance within province

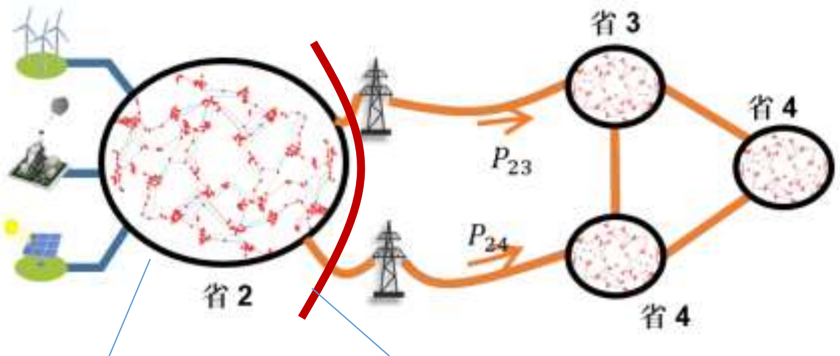
Regional Market

- Beijing-Tianjin-Hebei
- Yangtze River Delta
- The Greater Bay Area

- **Facilitate power trading among neighbors**

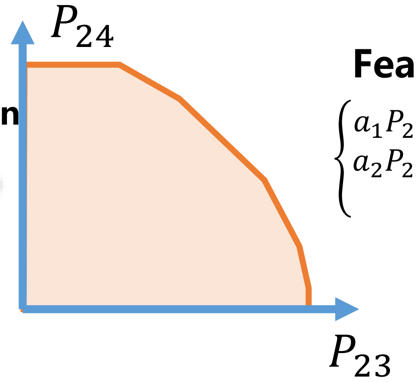
Application 4: Support Nationwide Electricity Market

- □ **Cross-region electricity trading model based on feasible region projection**
- □ **Tie-line schedule is feasible for all internal constraints**



Operation Constraints
- □ Power balance
- □ Transmission capacity
- □ Unit output characteristics

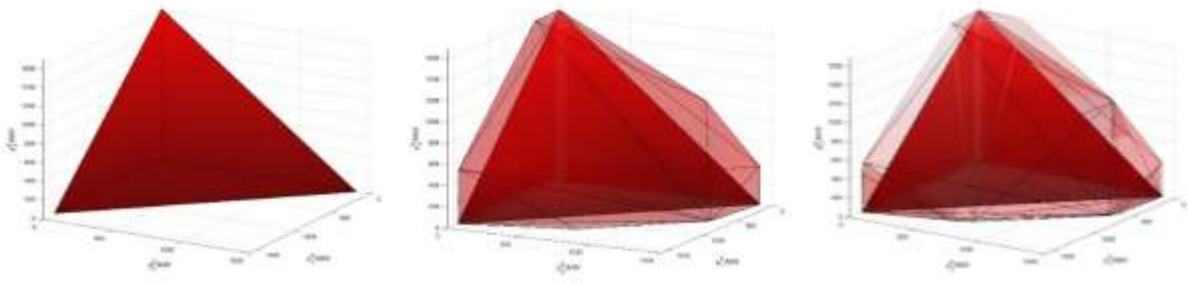
Projection



Tie-line Feasible Region

$$\left\{\begin{array}{l} a_1P_{23}+b_1P_{24}\le c_1 \\ a_2P_{23}+b_2P_{24}\le c_2 \\ \quad\vdots \end{array}\right.$$

Projection Process Based on Vertex Enumeration



Outer loop = 1 Outer loop = 3 Outer loop = 6

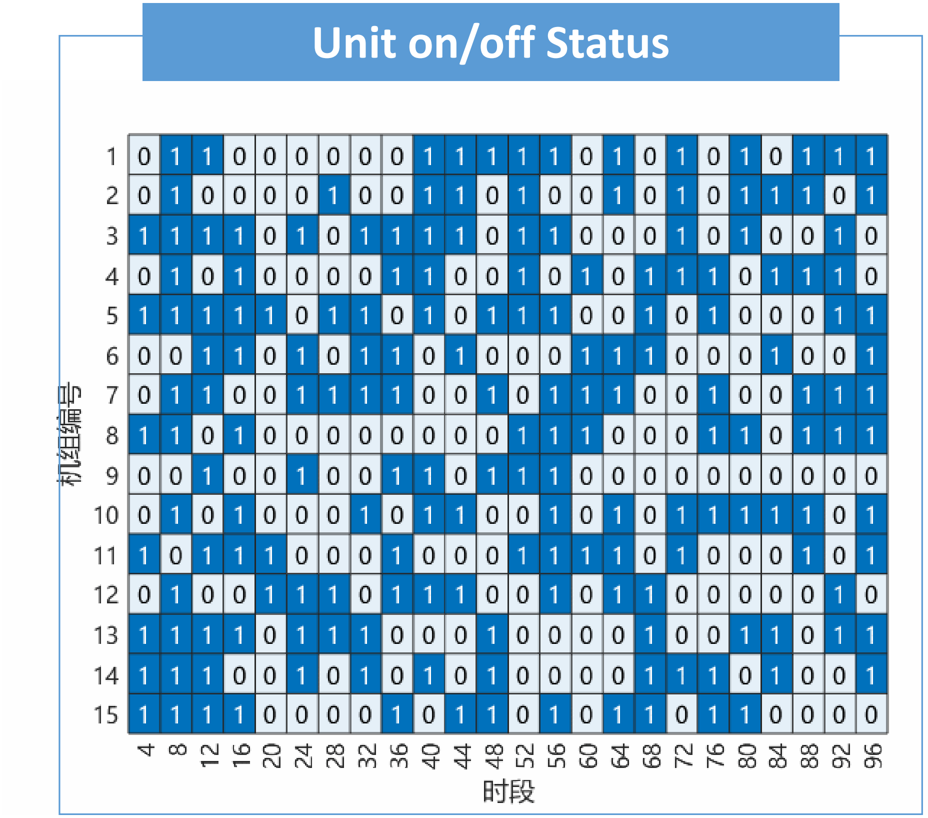
微信文章：电机系钟海旺等完成的“基于约束降维的多时空电力交易协调方法”获北京发明创新大赛金奖

Zenfei Tan, **Haiwang Zhong**, Jianxiao Wang, Qing Xia, Chongqing Kang. Enforcing Intra-regional Constraints in Tie-line Scheduling: A Projection-Based Framework. IEEE Transactions on Power Systems, 2019, 34(6): 4751-4761 Gold Award of Beijing Invention and Innovation Contest

Contents

Combinatorial Optimization

- ☐ **Large-scale unit commitment is faced with the challenge of “dimension curse”.**
- ☐ **Source-grid-load-storage interactive operation is even more challenging.**



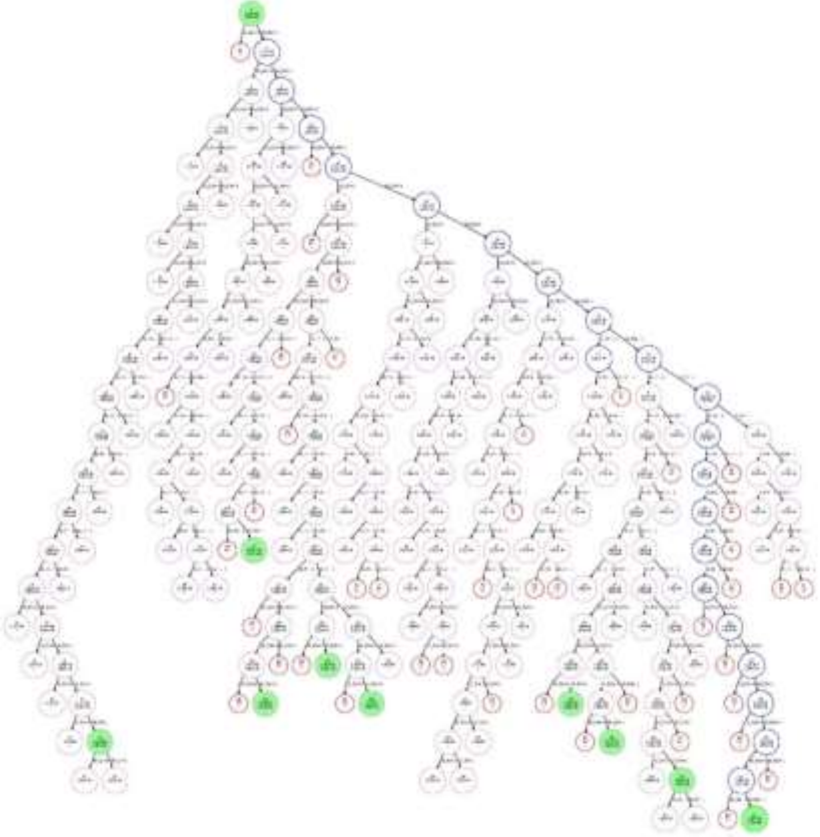
Unit on/off Status

	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96
1	0	1	1	0	0	0	0	0	0	1	1	1	1	1	0	1	0	1	0	1	0	1	1	1
2	0	1	0	0	0	0	1	0	0	1	1	0	1	0	0	1	0	1	0	1	1	1	0	1
3	1	1	1	1	0	1	0	1	1	1	1	0	1	1	0	0	0	1	0	1	0	0	1	0
4	0	1	0	1	0	0	0	0	1	1	0	0	1	0	1	0	1	1	1	0	1	1	1	0
5	1	1	1	1	1	0	1	1	0	1	0	1	1	1	0	0	1	0	1	0	0	0	1	1
6	0	0	1	1	0	1	0	1	1	0	1	0	0	0	1	1	1	0	0	0	1	0	0	1
7	0	1	1	0	0	1	1	1	1	0	0	1	0	1	1	1	0	0	1	0	0	1	1	1
8	1	1	0	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	0	1	1	1
9	0	0	1	0	0	1	0	0	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0
10	0	1	0	1	0	0	0	1	0	1	1	0	0	1	0	1	0	1	1	1	1	1	0	1
11	1	0	1	1	1	0	0	0	1	0	0	0	1	1	1	1	0	1	0	0	0	1	0	1
12	0	1	0	0	1	1	1	0	1	1	1	0	0	1	0	1	1	0	0	0	0	0	1	0
13	1	1	1	1	0	1	1	1	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1
14	1	1	1	0	0	1	0	1	0	1	0	1	0	0	0	0	1	1	1	0	1	0	0	1
15	1	1	1	1	0	0	0	0	1	0	1	1	0	1	0	1	1	0	1	1	0	0	0	0

机组编号

时段

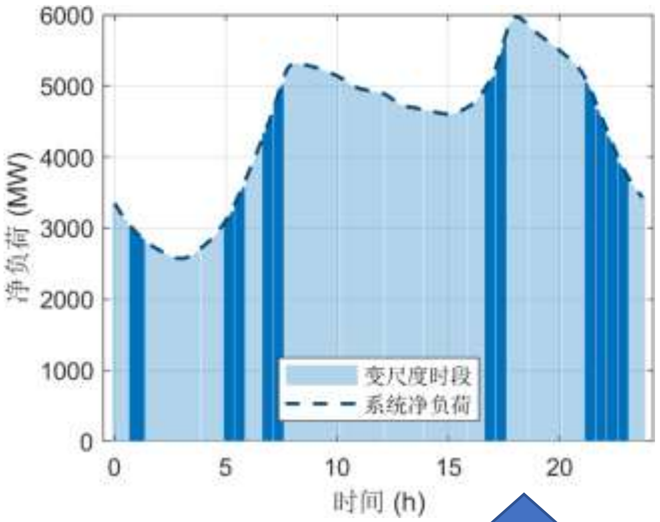
- ☐ **Limit of combinatorial optimization algorithms**
  - **Searching efficiency**
  - **Constraint effectiveness**
  - **Difficult to meet the time requirements of decision-making in new power system.**



Ma Z, **Zhong H**, Xia Q, et al. A unit commitment algorithm with relaxation-based neighborhood search and improved relaxation inducement[J]. IEEE Transactions on Power Systems, 2020, 35(5): 3800-3809.

Key Technique 1: Adaptive Time Period Aggregation

- Measure **challenge of net load changes** within each adaptive time period to system flexibility
- Based on which **time period similarity** is measured



☐ **Model for time period aggregation: integer programming**

Net load
Peak-valley difference

$$f(T,N)=\min_{t_1,t_2,\cdots,t_N}\sum_{i=1}^{N}\frac{\max\limits_{t=t_i,t_i+1,\cdots,t_{i+1}-1} D^t-\min\limits_{t=t_i,t_i+1,\cdots,t_{i+1}-1} D^t}{\max\limits_{t=t_i,t_i+1,\cdots,t_{i+1}-1} D^t}$$

Net load
maximum

$$t_1,t_2,\cdots t_N\in\mathbb{Z}$$

Start point of
adaptive time period

$$1=t_1<t_2<\cdots<t_N\le T$$

Dynamic Programming

$$f(t,n)=\min_{\tau=n,\cdots,t}\{f(\tau-1,n-1)+\lambda(\tau,t)\}$$

$$\tau_{t,n}=\arg\min_{\tau=n,\cdots,t}\{f(\tau-1,n-1)+\lambda(\tau,t)\}$$

$$f(t,1)=\lambda(1,t),\quad \forall 1\le t\le T$$

$$\tau_{t,1}=1,\quad \forall 1\le t\le T$$

$$t_N=\tau_{T,N}$$

$$t_i=\tau_{t_{i+1}-1,i},\quad \forall 1\le i\le N-1$$

$$d_i=\begin{cases} t_{i+1}-t_i, & 1\le i\le N-1\\ T-t_N+1, & i=N\end{cases}$$

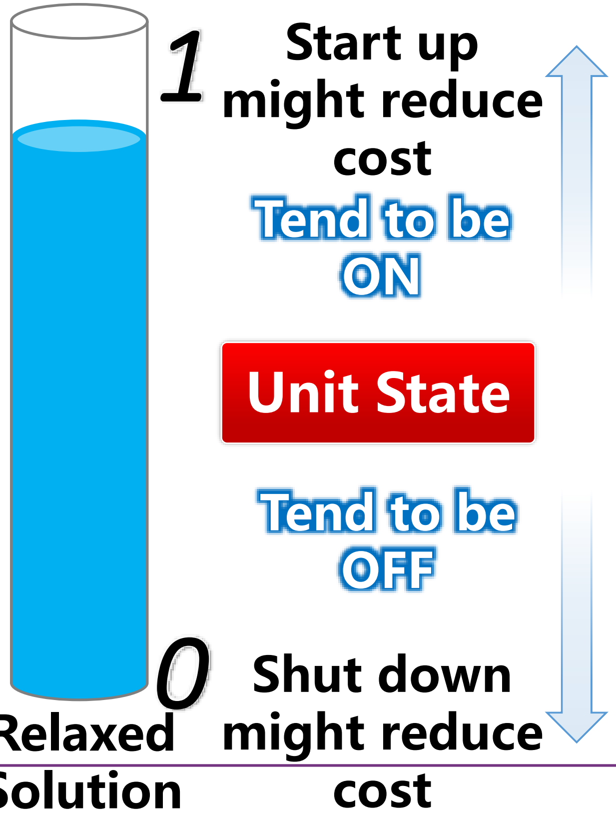
Measure

$$\lambda(t_S,t_F)=\begin{cases}\dfrac{\max\limits_{t=t_S,\cdots,t_F} D^t-\min\limits_{t=t_S,\cdots,t_F} D^t}{\max\limits_{t=t_S,\cdots,t_F} D^t}, & t_S<t_F\\ 0, & t_S\ge t_F\end{cases}$$

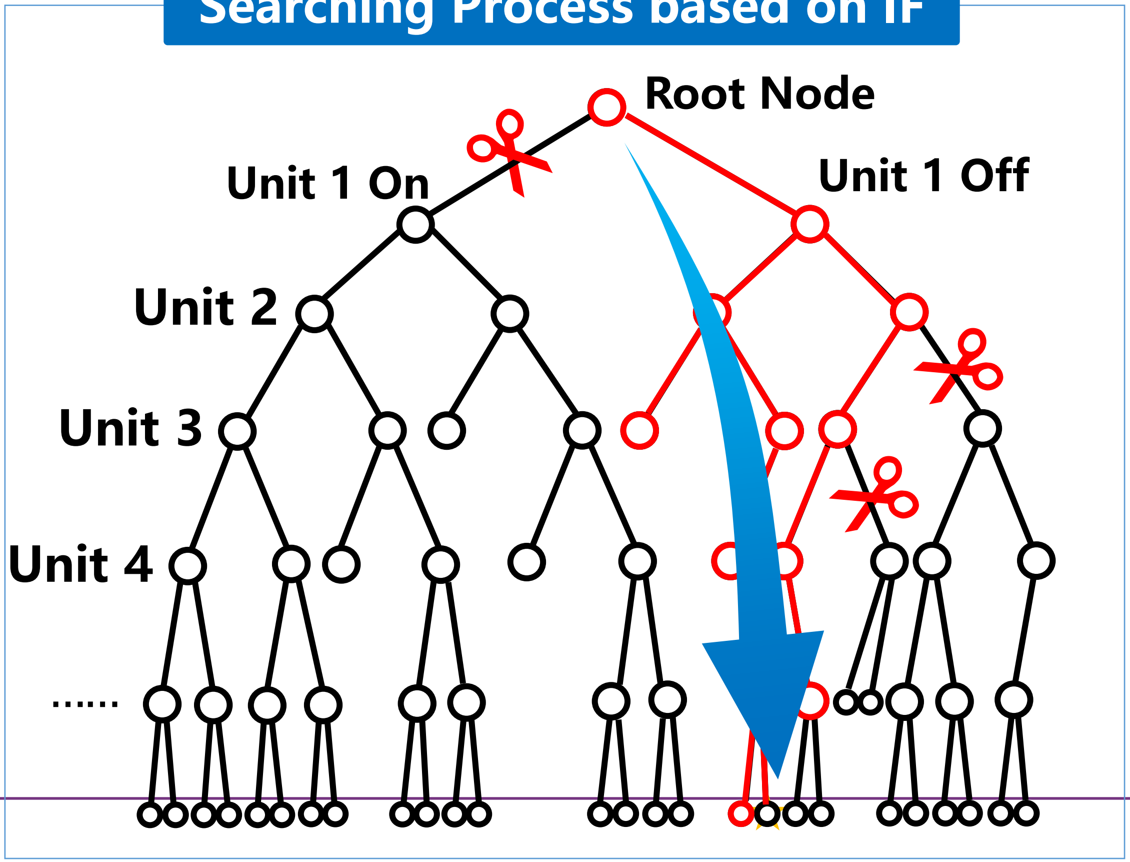
Yu Z, **Zhong H**, Ruan G, et al. Network-Constrained Unit Commitment With Flexible Temporal Resolution[J]. IEEE Transactions on Power Systems, 2024.

Key Technique 2: Induction Function

Using relaxed solution, construct **acceleration solution model with induction function (IF)** without changing original constraints. Induction function can help to **avoid unnecessary branching** and **increase searching efficiency**.



Searching Process based on IF



Model based on IF

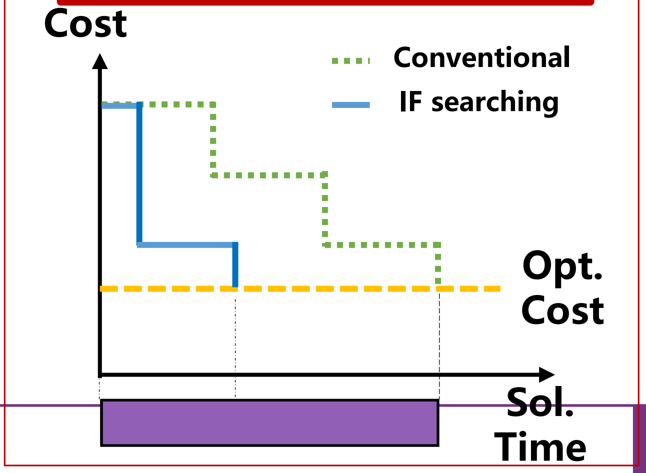
$$\min\ \mathbf{cx}+\sigma(\mathbf{x})$$

$$s.t.\ \mathbf{Ax}=\mathbf{b}$$

$$\mathbf{x}\geq 0, x_j=\{0,1\}\ \forall j\in I$$

Induction Function

Efficient Searching

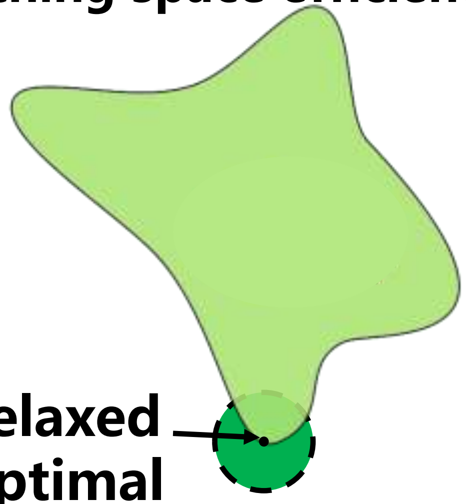


Key Technique 3: Relaxed Neighborhood Searching

- **Construct the relaxed neighborhood constraint:**

$$RD\left(x, x^{*}\right) \leq r$$

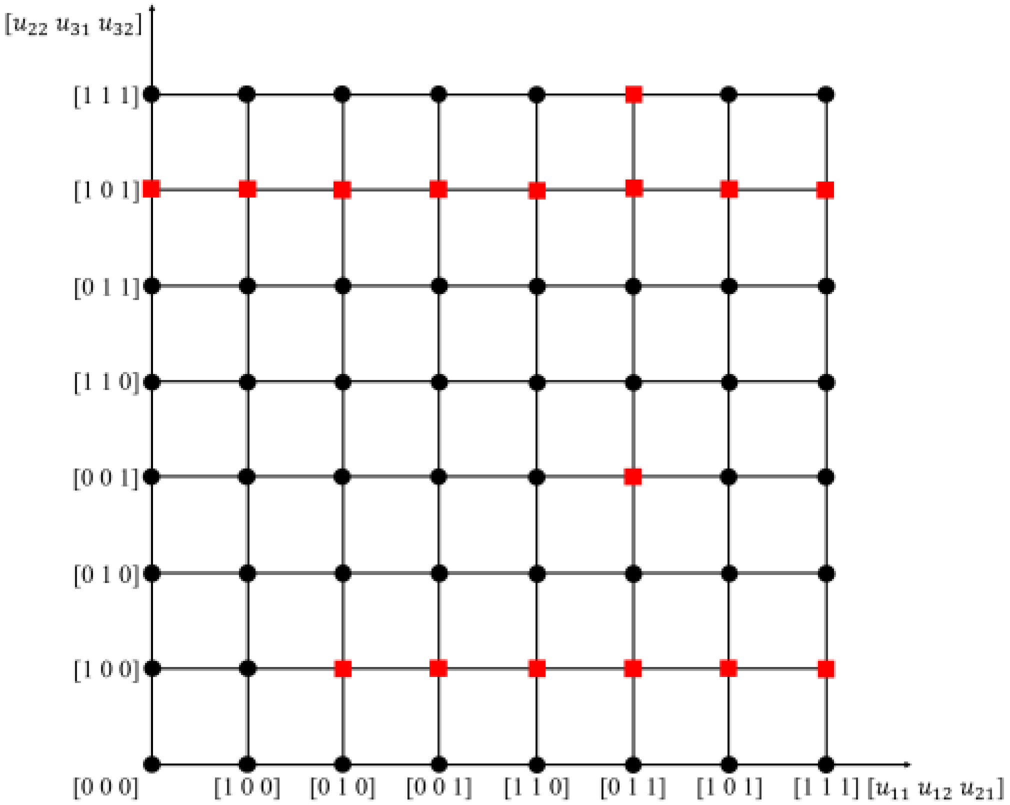
- **The neighborhood of the relaxed optimal solution.**
- **The deviation from the relaxed optimal solution is constrained.**
- **Searching space efficiency is improved.**



Relaxed Optimal Solution

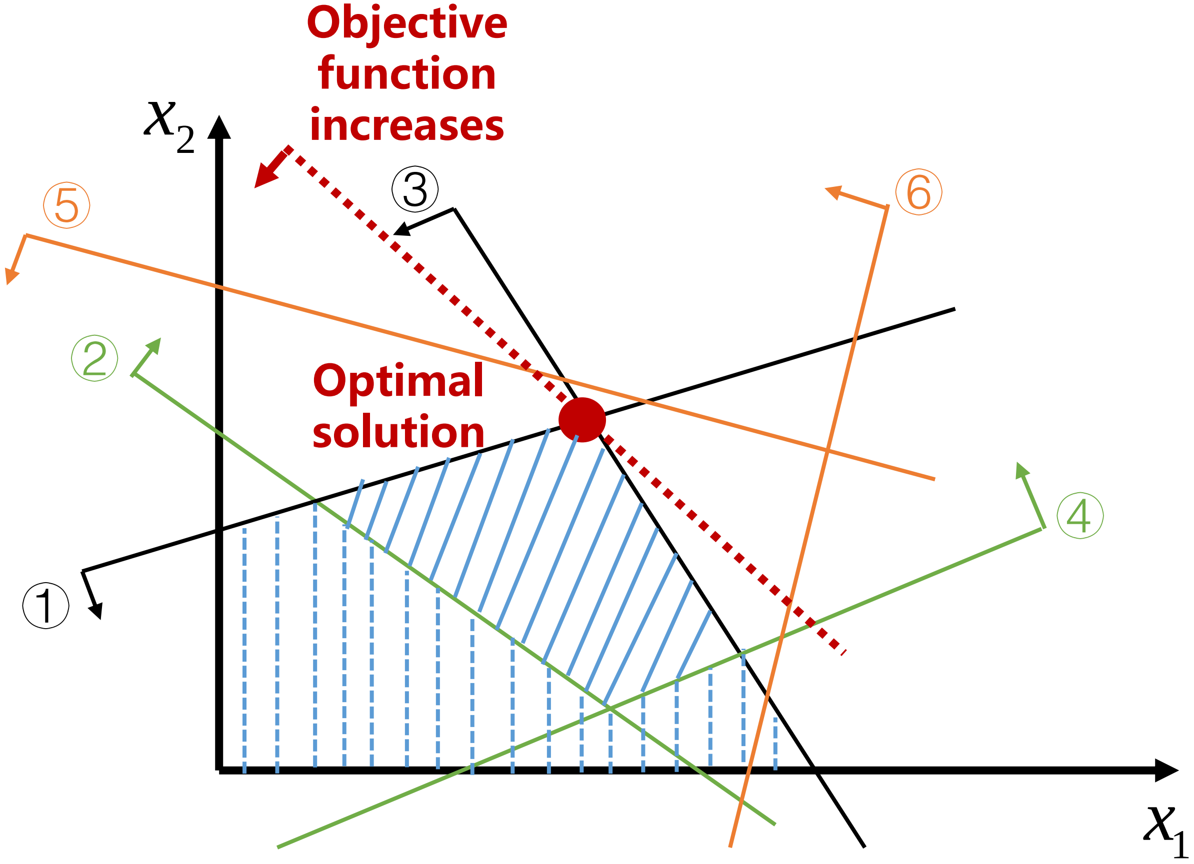
Three units two periods illustrative case:

- **Six 0-1 variables**
- **The size of searching space 64:16**



Key Technique 4: Effective Constraints Identification

☐ **For the constraint effectiveness, an inactive constraint identification algorithm is proposed.**



Linear Programming Example

Redundant Constraints

- Never violated in the feasible region
- Can be eliminated without changing the feasible region

Non-Binding Constraints

- Not violated at the optimal solution
- If eliminated, the feasible region is changed
- Might be violated if the objective function is changed

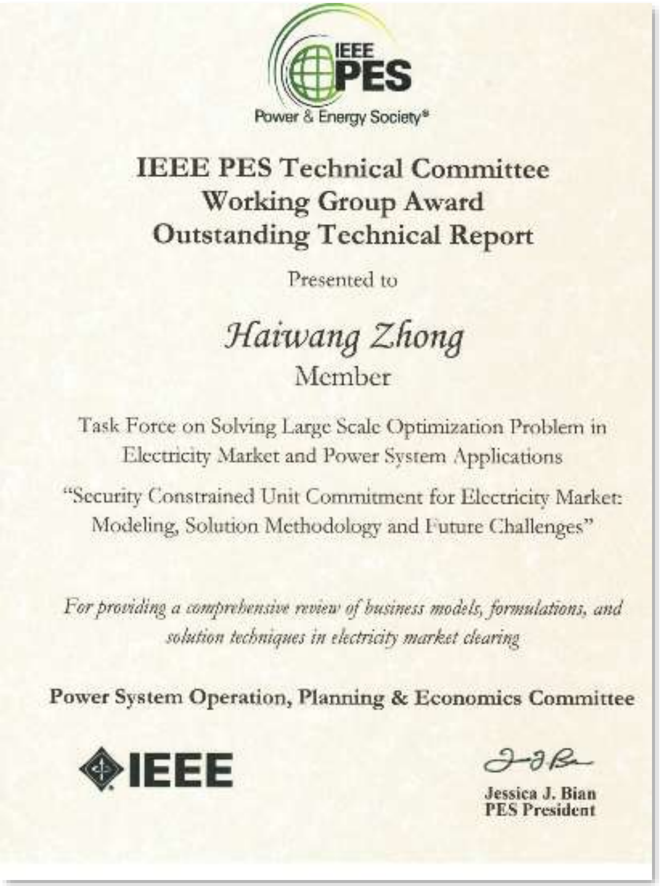
Ma Z, Zhong H, Cheng T, et al. Redundant and Nonbinding Transmission Constraints Identification Method Combining Physical and Economic Insights of Unit Commitment[J]. IEEE Transactions on Power Systems, 2021, 36(4): 3487-3495.

A Review on SCUC for Electricity Market

Security-Constrained Unit Commitment for Electricity Market: Modeling, Solution Methods, and Future Challenges

IEEE Task Force on Solving Large Scale Optimization Problems in Electricity Market and Power System Applications

Yonghong Chen, Feng Pan, Feng Qiu, Alinson S Xavier, Tongxin Zheng, Muhammad Marwali, Bernard Knueven, Yongpei Guan, Peter B. Luh, Lei Wu, Bing Yan, Mikhail A. Bragin, Haiwang Zhong, Anthony Giacomoni, Ross Baldick, Boris Gisin, Qun Gu, Russ Philbrick, Fangxing Li



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**IEEE PES Technical Committee
Working Group Award
Outstanding Technical Report**

Presented to

Haiwang Zhong
Member

Task Force on Solving Large Scale Optimization Problem in Electricity Market and Power System Applications

"Security Constrained Unit Commitment for Electricity Market: Modeling, Solution Methodology and Future Challenges"

For providing a comprehensive review of business models, formulations, and solution techniques in electricity market clearing

Power System Operation, Planning & Economics Committee

IEEE

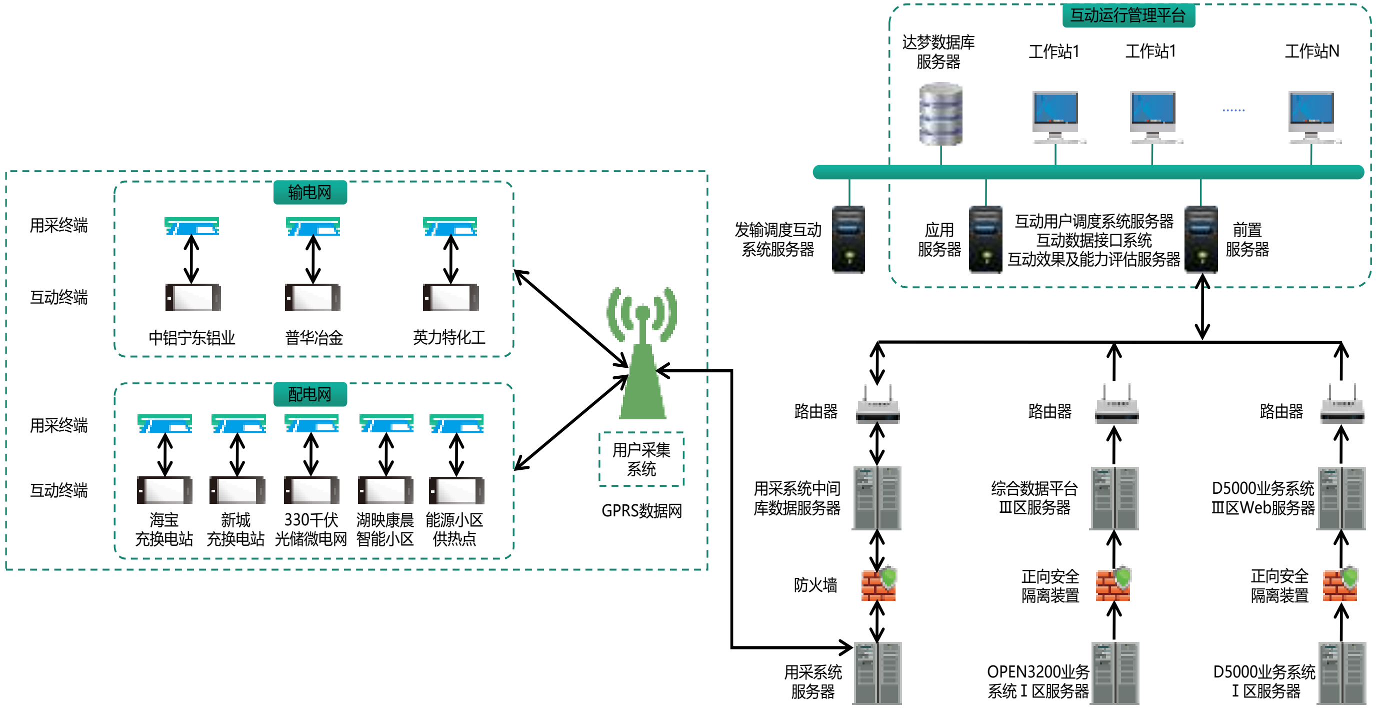
Jessica J. Bian
PES President

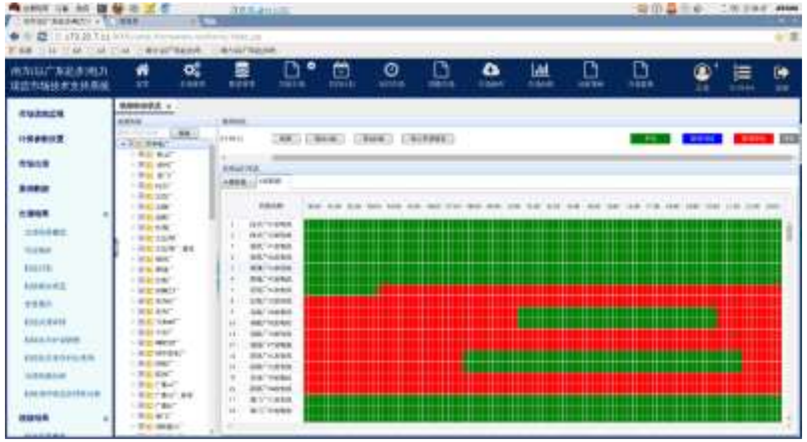
微信文章：最新研究 | 安全约束机组组合的建模、求解方法和未来挑战

Y. Chen *et al.*, "Security-Constrained Unit Commitment for Electricity Market: Modeling, Solution Methods, and Future Challenges," IEEE Transactions on Power Systems, vol. 38, no. 5, pp. 4668-4681, Sept. 2023, doi: 10.1109/TPWRS.2022.3213001.

Industry Applications

- □ **Generation scheduling software applied in 10+ provincial control centers**
- □ **Supporting electricity spot market as key clearing algorithm (SCUC/SCED)**



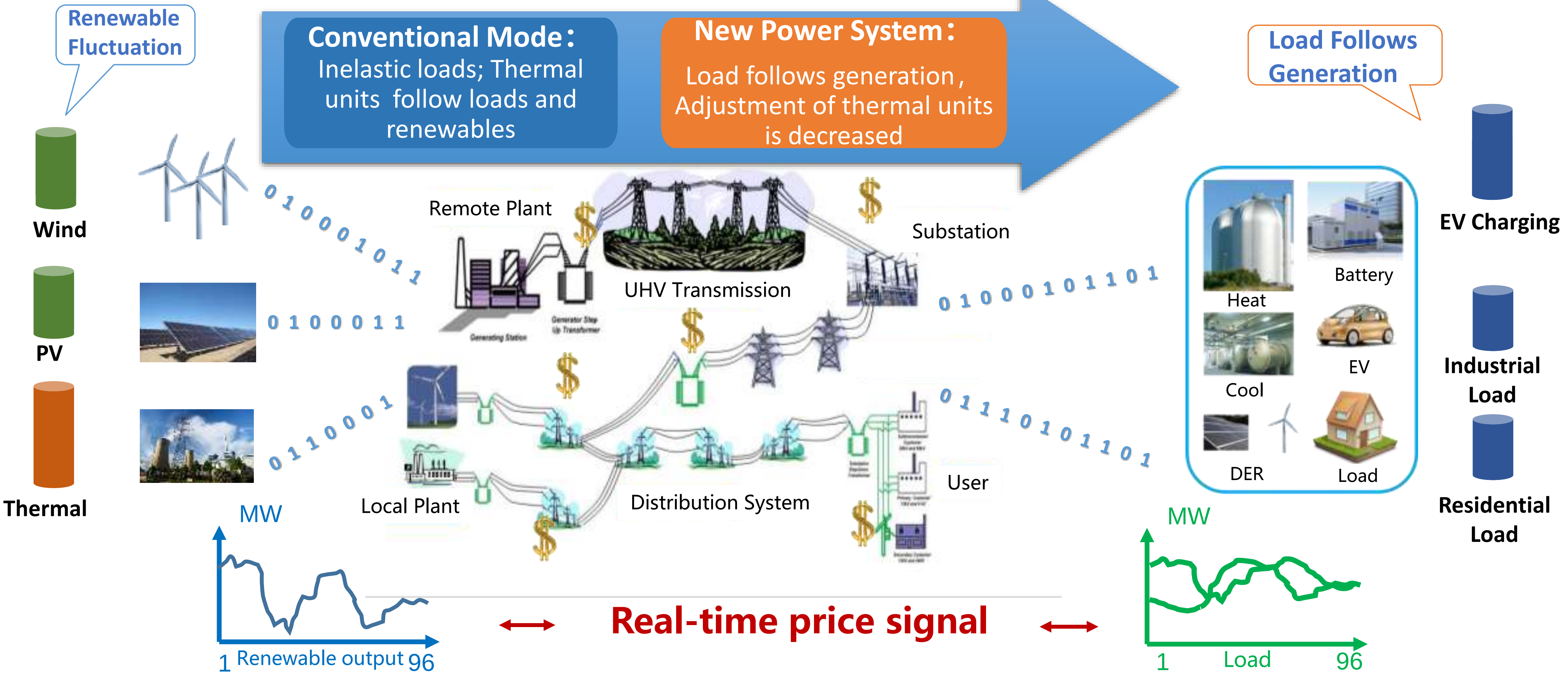


First Prize, China Power Science and Technology Award, 2019

Contents

Transition of operation pattern

- ☐ **Facilitated with IoT and mechanism design, participants are aware of external information and can adjust their behavior to realize “load following generation”.**



Renewable Fluctuation

Conventional Mode:
Inelastic loads; Thermal units follow loads and renewables

New Power System:
Load follows generation, Adjustment of thermal units is decreased

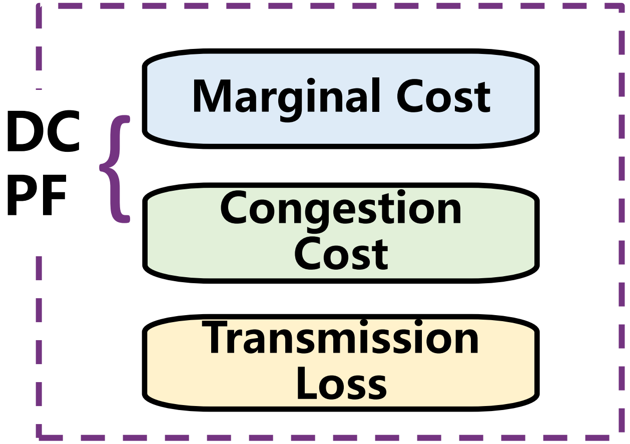
Load Follows Generation

Real-time price signal

Mechanism 1: LMP with Overall Costs

☐ LMP with Overall Costs: Form accurate price signals

Conventional Pricing Mechanism



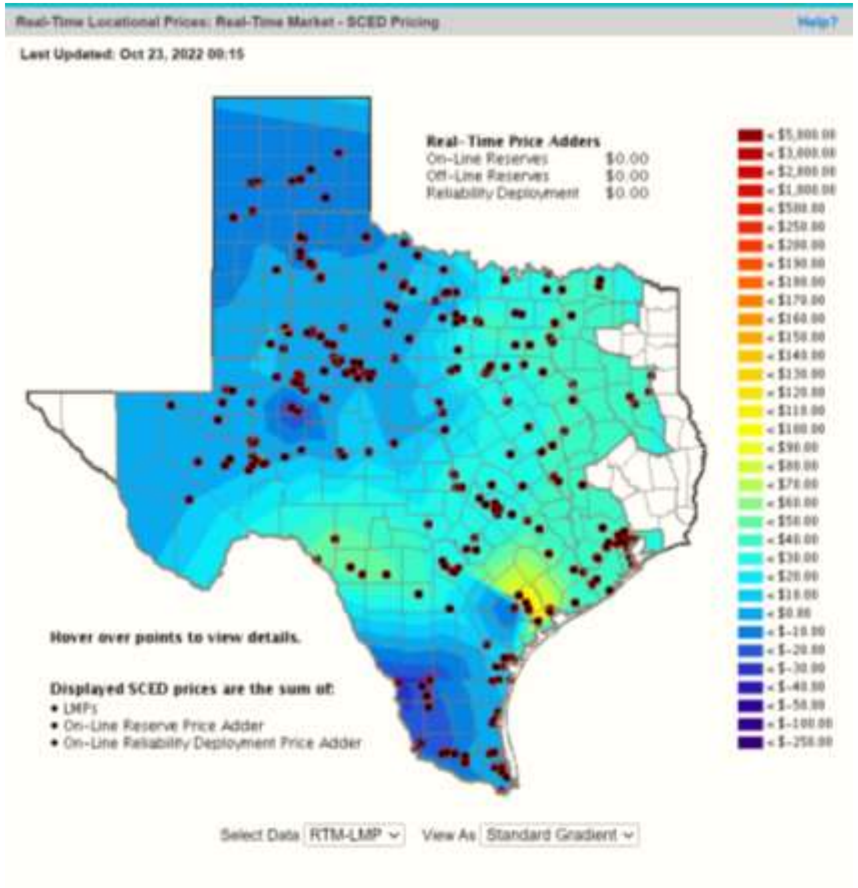
DC PF {

Marginal Cost

Congestion Cost

Transmission Loss

- ➢ **Can NOT reflect the difference in transmission cost in different regions**
- ➢ **Insufficient to incent source-grid-load-storage interaction**
- ➢ **Incomplete price information**
- ➢ **Might lead to unfair market**



Real-Time Locational Prices: Real-Time Market - SCED Pricing

Last Updated: Oct 23, 2022 00:15

Real-Time Price Adders	
On-Line Reserves	$0.00
Off-Line Reserves	$0.00
Reliability Deployment	$0.00

Hover over points to view details.

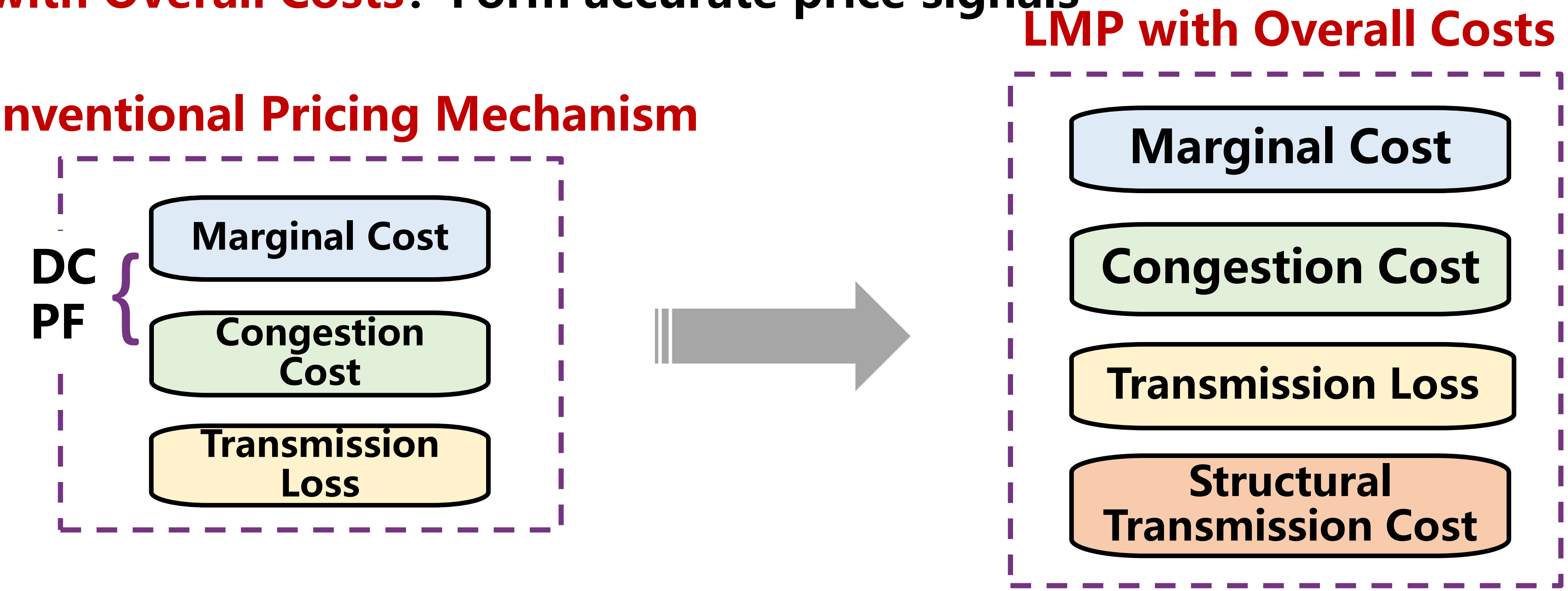
Displayed SCED prices are the sum of:
- LMPs
- On-Line Reserve Price Adder
- On-Line Reliability Deployment Price Adder

Select Data RTM-LMP
View As Standard Gradient

Spatial distribution of LMPs in Texas

Mechanism 1: LMP with Overall Costs

□ LMP with Overall Costs：Form accurate price signals



Conventional Pricing Mechanism

DC PF {
- Marginal Cost
- Congestion Cost
- Transmission Loss

LMP with Overall Costs

- Marginal Cost
- Congestion Cost
- Transmission Loss
- Structural Transmission Cost

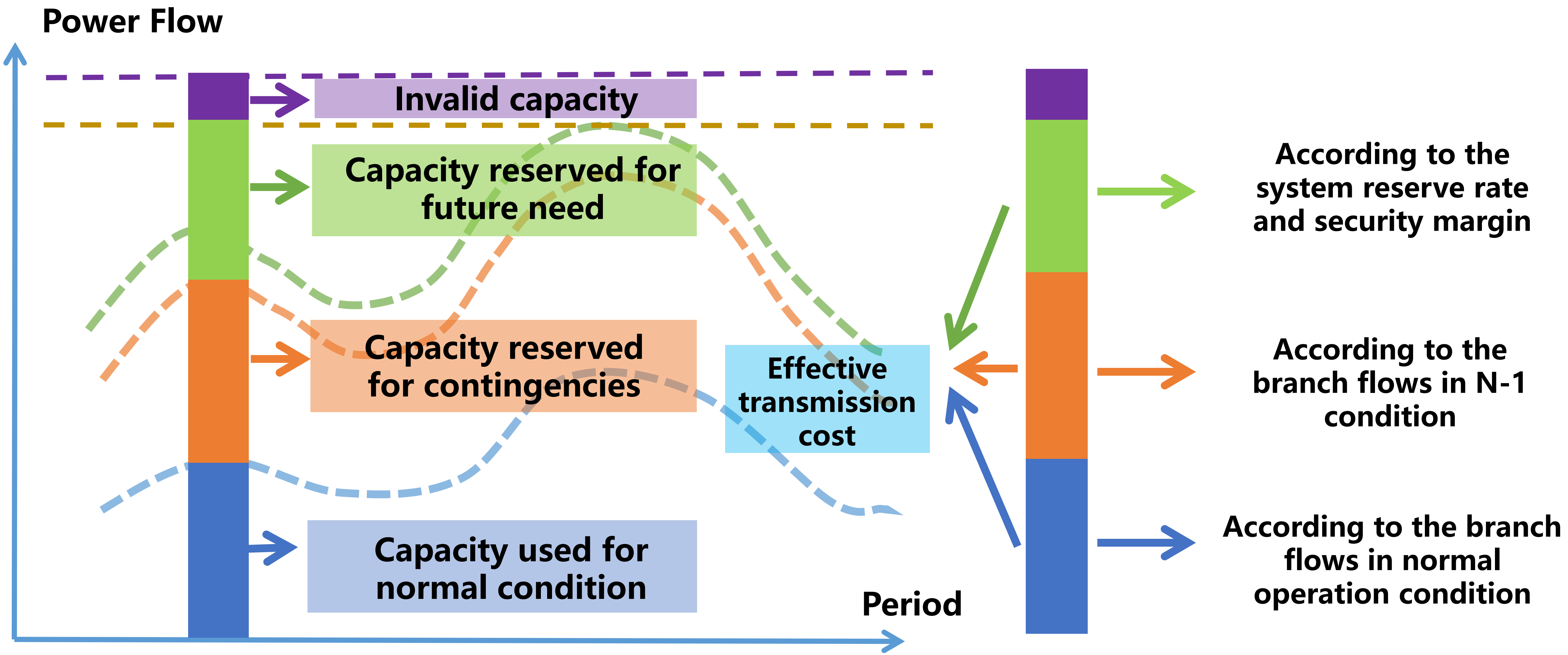
微信文章：最新研究进展|引导源网荷储高效互动的全成本节点电价

- ➢ Can NOT reflect the difference in cost in different regions
- ➢ Insufficient to incent source-grid-load-storage interaction
- ➢ Incomplete price information
- ➢ Might lead to unfair market

- ➢ Integrate marginal generation cost and effective transmission cost
- ➢ Reflect the actual utilization of generation and network resources
- ➢ Reflect the difference in power consumption cost of terminal nodes
- ➢ Incent source-grid-load-storage interaction

Mechanism 1: LMP with Overall Costs

- Identify the effective structural transmission cost



Power Flow

Invalid capacity

Capacity reserved for future need

Capacity reserved for contingencies

Capacity used for normal condition

Effective transmission cost

Period

According to the system reserve rate and security margin

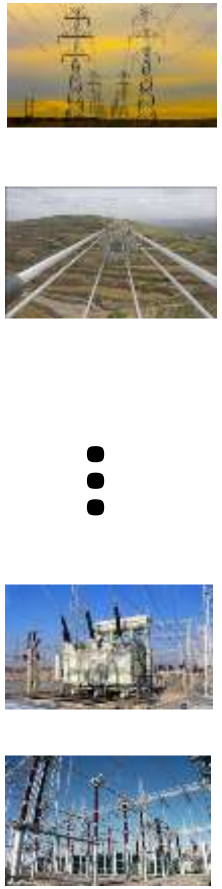
According to the branch flows in N-1 condition

According to the branch flows in normal operation condition

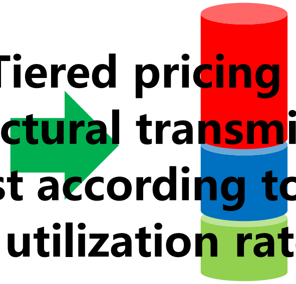
Yang Z, **Zhong H**, Xia Q, et al. A structural transmission cost allocation scheme based on capacity usage identification[J]. IEEE Transactions on Power Systems, 2015, 31(4): 2876-2884.

Mechanism 1: LMP with Overall Costs

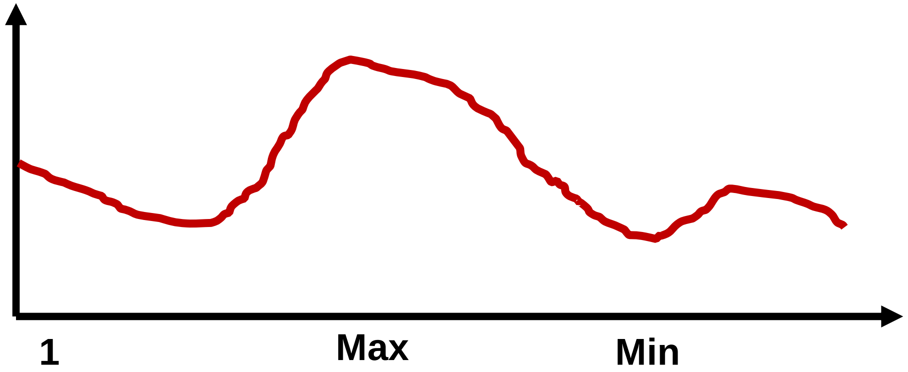
☐ Temporal allocation of structural transmission cost



Power system assets

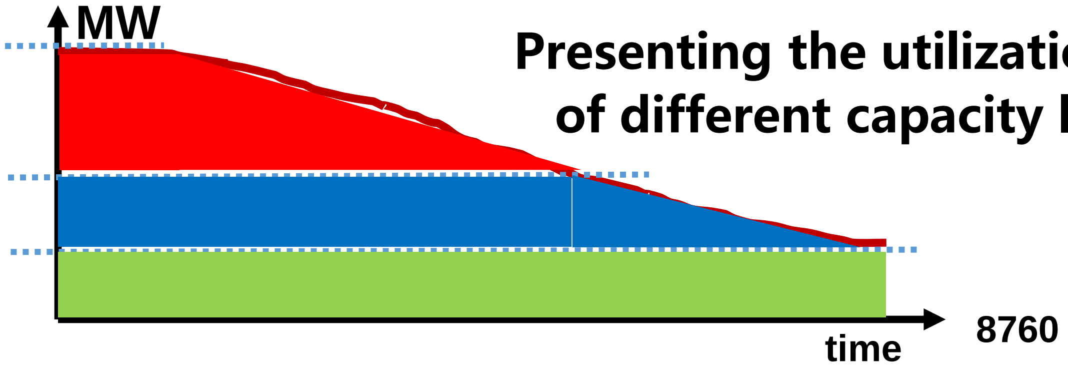


Tiered pricing of structural transmission cost according to the utilization rate



Time-sequential PF curve

Sort



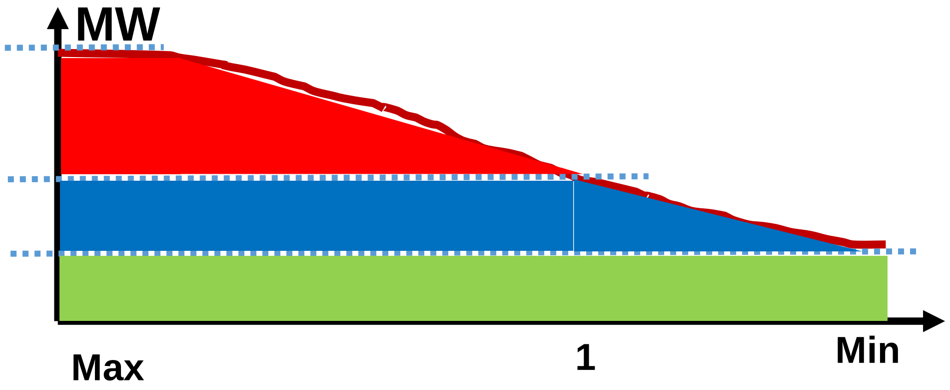
Presenting the utilization rate of different capacity levels

Continuous PF curve

Mechanism 1: LMP with Overall Costs

☐ Temporal allocation of structural transmission cost

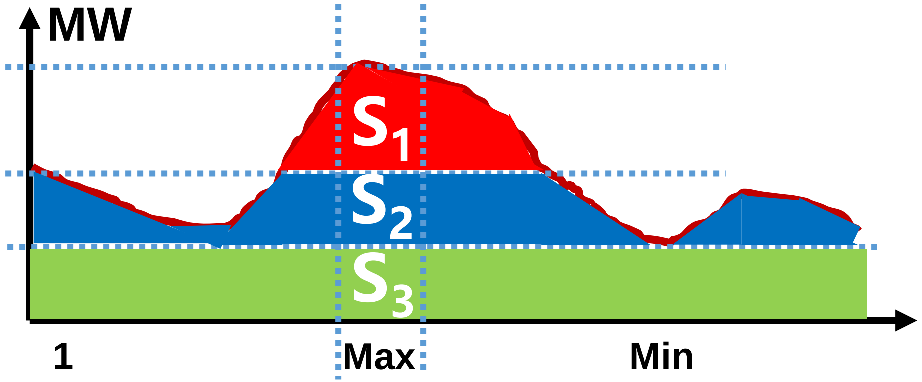
- **Recover the tiered pricing from continuous PF curve to time-sequential PF curve**



Continuous PF curve

The structural transmission cost on different PF level is significantly different

Area represents electricity



Time-sequential PF curve

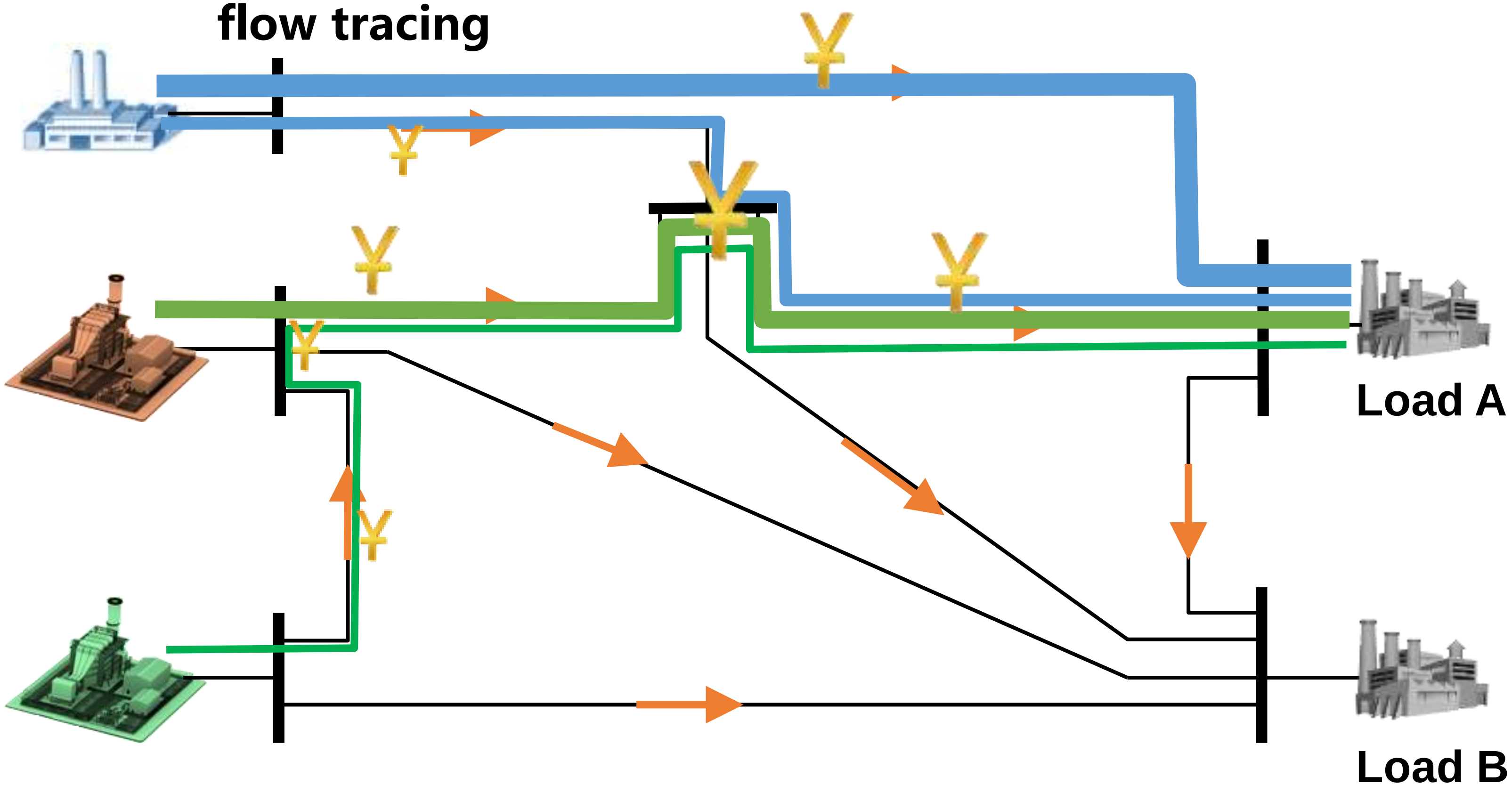
Structural transmission cost of each period

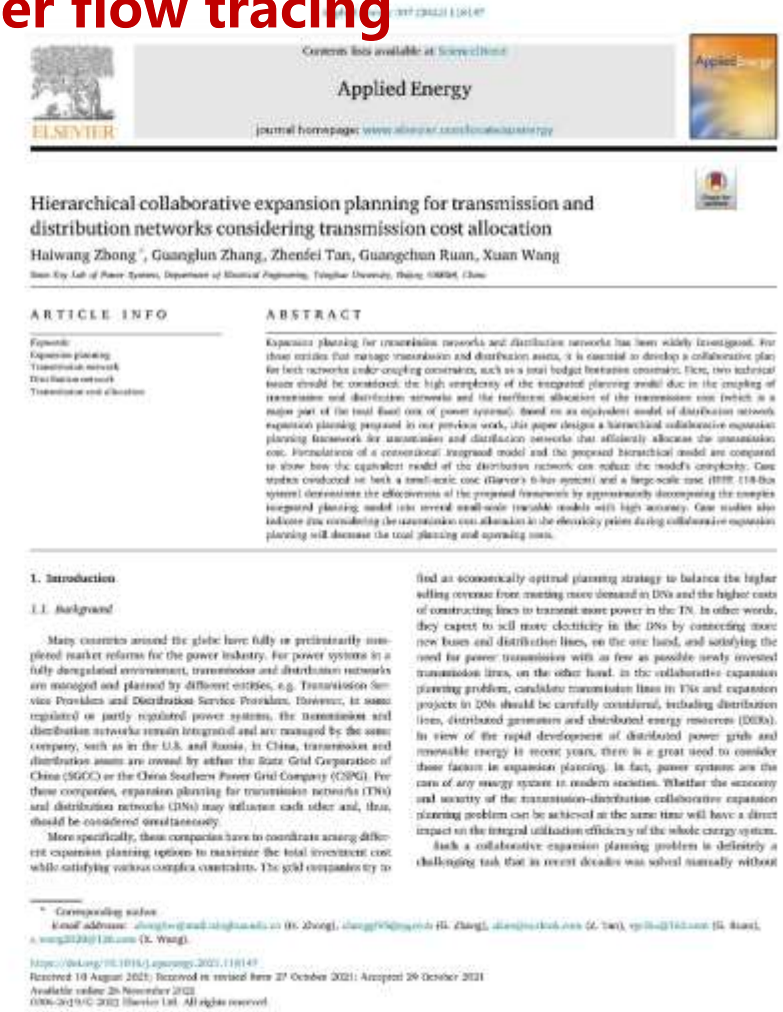
$=\Sigma\ (S_i \times \text{Tiered price})\ /\Sigma S_i$

Mechanism 1: LMP with Overall Costs

☐ Spatial allocation of generation and network costs: power flow tracing

- ➢ **Calculate power flows**
- ➢ **Transmission cost is allocated through power flow tracing**





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Hierarchical collaborative expansion planning for transmission and distribution networks considering transmission cost allocation

Haiwang Zhong *, Guanglun Zhang, Zhenfei Tan, Guangchun Ruan, Xuan Wang

ARTICLE INFO

ABSTRACT

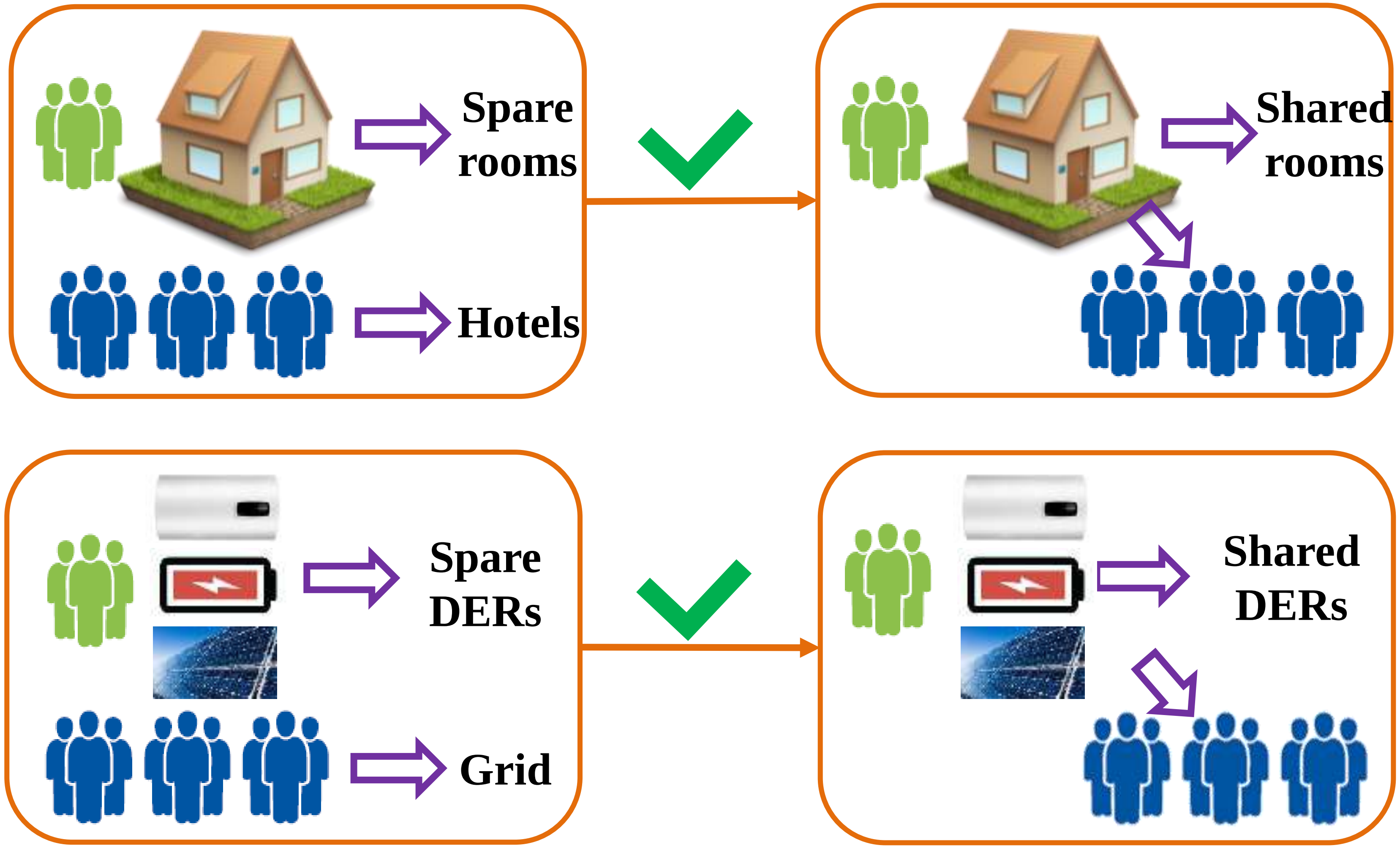
1. Introduction

Zhong H, Zhang G, Tan Z, Ruan G, Wang X. Hierarchical collaborative expansion planning for transmission and distribution networks considering transmission cost allocation. Applied Energy, 307 (2022) 118147

Mechanism 2: Energy Sharing

- **Energy Internet** is a natural platform for **energy sharing**

Airbnb



Spare rooms

Hotels

Shared rooms

Spare DERs

Grid

Shared DERs

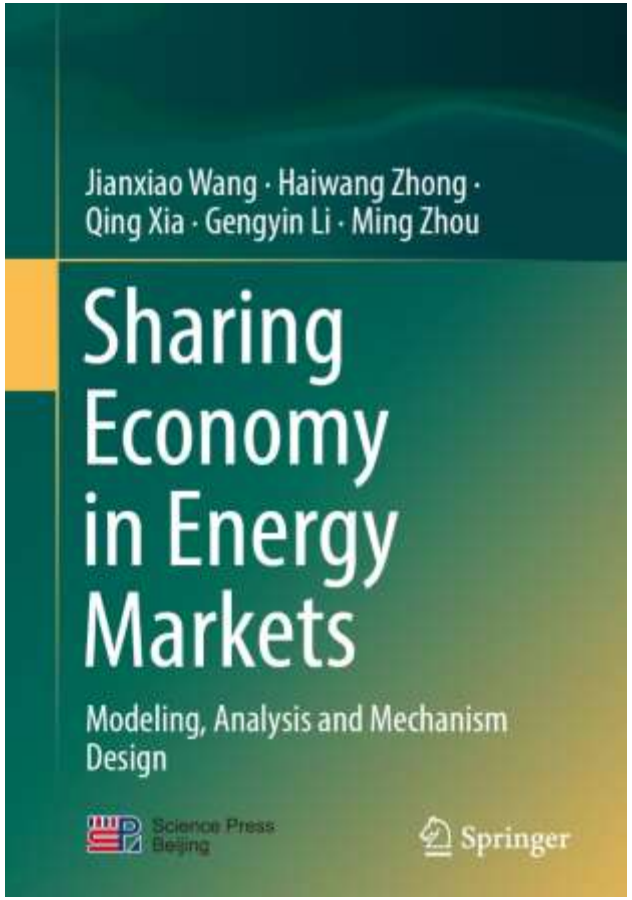
Energy sharing

王剑晓,**钟海旺**,夏清,汪洋,赖晓文,郭新志.基于价值公平分配的电力市场竞争机制设计[J].电力系统自动化,2019,43(02):7-17.
Jianxiao Wang, **Haiwang Zhong**, Qing Xia, Gengyin Li, Ming Zhou. Sharing Economy in Energy Markets: Modeling, Analysis and Mechanism Design, Springer

Mechanism 2: Energy Sharing

Sharing economy in source-grid-load-storage interactive operations

- With the core concept of ” access over ownership", use advanced ICT to improve the utilization rate of vacant energy resources.
- For the wholesale market, accurately identify the external value and cost and stimulate bidding strategies based on the true cost in the electricity market of high renewable penetration
- For the retail market, efficiently aggregate massive DERs and form a cooperative market of incentive-compatibility



Jianxiao Wang · Haiwang Zhong ·
Qing Xia · Gengyin Li · Ming Zhou

Sharing
Economy
in Energy
Markets

Modeling, Analysis and Mechanism
Design

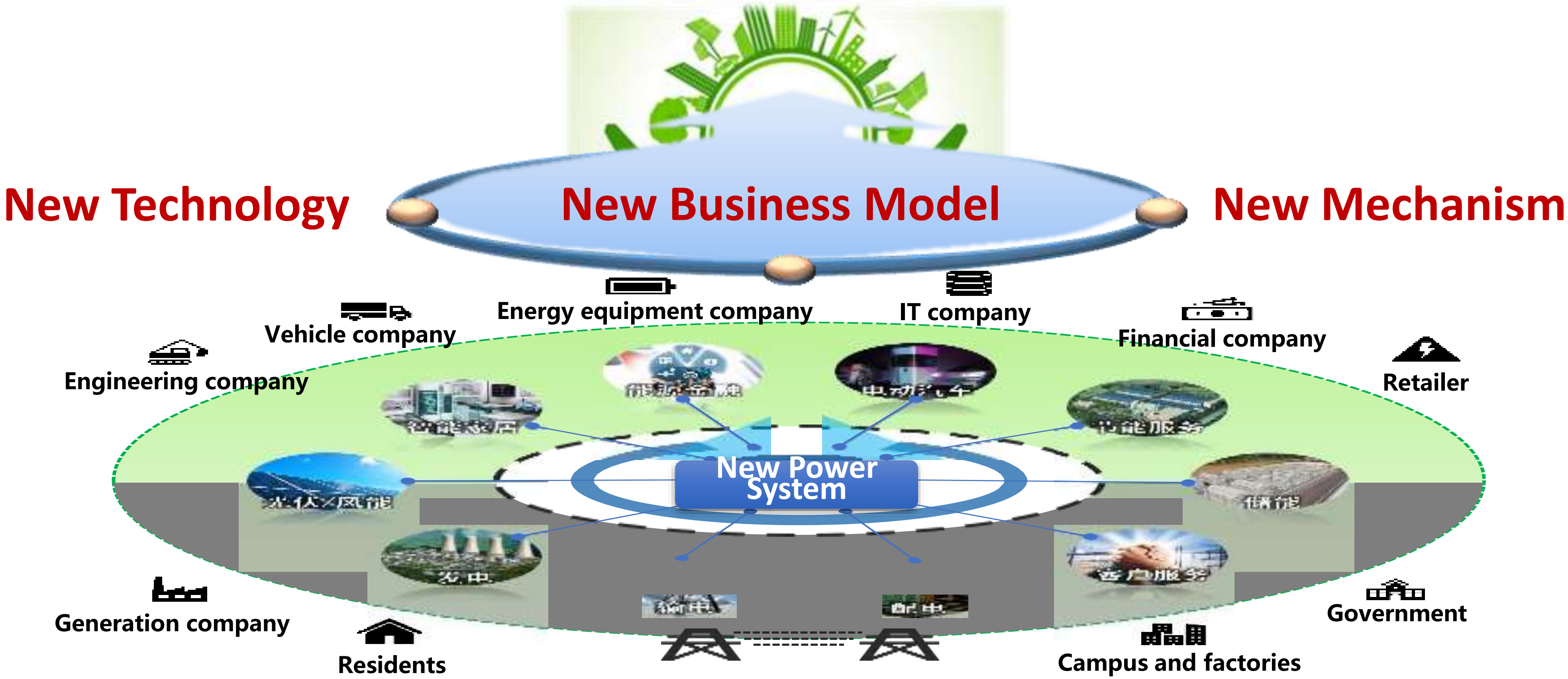
Science Press
Beijing

Springer

Jianxiao Wang, **Haiwang Zhong**, Qing Xia, Gengyin Li, Ming Zhou. Sharing Economy in Energy Markets: Modeling, Analysis and Mechanism Design, Springer

Conclusion

- The new power system is not only the innovation of technology, but also mechanism. The energy system will be reshaped by renewables, flexible loads and energy storage, forming a new form of source-grid-load-storage interaction and creating an open, shared, competitive and win-win energy ecosystem with Energy Internet technology and a fair value distribution mechanism.



Thanks!

Haiwang Zhong

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Tsinghua University
Director of the Trading and Operations Research Institute of
Sichuan Energy Internet Research Institute

November 21, 2024
Sydney

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Energy Insights