# Incorporating Massive Scenarios in Transmission Expansion Planning with High Renewable Penetration

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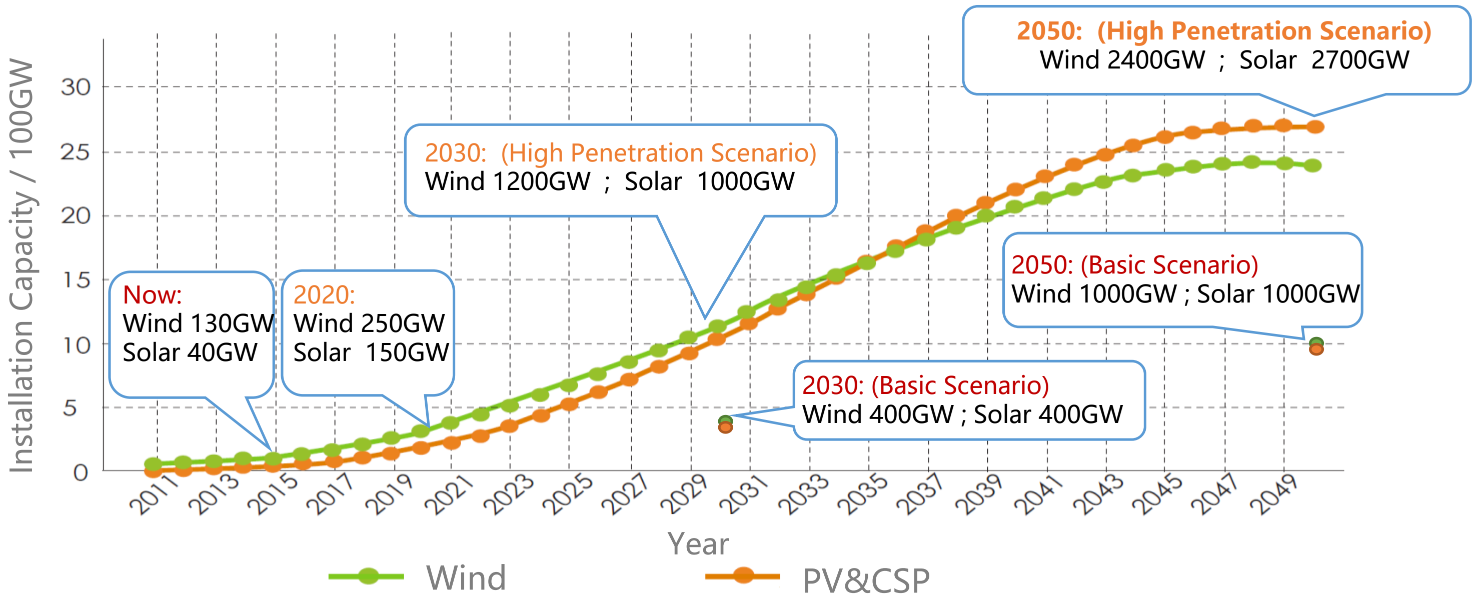
# Outline

## High penetrated renewable energy



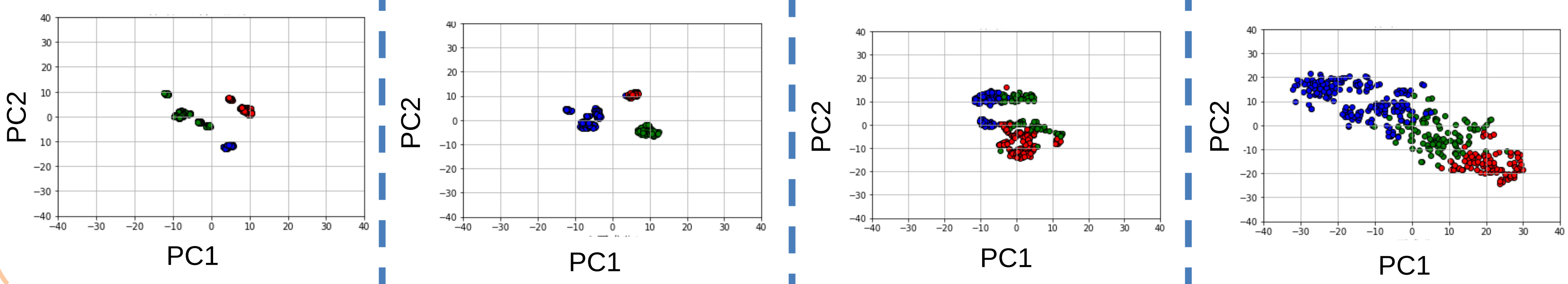

- The uncertainty and intermittency of renewable energy complicate the way of **real-time power balancing** and bring great challenges to the **transmission expansion planning**.

# Background



## ■ High renewable penetration diversifies the operation scenarios

### Distribution of operation states under different wind penetration (Case of Qinghai Province)

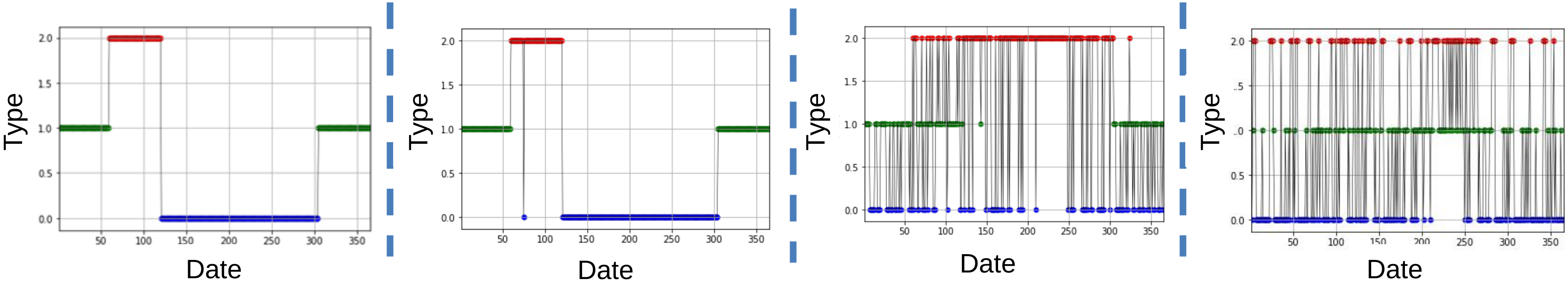



No wind power

Low wind penetration (7.4%)

Middle wind penetration (21%)

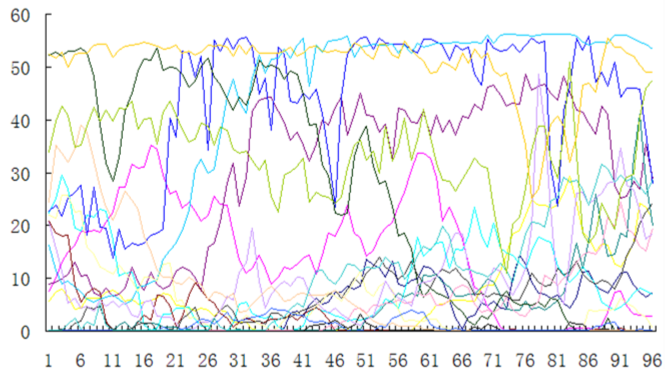
High wind penetration (50%)

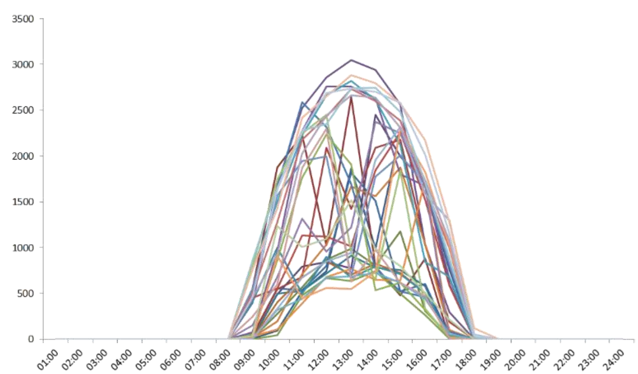


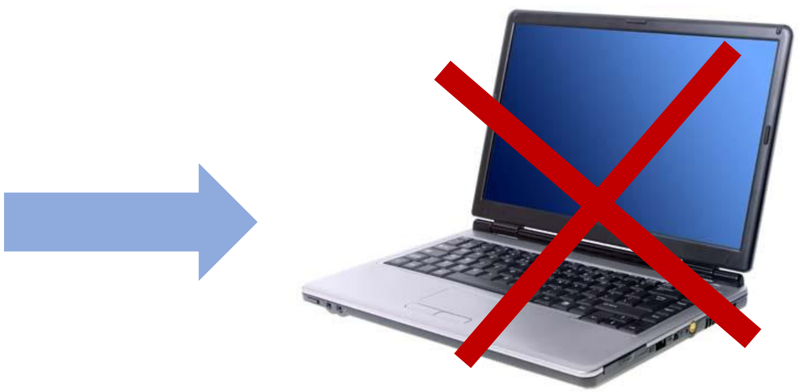
# Background

- **Massive renewable energy scenarios** are supposed to be considered in transmission planning with **high renewable penetration**.

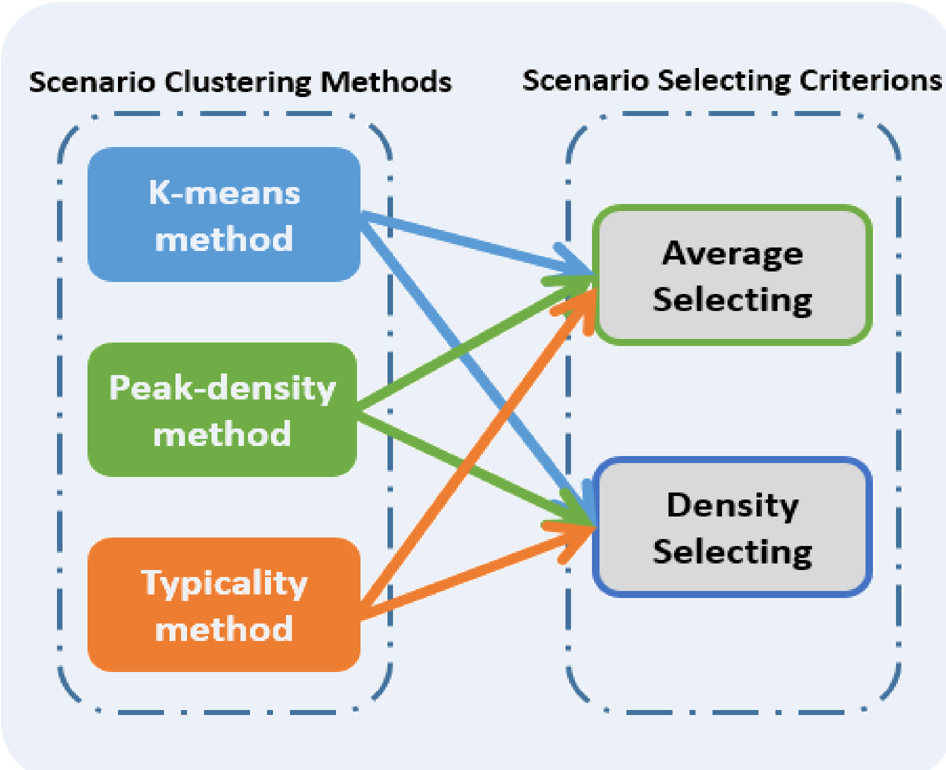
- Massive scenarios cause **gross computational burden**.



## ■ Scenario reduction method




- **connectivity-based**

(e.g. hierarchical clustering)

- **centroid-based**

(e.g. k-means clustering)

- **model-based**

(e.g. Gaussian mixture model (GMM))

- **density-based clustering**

(e.g. DBSCAN)

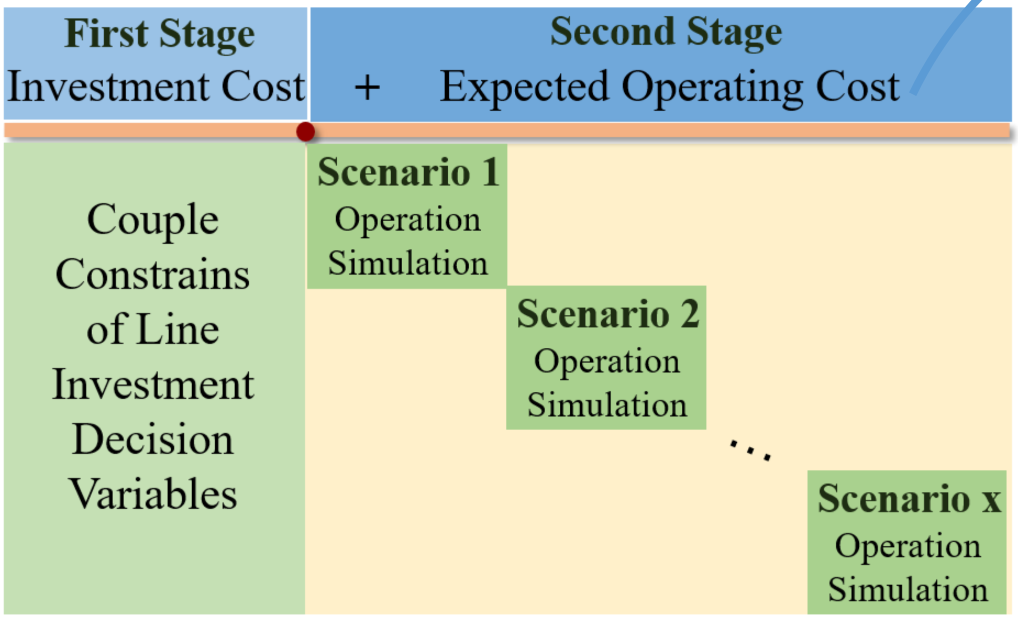
- ➢ Feature-based method, ignore the differences between problems
- ➢ The reduction changes the original model.


- Sun, M., et al. "An objective-based scenario selection method for transmission network expansion planning with multivariate stochasticity in load and renewable energy sources." *Energy*, vol.145 (2018): 871-885.

## ■ What we do

- ☐ Find a way to incorporate more scenarios under the condition that the problem is tractable.
- ☐ Cluster the scenarios according to their contributions to solution process.
- ☐ Change the original problem as less as possible to minimize the impacts to the optimal solution.

## ■ The two-stage TEP model




$$\min \sum_{lc\in\Omega_{lc}} C_{lc}^{inv} x_{lc} + \sum_{s\in\Omega_s} \pi_s \sum_{g\in\Omega_g} C_g^{op} P_{g,s}$$

$$s.t. \sum_{lc\in\Omega_{lc}^n} f_{lc,s} + \sum_{le\in\Omega_{le}^n} f_{le,s} + L_{n,s} =$$

$$\sum_{g\in\Omega_g^n} P_{g,s} + \sum_{r\in\Omega_r^n} P_{r,s} + Ls_{n,s} \quad \forall n,\forall s$$

$$f_{le,s} - B_{le,s}\left(\theta_{le,s}^i - \theta_{le,s}^j\right) = 0 \quad \forall le,\forall s$$

$$\left| f_{lc,s} - B_{lc,s}\left(\theta_{lc,s}^i - \theta_{lc,s}^j\right)\right| \le T(1-x_{lc}) \quad \forall lc,\forall s$$

$$\left| f_{le,s}\right| \le f_{le}^{\max} \quad \forall le,\forall s$$

$$\left| f_{lc,s}\right| \le x_{lc} f_{lc}^{\max} \quad \forall lc,\forall s$$

$$P_g^{\min} \le P_{g,s} \le P_g^{\max} \quad \forall g,\forall s$$

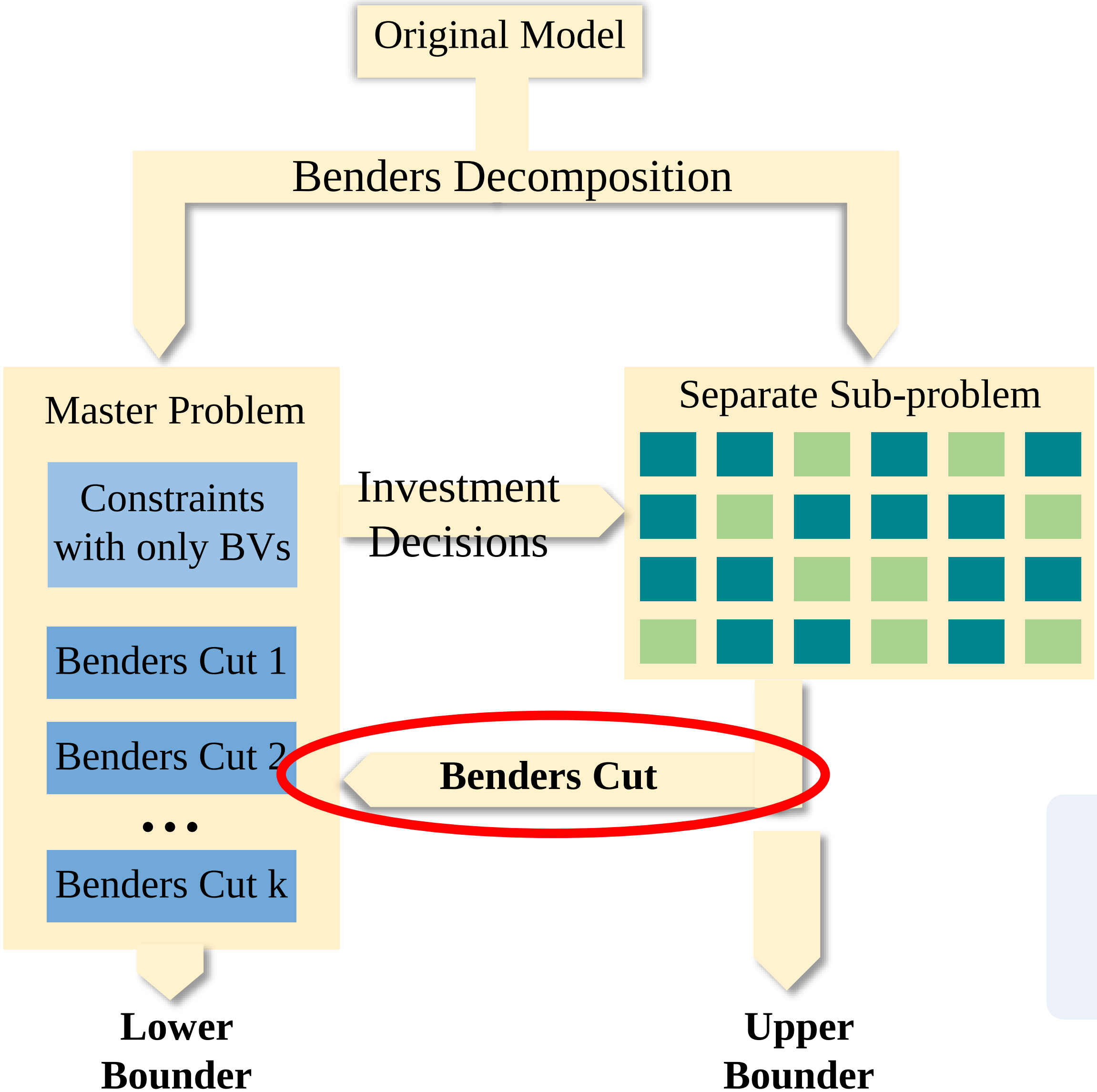
$$0 \le P_{r,s} \le P_{r,s}^{\max} \quad \forall g,\forall s$$

$$0 \le Ls_{n,s} \le L_{n,s} \quad \forall n,\forall s$$

$$x_{lc} \in \{0,1\}$$

- The first stage determines the investment decisions;
- The second stage is the operation simulation for each scenario;
- The scenarios indicate the hourly RE output and load level.

## ■ Benders decomposition




- Benders decomposition splits the model into two parts: **master problem** and **sub problems.**
- **Feasible investment decisions** are obtained by solving master problem.
- With the investment determined, sub problems corresponding to the scenarios can be solved separately.
- Benders cut shows how the sub problems influent the process.

# Problem statement and solution

## ■ Benders decomposition

$$\min \sum_{lc\in\Omega_{lc}} C_{lc}^{inv} x_{lc} + \sum_{s\in\Omega_s} \pi_s \sum_{g\in\Omega_g} C_g^{op} P_{g,s}$$

$$s.t. \sum_{lc\in\Omega_{lc}^n} f_{lc,s} + \sum_{le\in\Omega_{le}^n} f_{le,s} + L_{n,s} =$$

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$$f_{le,s} - B_{le,s}\left(\theta_{le,s}^i - \theta_{le,s}^j\right) = 0 \quad \forall le, \forall s$$

$$\left| f_{lc,s} - B_{lc,s}\left(\theta_{lc,s}^i - \theta_{lc,s}^j\right)\right| \le T(1 - x_{lc}) \quad \forall lc, \forall s$$

$$\left| f_{le,s} \right| \le f_{le}^{\max} \quad \forall le, \forall s$$

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$$P_g^{\min} \le P_{g,s} \le P_g^{\max} \quad \forall g, \forall s$$

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$$x_{lc} \in \{0,1\}$$

Sub problem in matrix form

$$\min cy$$

$$s.t. \quad Ay \ge b_0 + E\theta : \lambda$$

$$y \in R^n$$

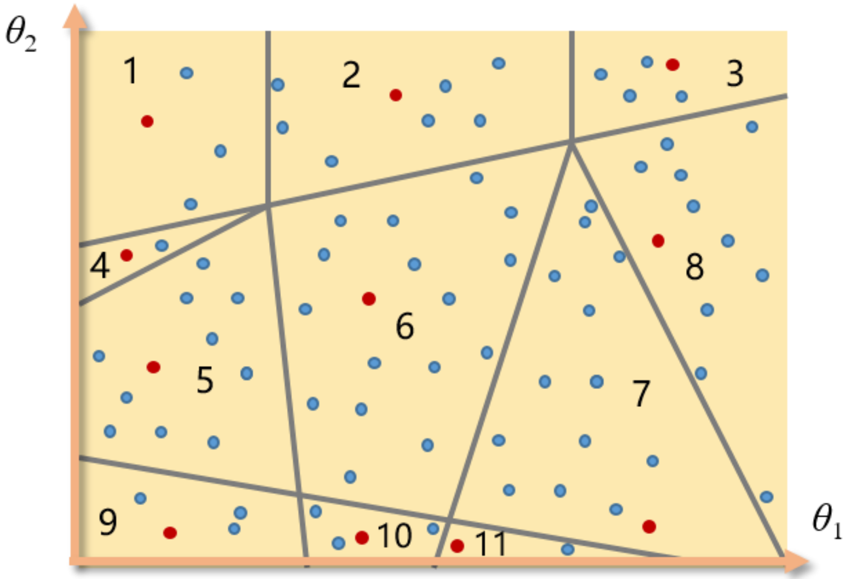
➢ Expression of benders cut:

$$c_{inv}^T x + \sum_s \pi_s * (b_0 + E\theta)\lambda \le z$$

- Benders cut is formed using the **Lagrange multiplier vectors λ of sub problems.**
- The differences of sub problems lie in the right-hand-side parameters.
- To cluster the scenarios according their impacts on the iteration, we need to understand **how the variations of right-hand-side parameters impact $\lambda$.**

# Problem statement and solution

## ■ Multiple parametric linear programming (MPLP)




- The theory of MPLP presents the influence of variations in multiple parameters on the optimal solution

- MPLP is based on the concept of **Critical Region (CR)**. CR is a polyhedron in the scenario hyperspace

➢ Expression of sub problem:

$$\min cy$$
$$s.t.\ Ay \geq b_0 + E\theta : \lambda$$
$$y \in R^n$$

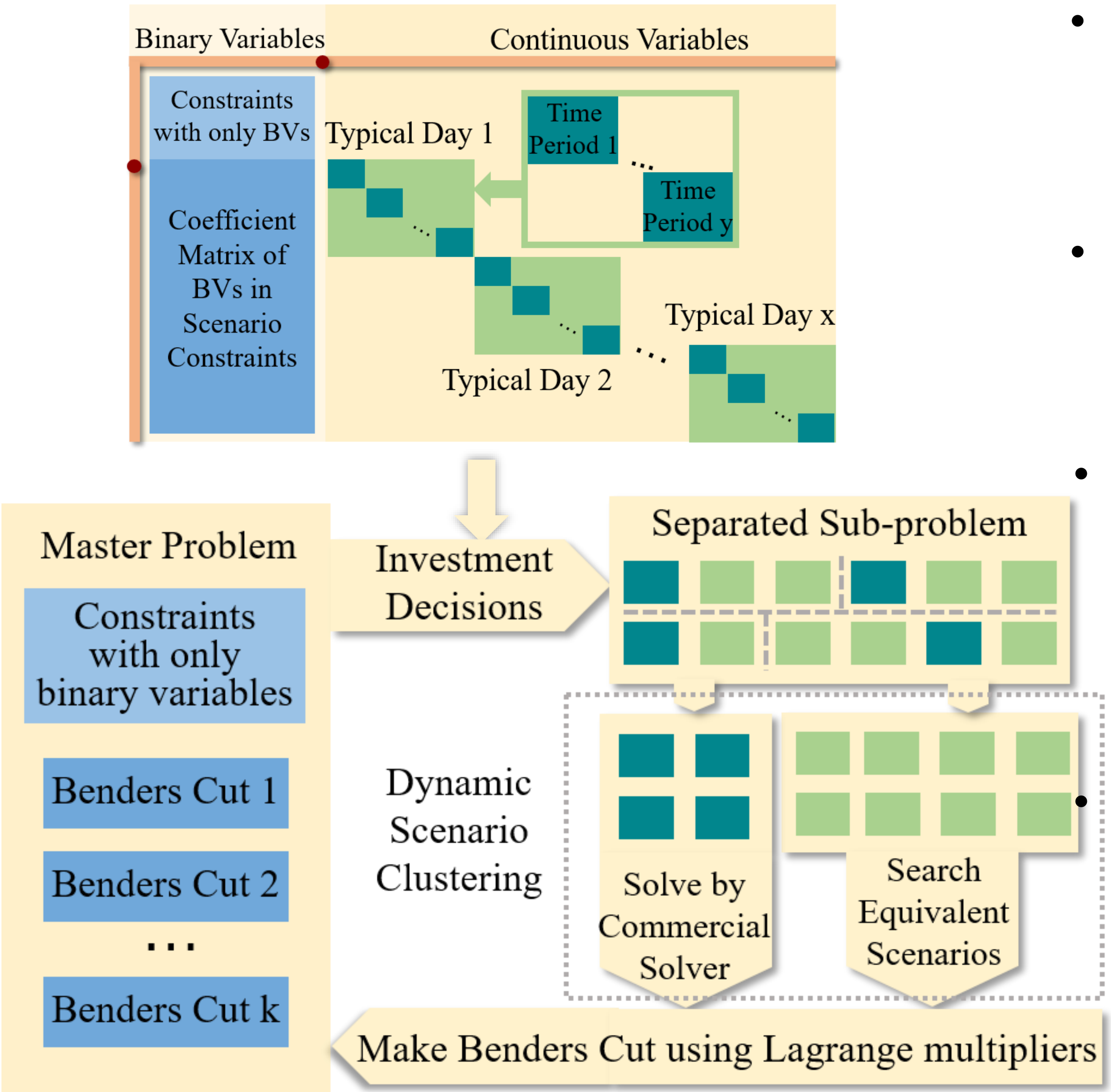
$$A^T = [B^T, N^T] \qquad b_0 + E\theta = \begin{bmatrix} b_B \\ b_0^N \end{bmatrix} = \begin{bmatrix} b_0^B + E_B\theta \\ b_0^N + E_N\theta \end{bmatrix}$$

$$\text{CR} = \{\theta | (NB^{-1}E_B - E_N)\theta > b_0^N - NB^{-1}b_0^B\}$$

- **The scenarios in the same Critical Region share the same $\lambda$.**


- T. Gal and J. Nedoma, "Multiparametric linear programming," Management Science, vol. 18, no. 7, pp. 406–422, 1972.
- F. Borrelli, A. Bemporad, and M. Morari, "Geometric algorithm for multiparametric linear programming," Journal of optimization theory and applications, vol. 118, no. 3, pp. 515–540, 2003.

## ■ The overall framework

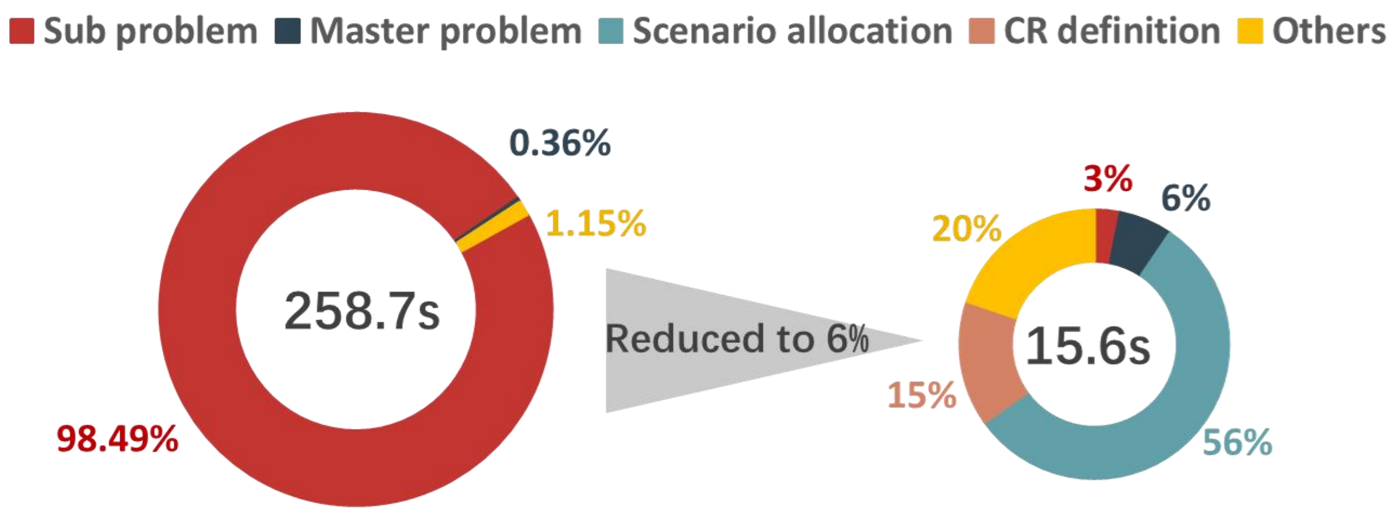



- Once a sub problem is solved, then a corresponding critical region can be defined.
- For the next sub problem, we **judge** whether it belongs to the existing critical regions or not.
- If so, the corresponding $\lambda$ can be obtained directly. If not, we solve it with commercial solver and define a new critical region
- Thus, dynamic scenarios clustering (DSC) is embedded into the traditional Benders decomposition (TBD).

# Case study

## ■ Graver's 6-node test system with 8760 scenarios

### ➢ Time consumption




TBD
traditional Benders decomposition

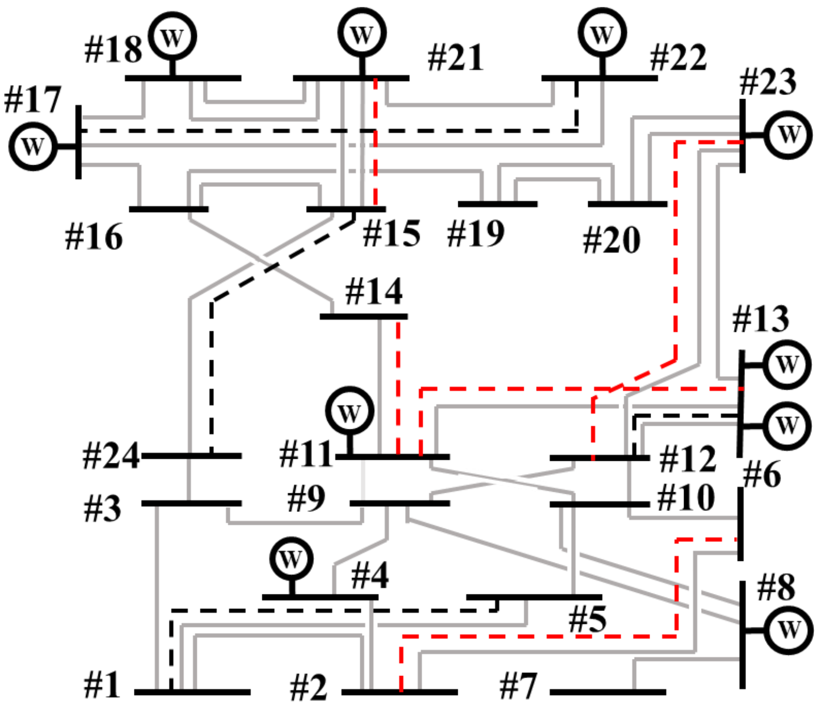
DSC
dynamic scenarios clustering

- The investment results are the same because the model are the same.

• R. Villasana, L. Garver, and S. Salon, "Transmission network planning using linear programming," IEEE transactions on power apparatus and systems, no. 2, pp. 349–356, 1985.

■ IEEE RTS-79 test system

➢ Network topology



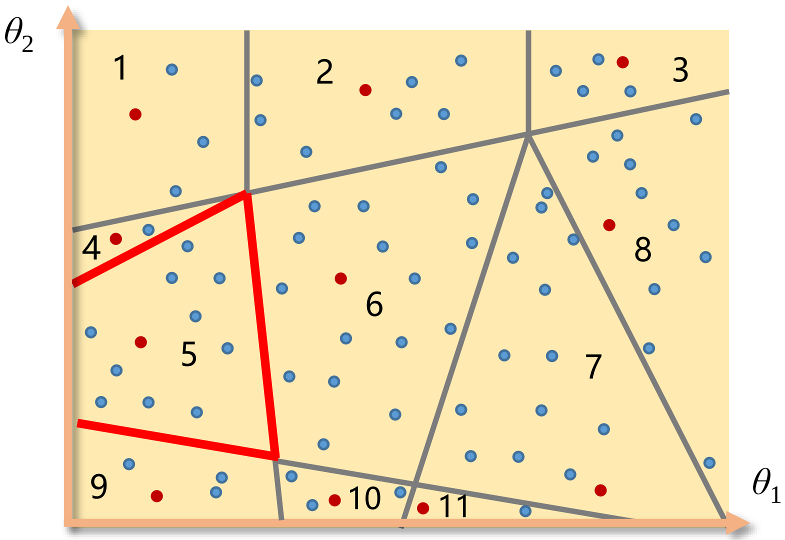

➢ Comparison of results and time consumption

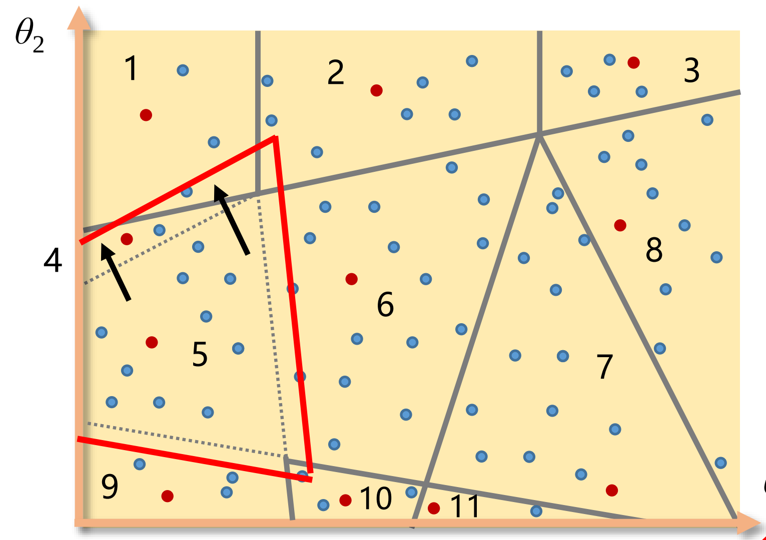
| Method | Time (s) | Investment decisions | Number of calling Cplex |
|---|---|---|---|
| TBD | 575.722 | 2-6,11-13, 11-14, 12-23, 15-21 | 595680 |
| DSC | 157.718 | | 31558 |

- The investment results are the same.
- The proposed method reduces the time to 27.4%

Wind penetration is over 50%
The number of critical regions is over 370

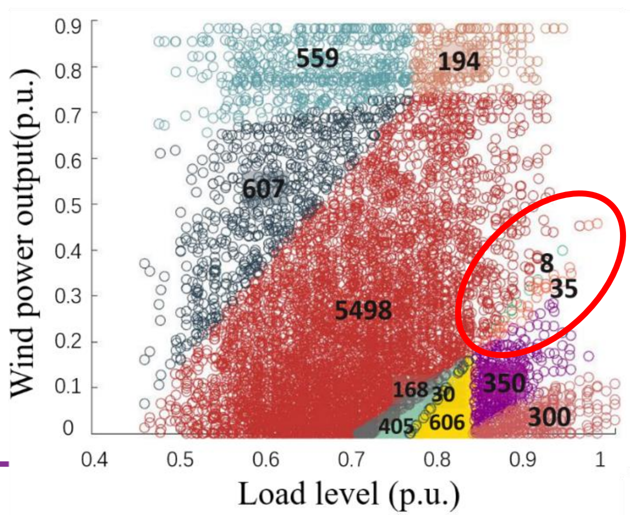
## ■ Merging CRs by Adjustable Slacking




$$\text{CR}=\left\{\theta \mid \left(NB^{-1}E_B-E_N\right)\theta > b_0^N - NB^{-1}b_0^B\right\}$$

$$\text{CR}=\bigcup_i\left\{\theta \mid \left(NB^{-1}E_B-E_N\right)\theta > b_0^N - NB^{-1}b_0^B - \alpha I(i)\right\}$$




- **With the strict CR definition, lots of small CRs exist in the hyperspace.**
- **A small number of scenarios allocate in the small CRs.**
- **Introduce the limitation coefficient (α) in the expression to expand the bounders.**

清華大學 Ellab Energy Intelligence Laboratory 智慧能源实验室

## ■ IEEE RTS-79 test system

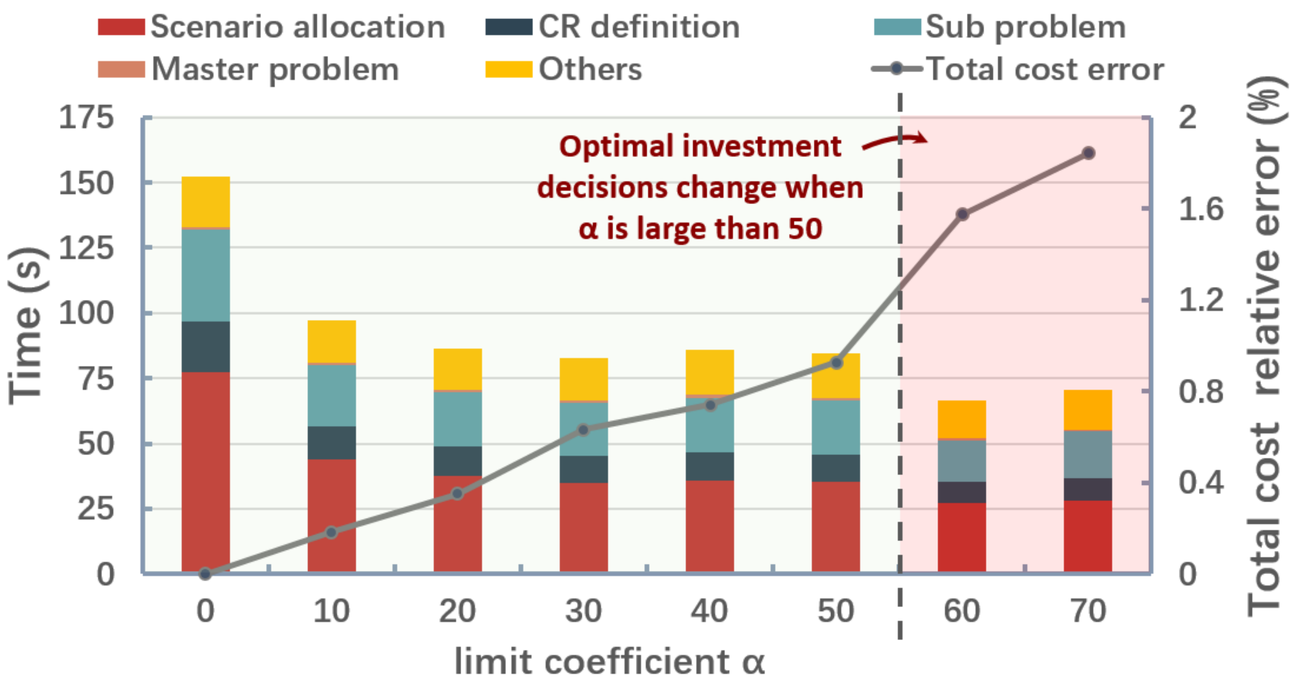
### ➢ Comparison of results and time consumption

| Method | Time (s) | Investment decisions | Number of calling Cplex | Average number of CRs |
|---|---|---|---|---|
| TBD | 575.722 | 2-6,11-13, 11-14, 12-23, 15-21 | 595680 | N/A |
| DSC (α=0) | 157.718 | | 31558 | 370.76 |
| **DSC (α=40)** | **85.698** | | **18206** | **185.28** |

- The investment results are still the same.
- The number of CRs is decreased by 50%.
- The modified method further reduces the time to 14.9%

■ IEEE RTS-79 test system

➢ Sensitivity analysis on limitation coefficient α




- A **larger α** leads to **shorter computation time** but **larger relative error.**
- When α is greater than 50, the optimal investment decisions change.
- Note that the computation time decreases rapidly with small α, but the speed of decreasing slows down with increasing α.

## ■ Guizhou 230-bus system

- 230 buses, 275 corridors and 21 candidate branches
- RE penetration is 43%
- 17520 scenarios are integrated into the model.

| Method | Time (s) | Investment decisions | Number of calling Cplex | Average number of CRs |
|---|---|---|---|---|
| TBD | 11307.490 | 21-66, 98-227, 53-228, 94-229, 69-230, 157-193, 193-220, 24-190 | 2610480 | N/A |
| DSC (α=0) | 3081.228 | | 183688 | 616.40 |
| DSC (α=30) | 1373.755 | | 616.40 | 409.29 |

- The investment results are still same.
- The proposed method reduces the time to 12.15%
- This method is applicable to realistic-sized systems.

# Summary

- Embed the dynamic scenario clustering into the traditional benders decomposition

- The time consumption can be reduced to around 15% for high renewable penetrated system while keep the optimal solution unchanged.

- Note that the proposed method is not an alternative for the scenario reduction method. The two can be combined to deal with TEP problem with much more scenarios.

# Thank you for your attention