Energy Intelligence Laboratory
智慧能源实验室

Multi Energy Systems Planning in China

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Major International (Regional) Joint Research Project "Fundamental research on low-carbon and efficient multiple energy systems towards renewable energy integration"

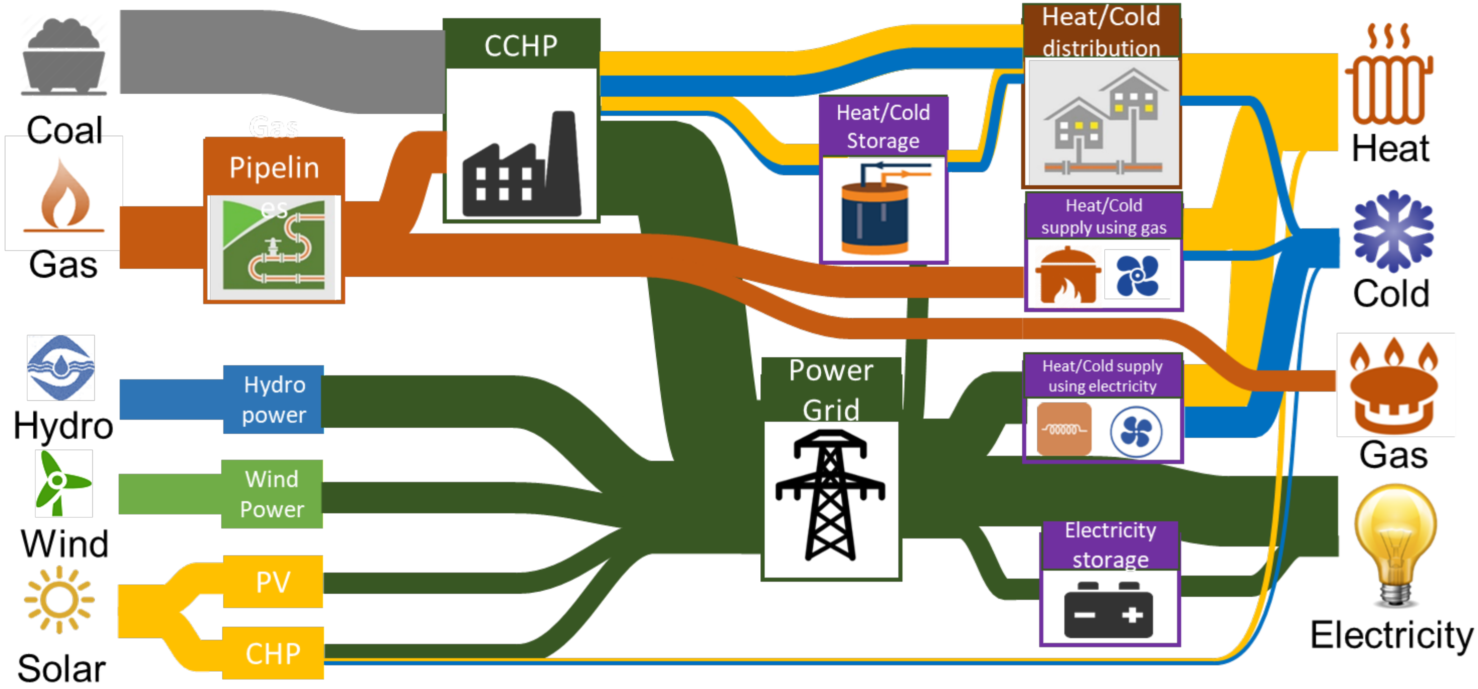
Self introduction

- Chongqing Kang (M'01-SM'08-F'17) received the Ph.D. degree from the Department of Electrical Engineering in Tsinghua University, Beijing, China, in 1997. He is currently a Professor at the same university. His research interests include load forecasting, electricity market, power system planning and generation scheduling optimization.

- Ning Zhang (S'10-M'12) received both a B.S. and Ph.D. from the Electrical Engineering Department of Tsinghua University in China in 2007 and 2012, respectively. He is now an Associate Professor at the same university. His research interests include multiple energy system integration, stochastic analysis and simulation of renewable energy, power system planning and scheduling with renewable energy.

Outline

- Energy Systems integration in China
- Standard Modeling of Multiple Energy Systems
- Planning of Energy Hub: Starting from Scratch
- Multi Energy Systems Planning of Subsidiary Administrative Center of Beijing

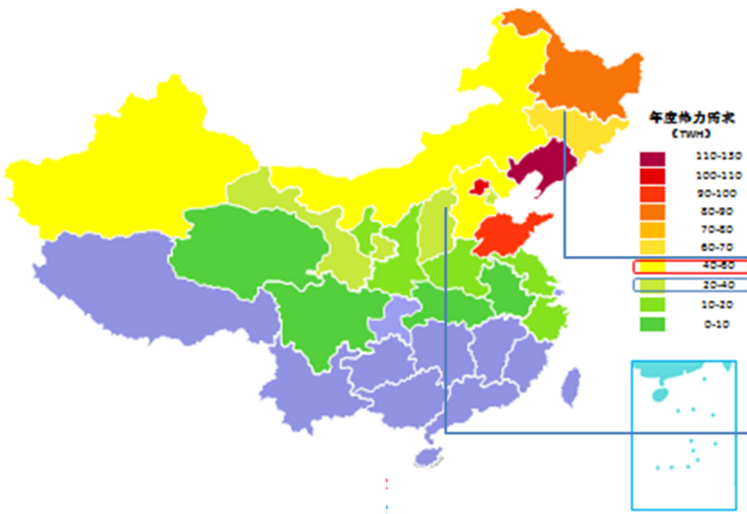


Energy Systems integration in China

Background of Energy Systems integration in China

- Why is the multiple energy systems integration important in China?

Heating demand distribution in China

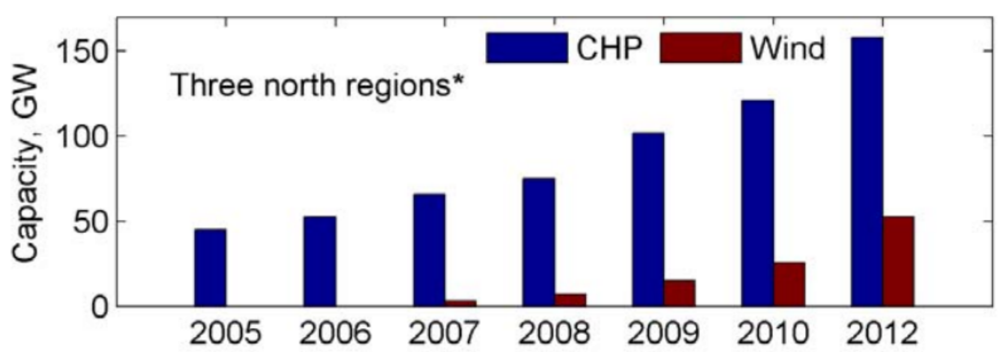


Percentage of CHP in coal-fired units:

National: 18%

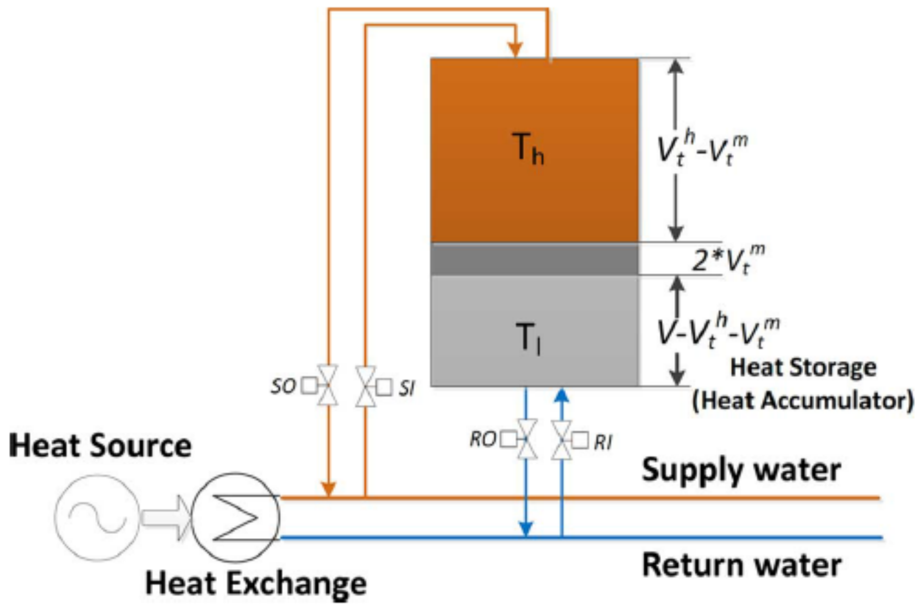
North East: 70%

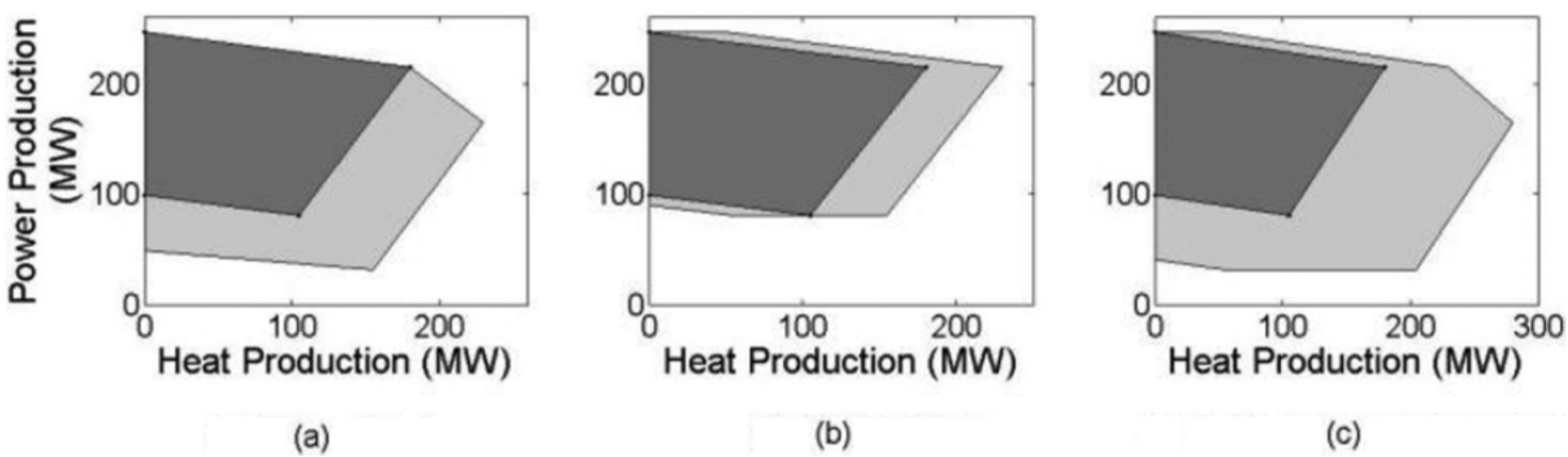
Northern China: 50%



- Large-sized Combined Heat and Power (CHP) units have been installed
- The output power of CHP is determined by heat demand, which makes the CHP units less flexible
- This leads to huge wind power curtailment

Electric-Heat Coupling



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Demonstration project

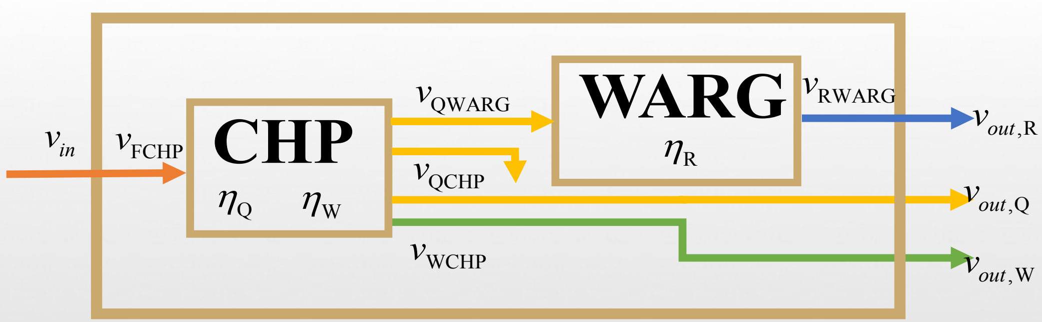
- NDRC has announced 56 demonstration project of Energy Internet in this March.
  - Including 24 projects for campus and city multi-energy systems
  - Including inter-regional multi-energy systems

Standard Modeling of Multiple Energy Systems

Multiple Energy Systems and Energy Hub

➢ EH models the energy conversion as port based unit with multiple inputs and multiple outputs.

$$V_{\mathrm{out}} = CV_{\mathrm{in}}$$

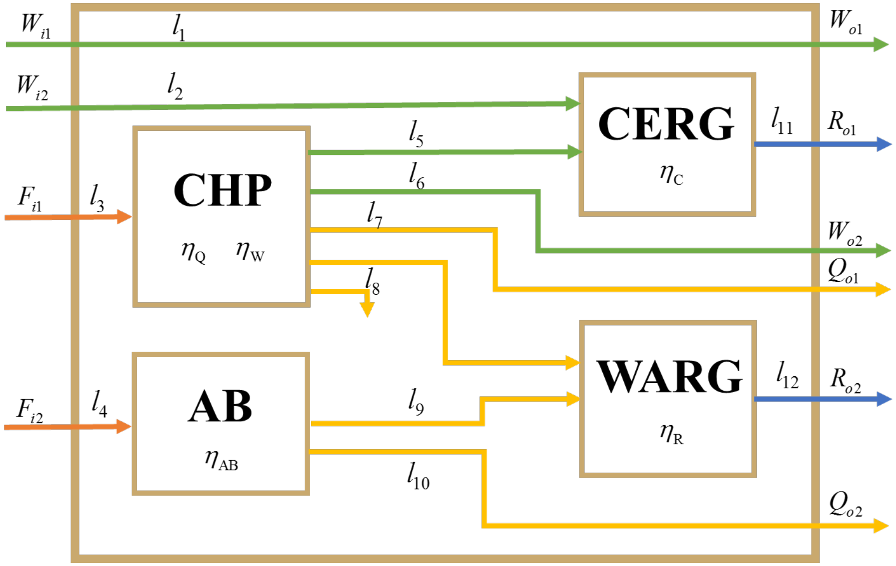


$$V_{in} = \left[v_{in,\mathrm{F}} \right]$$

$$V_{out} = \left[v_{out,\mathrm{R}} \;\; v_{out,\mathrm{Q}} \;\; v_{out,\mathrm{W}} \right]^T$$

$$C = \left[\eta_{\mathrm{Q}}\alpha_{\mathrm{R}}\eta_{\mathrm{R}} \quad \eta_{\mathrm{Q}}\alpha_{\mathrm{Q}} \quad \eta_{\mathrm{W}} \right]^T$$

Multiple Energy Systems and Energy Hub



- **Complex multiple energy systems are hard to be modeled and introduces nonlinearity to the coupling matrix.**

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ \alpha_{WW}^{CHP}\eta_W\alpha_{YF}^{GDS} & \alpha_{WW}^{EDS} & 0 & 0 \\ \alpha_{QQ}^{AB}\eta_t(1-\alpha_{YF}^{GDS})+\alpha_{QQ}^{CHP}\eta_Q\alpha_{YF}^{GDS} & 0 & 0 & 0 \\ \eta_{RF} & COP^{CERG}(1-\alpha_{WW}^{EDS}) & 0 & 0 \end{pmatrix}$$

$$\eta_{RF} = COP^{CERG}(1-\alpha_{WW}^{CHP})\eta_W\alpha_{YF}^{GDS} + COP^{WARG} \times \left[(1-\alpha_{QQ}^{CHG})\eta_t(1-\alpha_{YF}^{GDS})+\alpha_{RQ}^{CHP}\eta_Q\alpha_{YF}^{GDS}\right]$$

Hard to be modeled automatically

Introduce high degree nonlinearity

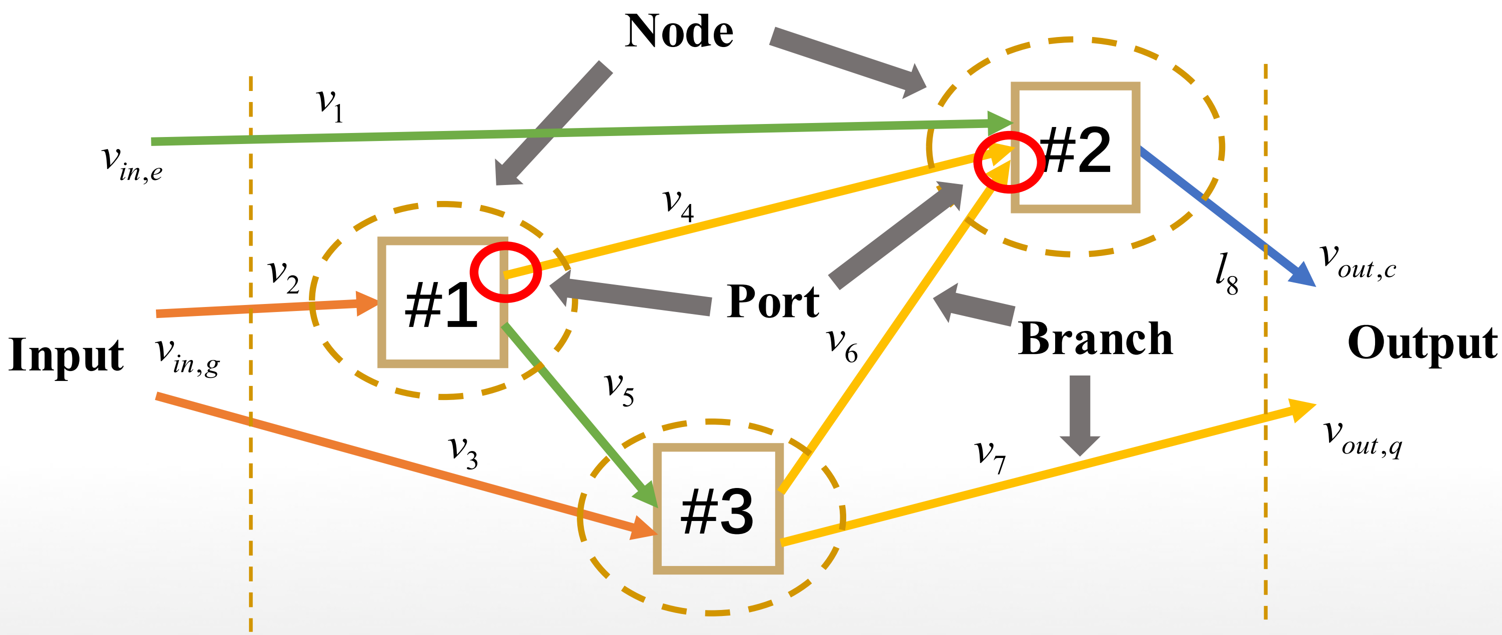
Gianfranco Chicco, Pierluigi Mancarella, Matrix modelling of small-scale trigeneration systems and application to operational optimization, Energy, Volume 34, Issue 3, 2009, Pages 261-273

Questions

- How to automatically model arbitrary multiple energy systems?
- How to linearize the non-linearity in the model?

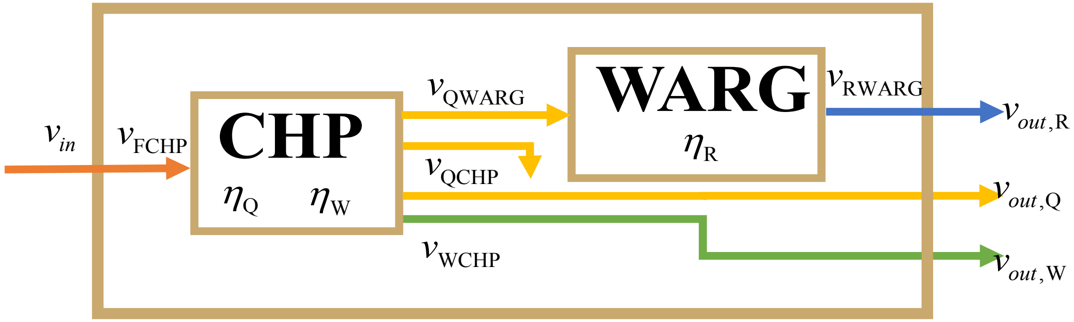
Standard Modeling of Energy Hub

- A MES consists of two basic elements: **energy conversion devices** and **their connection relationship.**



Branch, describes the energy flow.
Node, describes the energy convertor, or storage, or input and output terminal.
Port, is defined as the interface of a node that exchange energy with others.

Basic Matrices



For the g-th node, we define ***converter characteristic matrix***, $\boldsymbol{H}_g$ to describe the characteristics of the node.

$$\boldsymbol{H}_{1,2\times 3}=\begin{bmatrix}\eta_{\mathrm{Q}} & 1 & 0\\ \eta_{\mathrm{W}} & 0 & 1\end{bmatrix}$$

The ***port-branch incidence matrix A*** is defined to describe the connection relation between the ports of a node and the branches.

$$m_b=\begin{cases}1 & \text{branch } b \text{ is connected to input port } k \text{ of node } g\\ -1 & \text{branch } b \text{ is connected to output port } k \text{ of node } g\\ 0 & \text{branch } b \text{ is not connected to any port of node } g\end{cases}$$

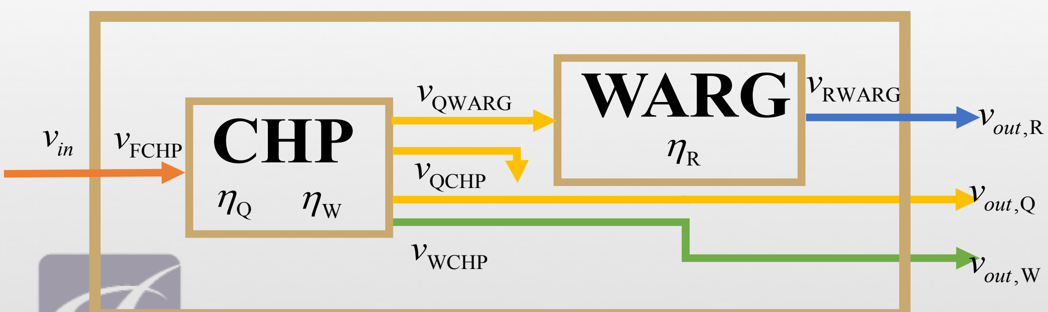
◆ Energy Conversion Matrices

Given the port-branch incidence matrix and the converter characteristic matrix, we can calculate the ***branch energy conversion matrix*** for node g:

$$\boldsymbol{Z}_g = \boldsymbol{H}_g \boldsymbol{A}_g$$

The ***system energy conversion matrix Z*** is the combination of the nodal energy conversion matrix of all nodes in EH:

$$\boldsymbol{Z} = \left[\boldsymbol{Z}_1^{\mathrm{T}}, \boldsymbol{Z}_2^{\mathrm{T}}, \ldots, \boldsymbol{Z}_N^{\mathrm{T}}\right]^T$$



$$\boldsymbol{Z}_1 = \begin{bmatrix} \eta_{\mathrm{Q}} & -1 & -1 & 0 & 0 \\ \eta_{\mathrm{W}} & 0 & 0 & -1 & 0 \end{bmatrix}$$

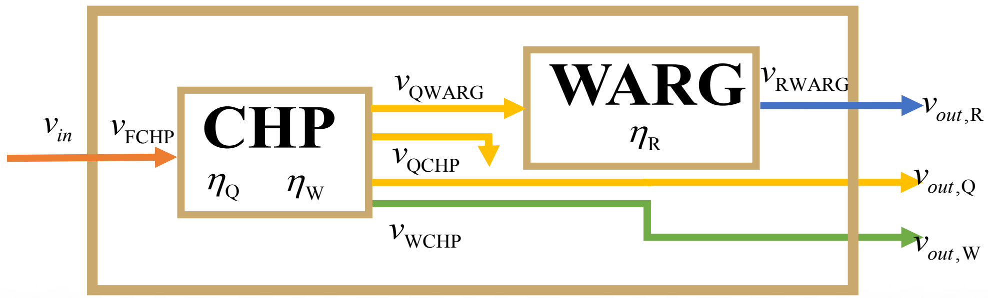
$$\boldsymbol{Z}_2 = \begin{bmatrix} 0 & \eta_{\mathrm{R}} & 0 & 0 & 1 \end{bmatrix}$$

Basic Model

The ***system energy conversion matrix Z*** is the combination of the nodal energy conversion matrix of all nodes in EH:

$$\boldsymbol{Z} = \left[\boldsymbol{Z}_1^{\mathrm{T}}, \boldsymbol{Z}_2^{\mathrm{T}}, \ldots, \boldsymbol{Z}_N^{\mathrm{T}}\right]^T$$

For the MES, the system energy conversion matrix $\boldsymbol{Z}$ is:



$$\boldsymbol{Z} = \begin{bmatrix} \eta_{\mathrm{Q}} & -1 & -1 & 0 & 0 \\ \eta_{\mathrm{W}} & 0 & 0 & -1 & 0 \\ 0 & \eta_{\mathrm{R}} & 0 & 0 & -1 \end{bmatrix}$$

Then, we can obtain the ***energy conversion equation*** of the EH:

$$\boldsymbol{Z}\boldsymbol{V} = \boldsymbol{0}$$

The vector of energy flow in branches

Define input and output relationship

We define can obtain the ***input incidence matrix*** and ***output incidence matrix*** of the EH to describe the mapping relationship between energy inputs and outputs of EH and its branch energy flows:

$$\boldsymbol{V_{in}} = \boldsymbol{XV}$$

$$\boldsymbol{V_{out}} = \boldsymbol{YV}$$

Thus, we form the ***comprehensive energy flow equations*** of EH:

$$\begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{Y} \\ \boldsymbol{Z} \end{bmatrix} \boldsymbol{V} = \begin{bmatrix} \boldsymbol{V}_{in} \\ \boldsymbol{V}_{out} \\ \mathbf{0} \end{bmatrix} \Rightarrow \begin{bmatrix} \mathbf{0} & \boldsymbol{Y} \\ \mathbf{-}\boldsymbol{I} & \boldsymbol{X} \\ \mathbf{0} & \boldsymbol{Z} \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_{in} \\ \boldsymbol{V} \end{bmatrix} = \begin{bmatrix} \boldsymbol{V}_{out} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix}$$

Energy conversion equation acts as a bridge between the input vector $\boldsymbol{V}_{in}$ and output vector $\boldsymbol{V}_{out}$. The visible function expressions between $\boldsymbol{v}_{in}$ and $\boldsymbol{V}_{out}$, i.e. coupling matrix, can be produced through Gauss elimination.

Gaussian elimination to obtain coupling matrix

The visible relationship between V_{in} and V_{out}, i.e. coupling matrix, can be produced through Gaussian elimination.

$$\begin{bmatrix} 0 & Y \\ -I & X \\ 0 & Z \end{bmatrix} \begin{bmatrix} V_{in} \\ V \end{bmatrix} = \begin{bmatrix} V_{out} \\ 0 \\ 0 \end{bmatrix} \Rightarrow \underbrace{\begin{bmatrix} -I \\ 0 \end{bmatrix}}_{R} V_{in} + \underbrace{\begin{bmatrix} X \\ Z \end{bmatrix}}_{Q} V = 0$$

$$Q = \begin{bmatrix} X \\ Z \end{bmatrix}$$

Q invertible $\Rightarrow$

$$V = -Q^{-1} R V_{in}$$

$$V_{out} = -YQ^{-1} R V_{in}$$

$$\Rightarrow V_{out} = \underbrace{-YQ^{-1} R}_{C} V_{in}$$

Q is not invertible $\Rightarrow$

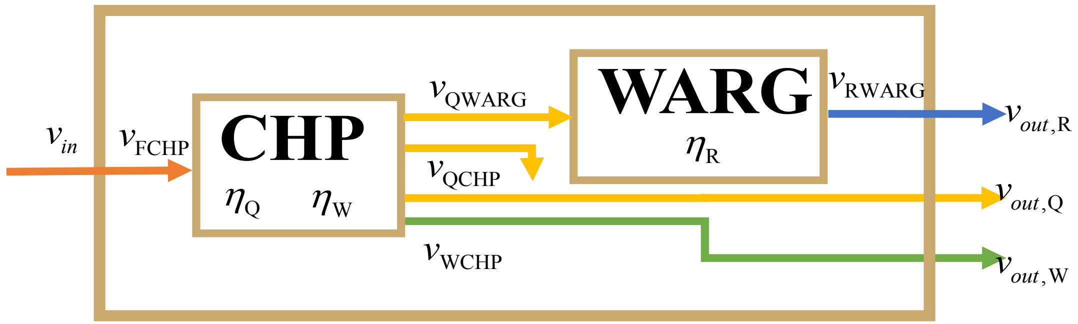
$$R V_{in} + \begin{bmatrix} Q_1 & Q_2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = 0$$

$$V_{out} = \begin{bmatrix} Y_1 & Y_2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

$$\Rightarrow V_{out} = \begin{bmatrix} \underbrace{-Y_1 Q_1^{-1} R}_{C_1} & \underbrace{Y_2 - Y_1 Q_1^{-1} Q_2}_{C_2} \end{bmatrix} \begin{bmatrix} V_{in} \\ V_2 \end{bmatrix}$$

Computerized modeling

◆ **Standardized Data Structure**



Node Table:

- *node ID*
- *node type*
- *node parameters*

TABLE I
NODE TABLE OF THE EH IN FIG. 2

No.	Node Type	Parameters	
-1	-1	0	0
0	0	0	0
1	3	η_Q	η_W
2	1	η_{WARG}	0

Branch Table

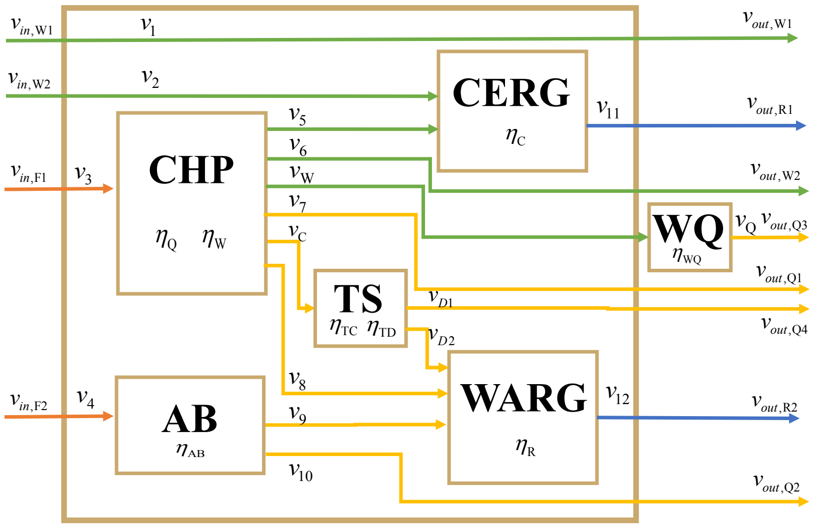
- *branch ID*
- *branch type*
- *source node*
- *sink node*
- *branch parameters*

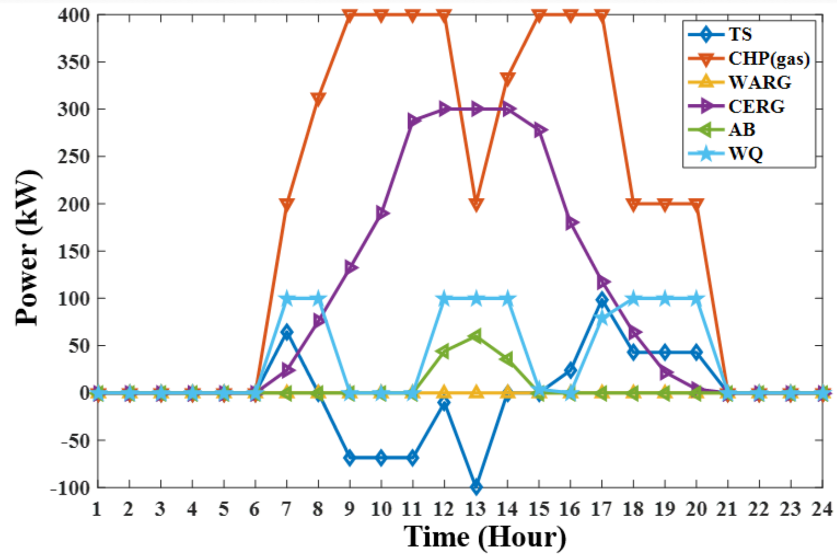
TABLE II
BRANCH TABLE OF THE EH IN FIG. 2

No.	Branch Type	Source	Sink	Parameters
1	4	-1	1	0
2	3	1	2	0
3	3	1	0	300
4	1	1	0	0
5	2	2	0	0

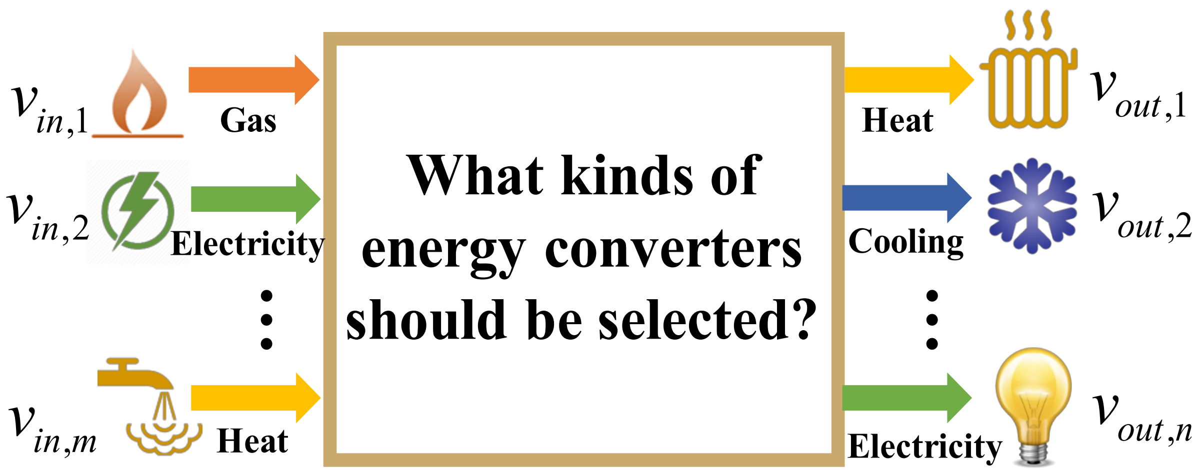
Extended Analysis

◆ Case Studies





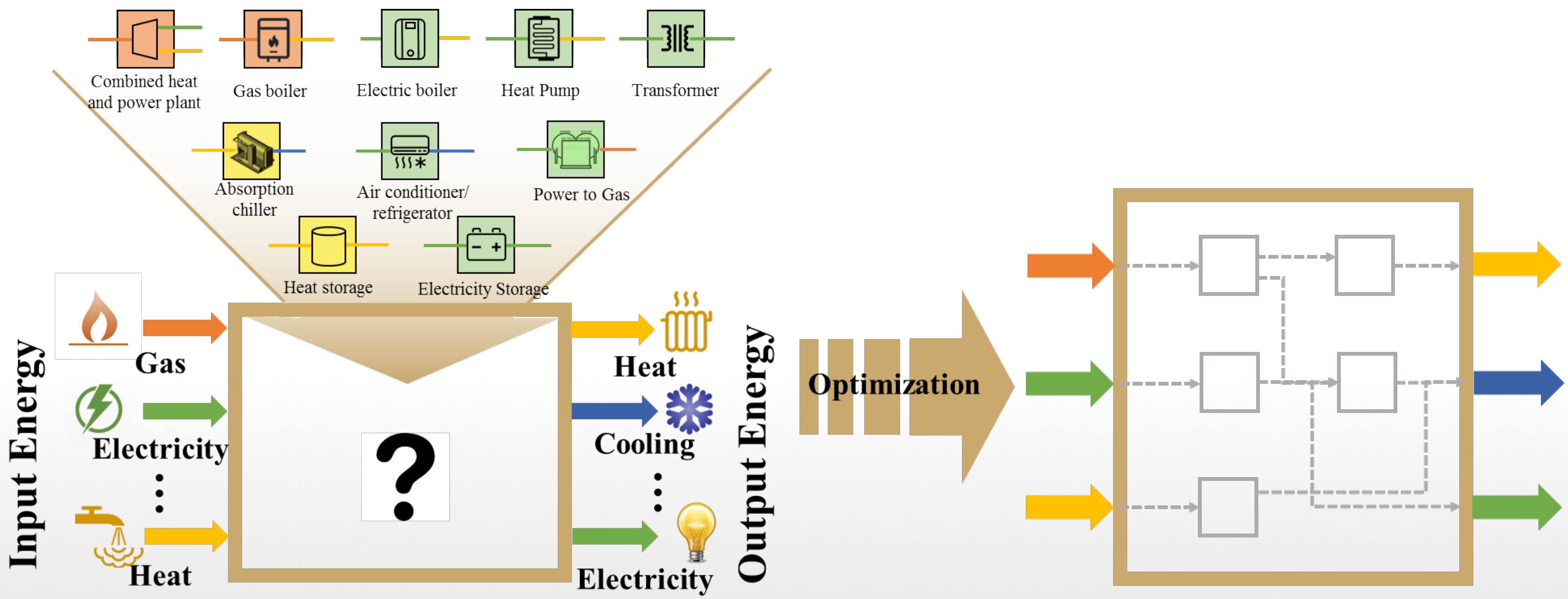
$$
\left[\begin{array}{cc:c:cccccccccccc:ccc:cc}
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
\hdashline
-1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hdashline
0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \eta_{TC} & -1/\eta_{TD} & -1/\eta_{TD} & 0 & 0 \\
\hdashline
0 & 0 & 0 & 0 & 0 & \eta_Q & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & \eta_W & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \eta_{AB} & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \eta_C & 0 & 0 & \eta_C & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \eta_R & \eta_R & 0 & 0 & -1 & 0 & 0 & \eta_R & 0 & 0 \\
\hdashline
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \eta_{WQ} & -1
\end{array}\right]
\left[\begin{array}{c}
v_{in,F} \\ \hdashline \dot{E} \\ \hdashline v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \\ v_6 \\ v_7 \\ v_8 \\ v_9 \\ v_{10} \\ v_{11} \\ v_{12} \\ \hdashline v_C \\ v_{D1} \\ v_{D2} \\ \hdashline v_W \\ v_Q
\end{array}\right]
=
\left[\begin{array}{c}
v_{out,W} \\ v_{out,R} \\ v_{out,Q} \\ \hdashline 0 \\ 0 \\ \hdashline 0 \\ \hdashline 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \hdashline 0
\end{array}\right]
$$



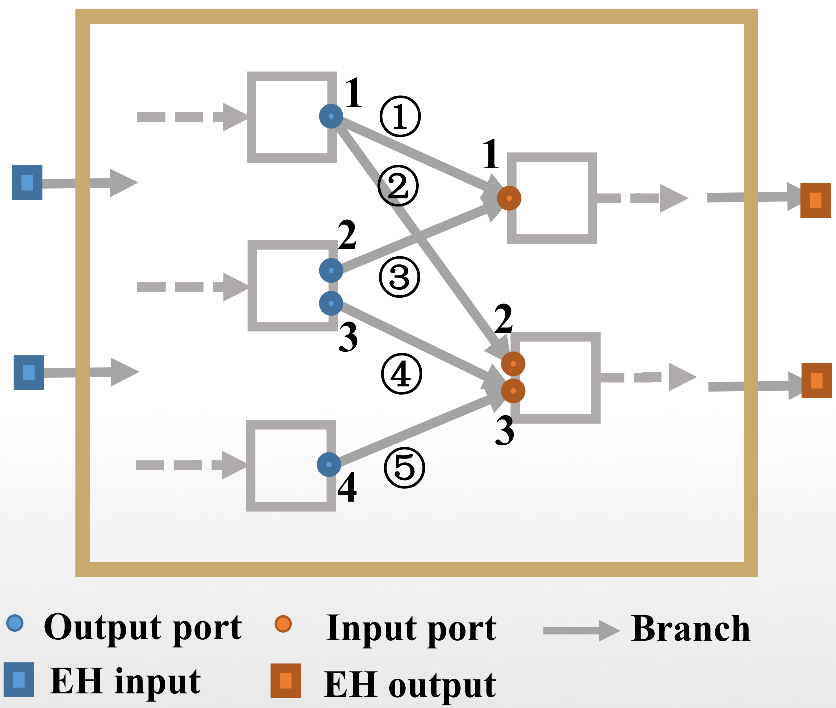
Planning of Energy Hub: Starting from Scratch

Planning: Starting from Scratch

◆ Problem Statement



Modeling connections of possible components



	#1	#2		#3	···	#N	Output	
Input	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	$x_{1,4}$	L	$x_{1,n-2}$	$x_{1,n-1}$	$x_{1,n}$
	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	$x_{2,4}$	L	$x_{2,n-2}$	$x_{2,n-1}$	$x_{2,n}$
#1	$x_{3,1}$	$x_{3,2}$	$x_{3,3}$	$x_{3,4}$	L	$x_{3,n-2}$	$x_{3,n-1}$	$x_{3,n}$
#2	$x_{4,1}$	$x_{4,2}$	$x_{4,3}$	$x_{4,4}$	L	$x_{4,n-2}$	$x_{4,n-1}$	$x_{3,n}$
⋮	M	M	M	M	O	M	M	M
#N-1	$x_{m-2,1}$	$x_{m-2,2}$	$x_{m-2,3}$	$x_{m-2,4}$	L	$x_{m-2,n-2}$	$x_{m-2,n-1}$	$x_{m-2,n}$
	$x_{m-1,1}$	$x_{m-1,2}$	$x_{m-1,3}$	$x_{m-1,4}$	L	$x_{m-1,n-2}$	$x_{m-1,n-1}$	$x_{m-1,n}$
#N	$x_{m,1}$	$x_{m,2}$	$x_{m,3}$	$x_{m,4}$	L	$x_{m,n-2}$	$x_{m,n-1}$	$x_{m,n}$

Energy flow matrix

	#1	#2		#3	···	#N	Output	
Input	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	$x_{1,4}$	L	$x_{1,n-2}$	$x_{1,n-1}$	$x_{1,n}$
	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	$x_{2,4}$	L	$x_{2,n-2}$	$x_{2,n-1}$	$x_{2,n}$
#1	$x_{3,1}$	$x_{3,2}$	$x_{3,3}$	$x_{3,4}$	L	$x_{3,n-2}$	$x_{3,n-1}$	$x_{3,n}$
#2	$x_{4,1}$	$x_{4,2}$	$x_{4,3}$	$x_{4,4}$	L	$x_{4,n-2}$	$x_{4,n-1}$	$x_{3,n}$
⋮	M	M	M	M	O	M	M	M
#N-1	$x_{m-2,1}$	$x_{m-2,2}$	$x_{m-2,3}$	$x_{m-2,4}$	L	$x_{m-2,n-2}$	$x_{m-2,n-1}$	$x_{m-2,n}$
	$x_{m-1,1}$	$x_{m-1,2}$	$x_{m-1,3}$	$x_{m-1,4}$	L	$x_{m-1,n-2}$	$x_{m-1,n-1}$	$x_{m-1,n}$
#N	$x_{m,1}$	$x_{m,2}$	$x_{m,3}$	$x_{m,4}$	L	$x_{m,n-2}$	$x_{m,n-1}$	$x_{m,n}$

Input and output ports incidence matrix

MES Planning optimization problem

$$\min \quad TC = C_I + C_O \qquad C_I = \sum_{g=1}^{G} \frac{r(1+r)^K}{(1+r)^K - 1} C_g I_g \qquad C_{\boldsymbol{o}} = \sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{m=1}^{M} \omega_s f_{m,t,s} V_{m,t,s}^{in}$$

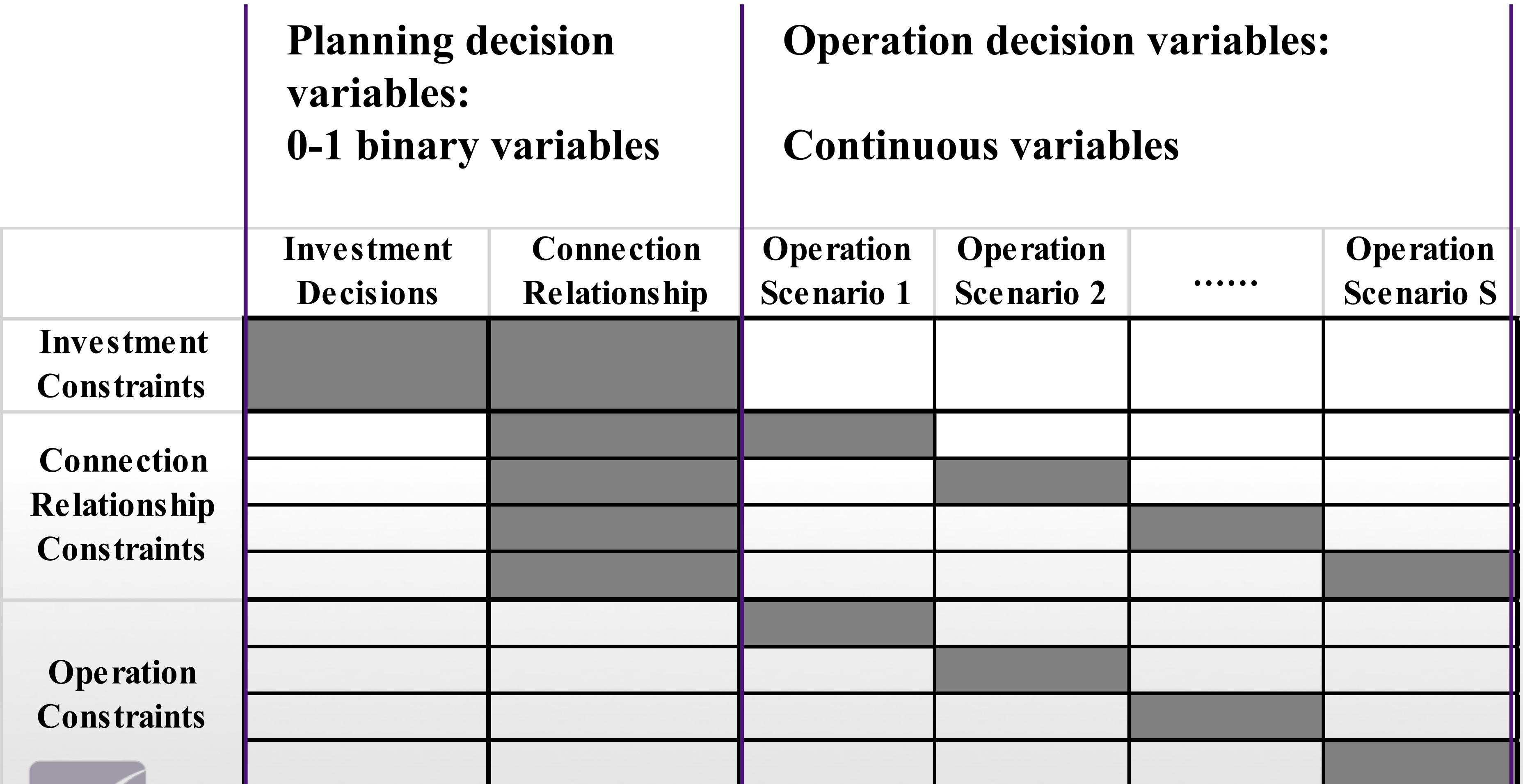
s.t.

$$0 \le \sum_{l \in g} x_l \le I_g M_2 \;\; \forall l, g \qquad x_{ij} \in \{0,1\}$$

$$0 \le V_{l,t,s} \le x_l M_1 \;\; \forall l, t, s$$

$$\begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{Y} \\ \boldsymbol{Z} \end{bmatrix} \boldsymbol{V} = \begin{bmatrix} \boldsymbol{V}_{in} \\ \boldsymbol{V}_{out} \\ \boldsymbol{0} \end{bmatrix}$$

Configuration of the planning problem



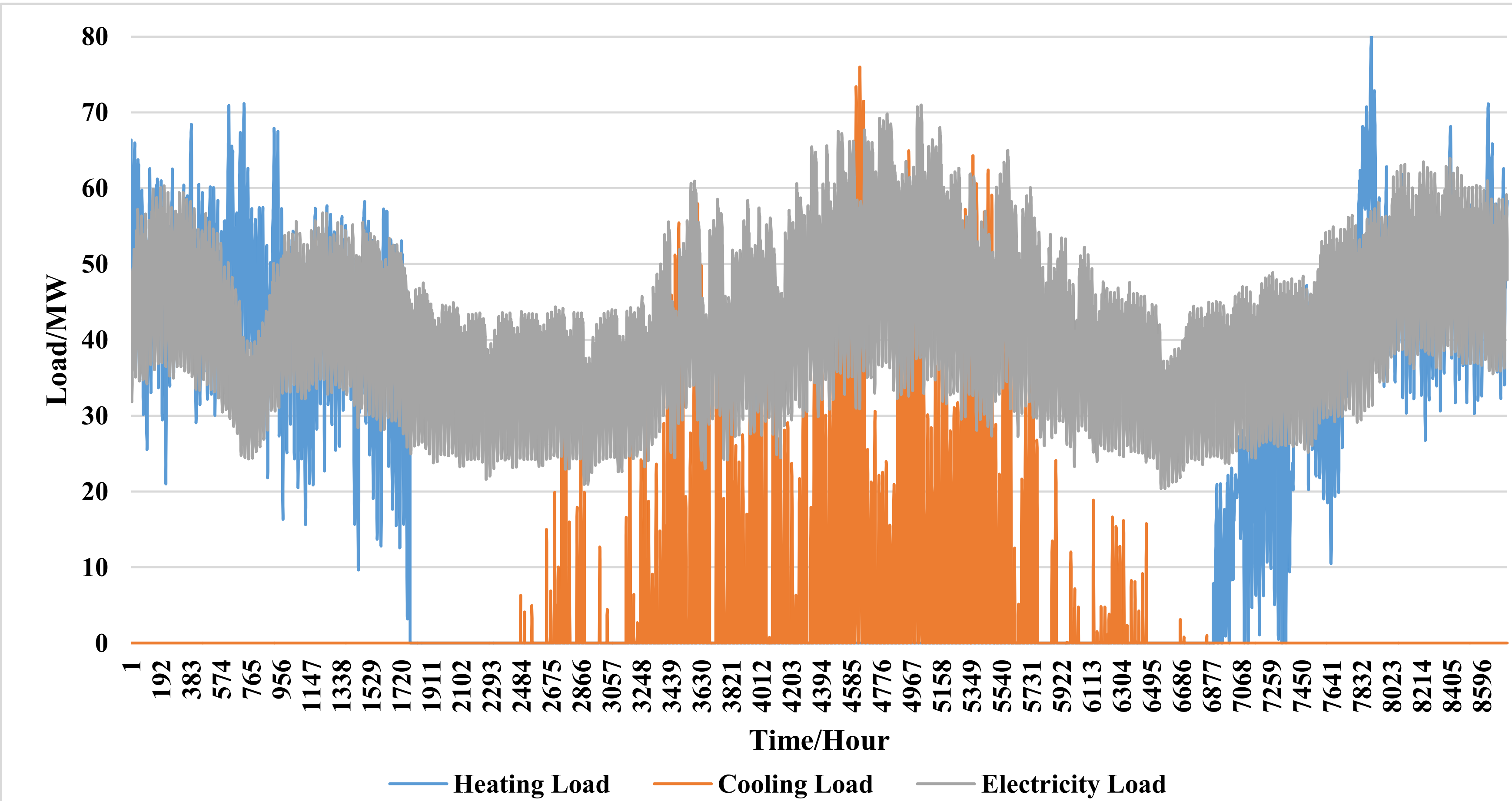
Multi Energy Systems Planning of Subsidiary Administrative Center of Beijing

Background

- The Beijing government is planning to build a subsidiary administrative center in the undeveloped district of Tongzhou in the southeast of Beijing, containing Beijing municipal government and consist of offices, commercial buildings and residential buildings.

- Total area:
  - 155 square kilometers
- Core district area:
  - 6 square kilometers
- Planned building area
  - 3.8 million square meters.

Loads of the Multi-Energy Systems



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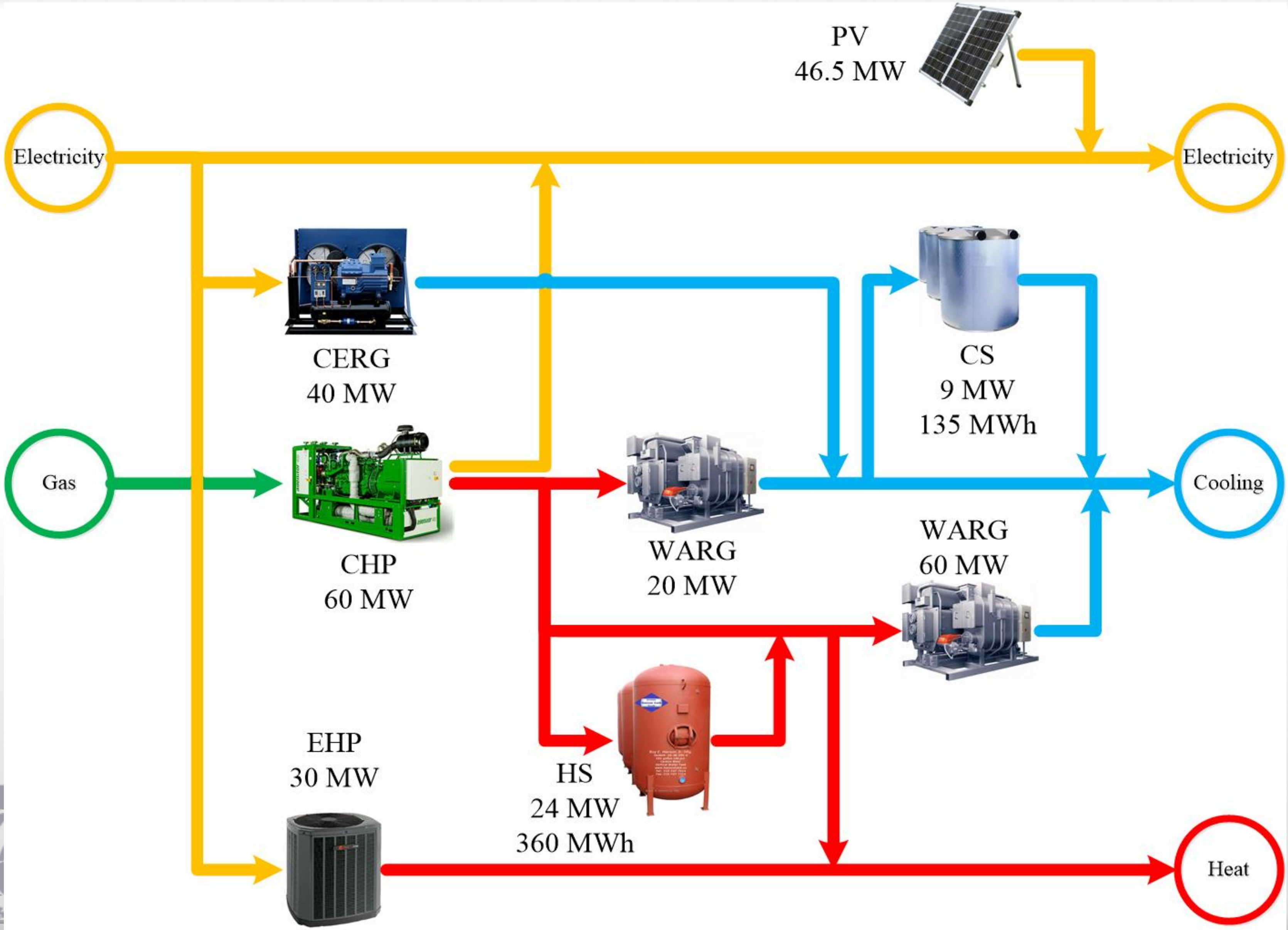
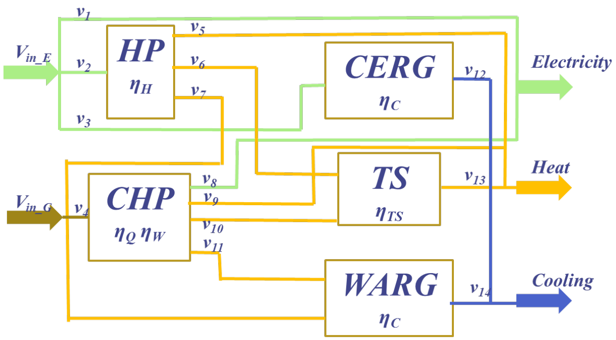
Optimal Planning



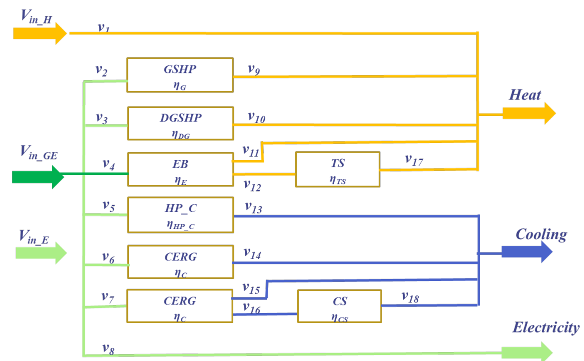
Planning scheme comparison for Subsidiary administrative center of Beijing

◆ Potential planning for Tongzhou

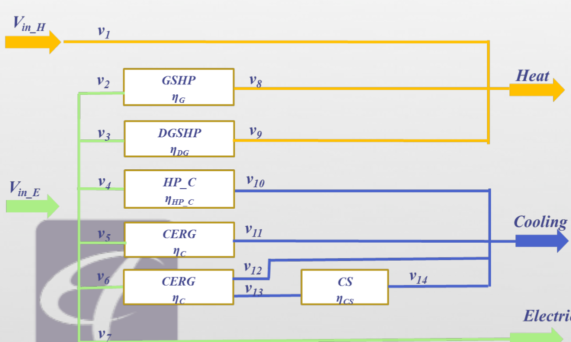
Case 1:
Planning results from the model



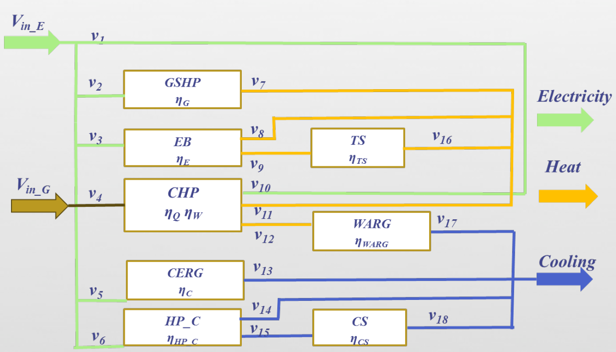
Case 2:
Wind power heating case



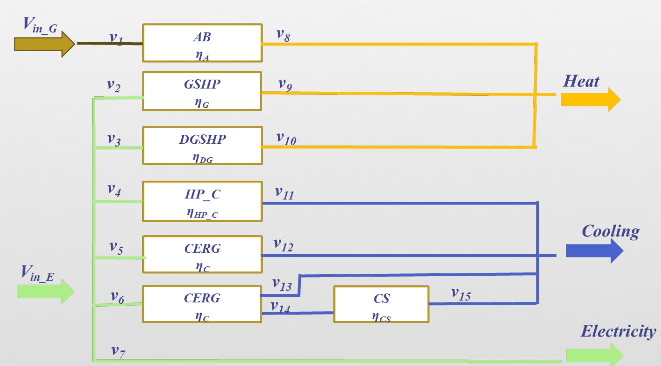
Case 3
Import city heat network plan



Case 4
Combine cooling and heating plan



Case 5
Gas boiler plan



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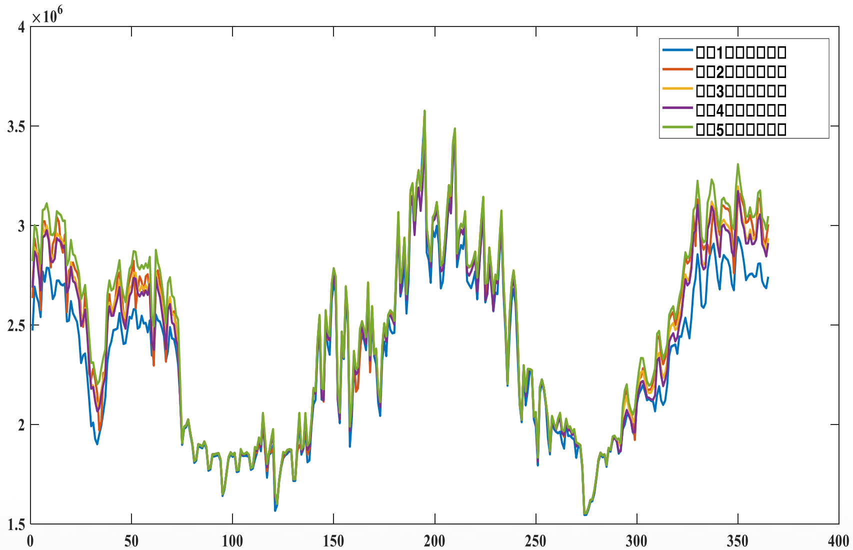
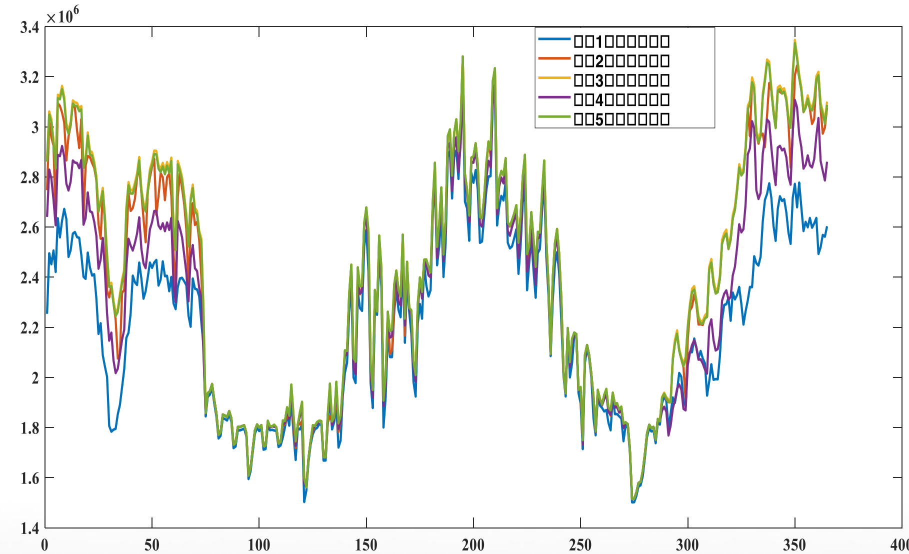
Planning scheme comparison for Subsidiary administrative center of Beijing

Comparison of the costs and emissions





Plan	1	2	3	4	5
Total operation cost (10^4 ￥)	85049	88673	88622	87677	126582
Total emission (10^4 kg CO2)	220.97	238.92	241.82	231.22	241.27

Concluding Remarks

- Based on the concept of EH, a standardized matrix modeling method can be build for MES that facilities automated modeling of MES.

- A starting from scratch planning of MES can be modeled using the standardized matrix modeling method.

- The optimal configuration of multi-energy system in Beijing:
  - Electricity: import electricity (renewable energy) + CHP
  - Heat: CHP + Heat pump+ Heat storage
  - Cooling: compression electric refrigerator group + water absorption refrigerator group+ cooling storage

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Thanks

Q&A