# Multiple energy system planning: methodology and application

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# Our Department

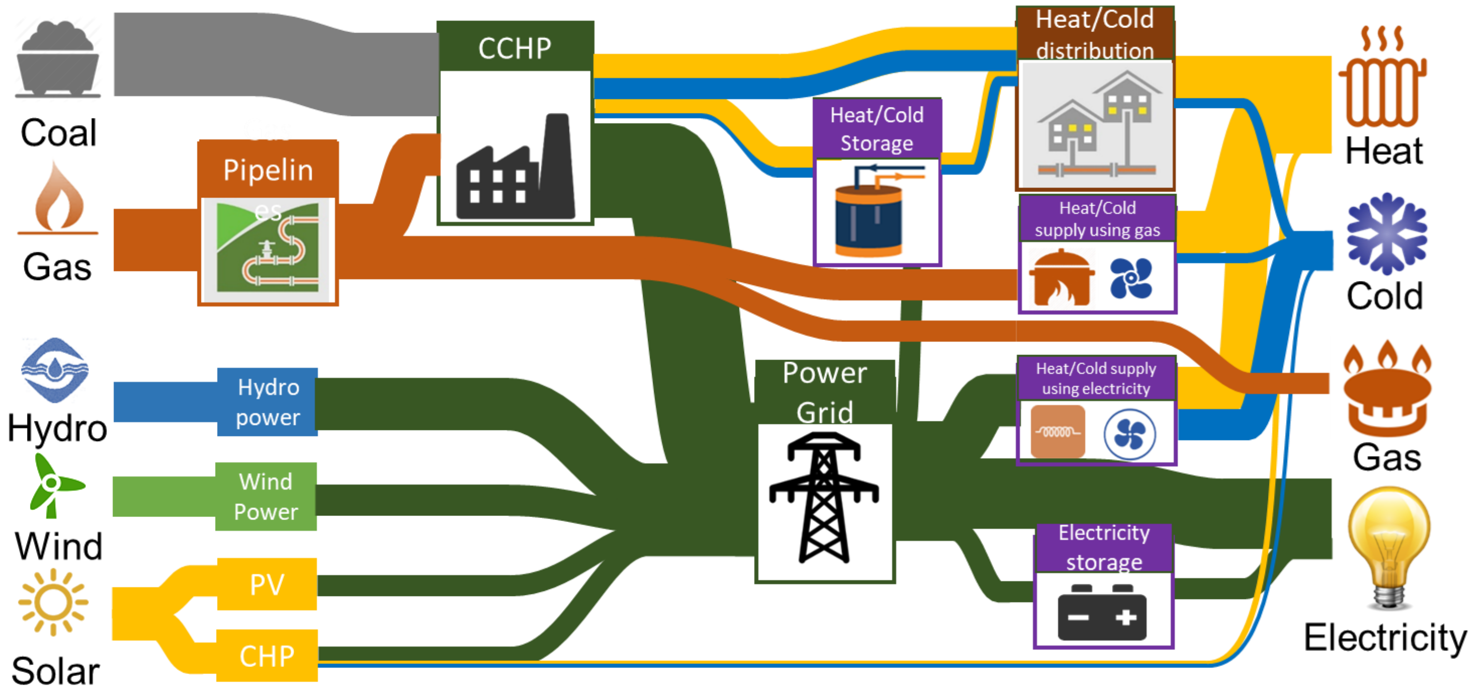
# Self Introduction

- 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-SM'18) 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 systems integration, stochastic analysis and simulation of renewable energy, power system planning and scheduling with renewable energy.

# Outline

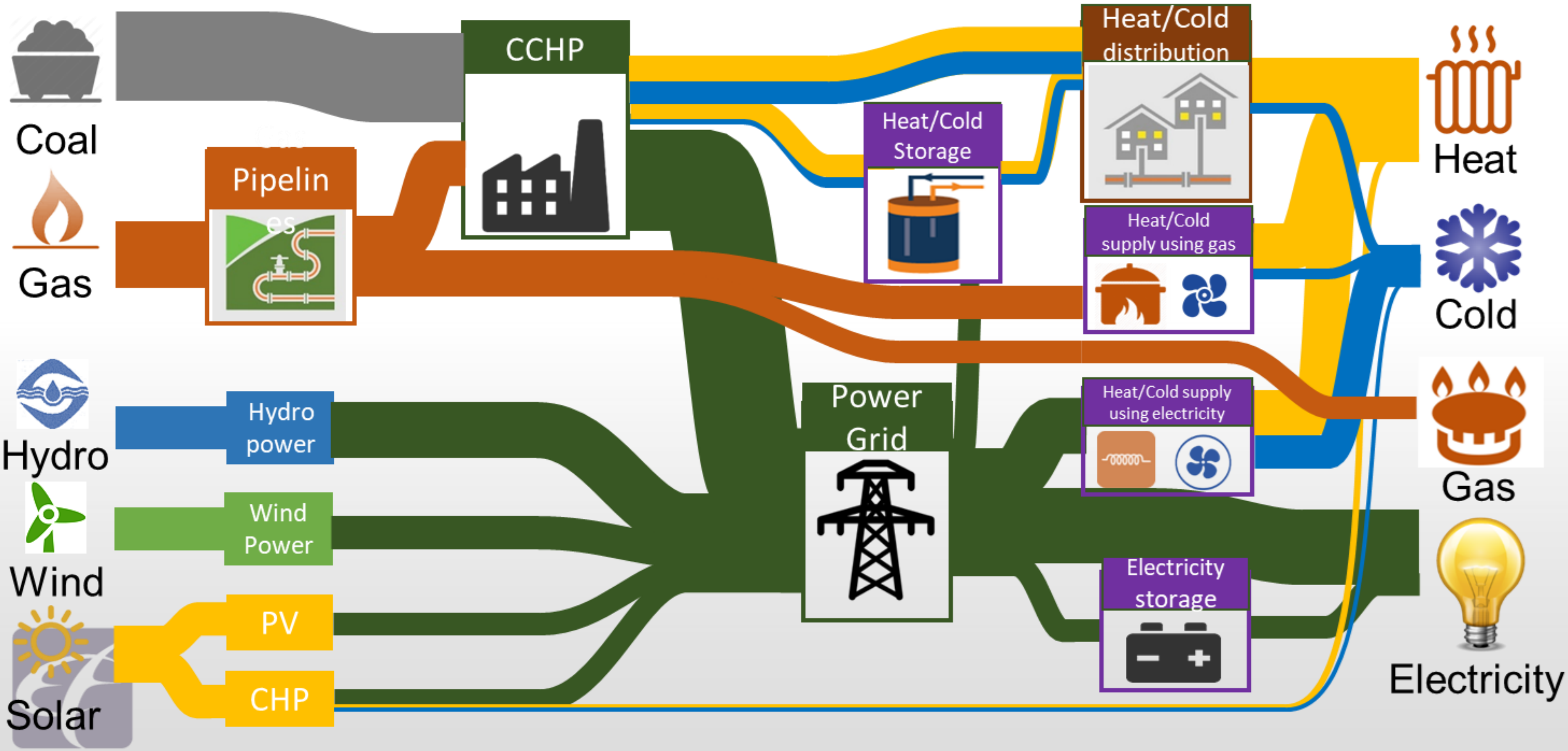
- Energy systems integration in China
- Modeling of multiple energy networks
- Planning of multiple energy systems
- Case study of Beijing


Coal
Gas
Hydro
Wind
Solar
Pipelin es
CCHP
Hydro power
Wind Power
PV
CHP
Power Grid
Heat/Cold Storage
Heat/Cold distribution
Heat/Cold supply using gas
Heat/Cold supply using electricity
Electricity storage
Heat
Cold
Gas
Electricity

# Back Ground

# Multiple Energy Systems

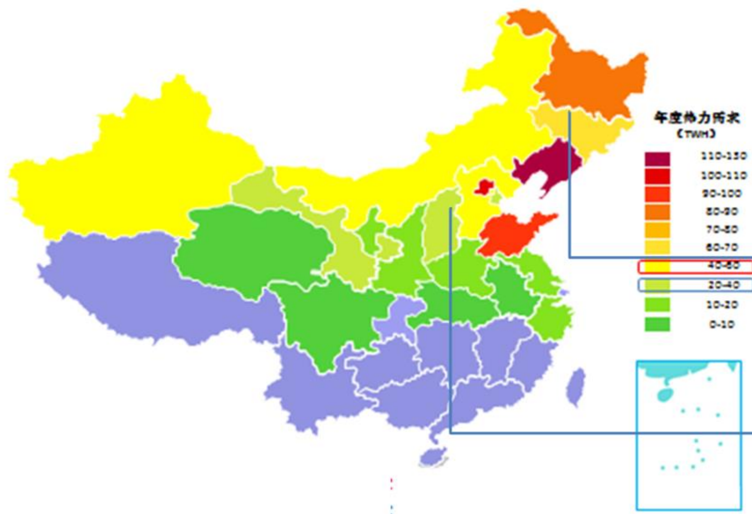
- What is multiple energy system?
- NREL: The process of optimizing energy systems across multiple pathways, scales and time horizons.



# Energy Systems Integration in China

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

**Heating demand distribution in China**

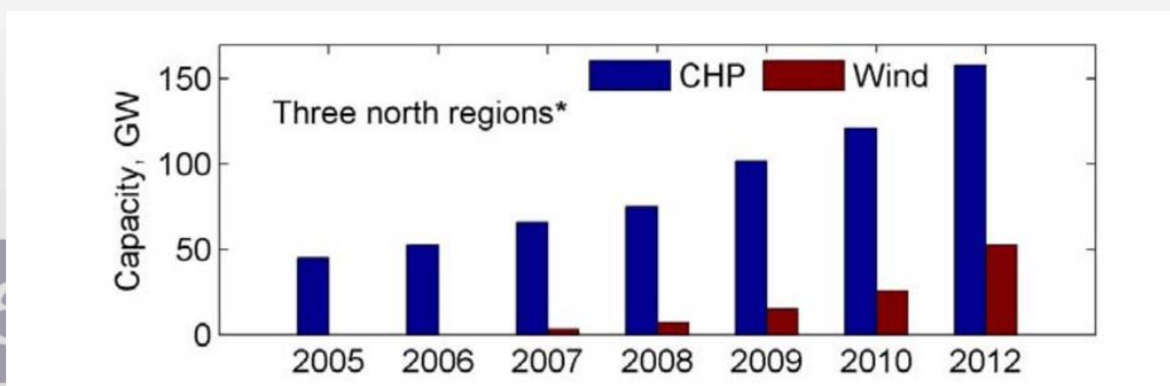


**Percentage of CHP in coal-fired units:**

National: 18%

North East: 70%

Northern China: 50%

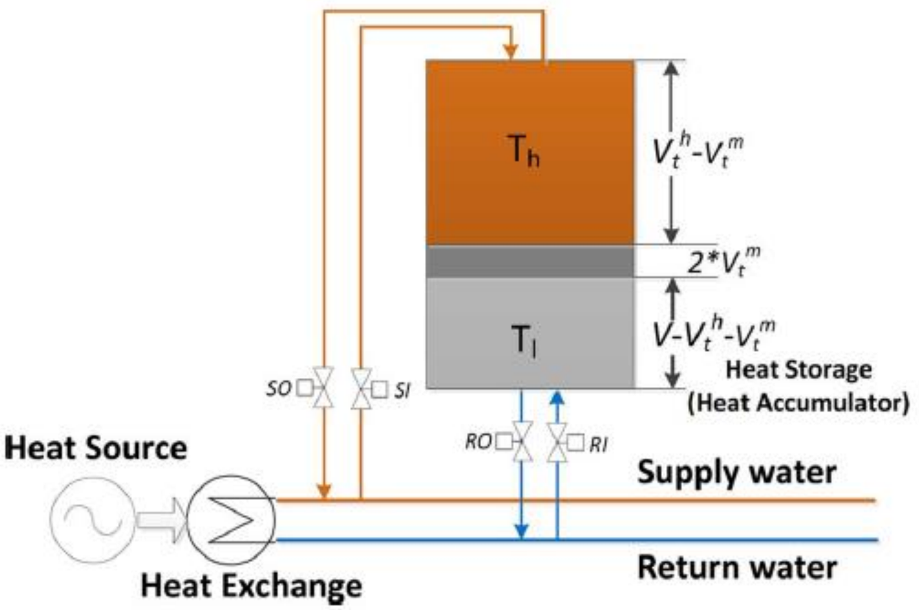


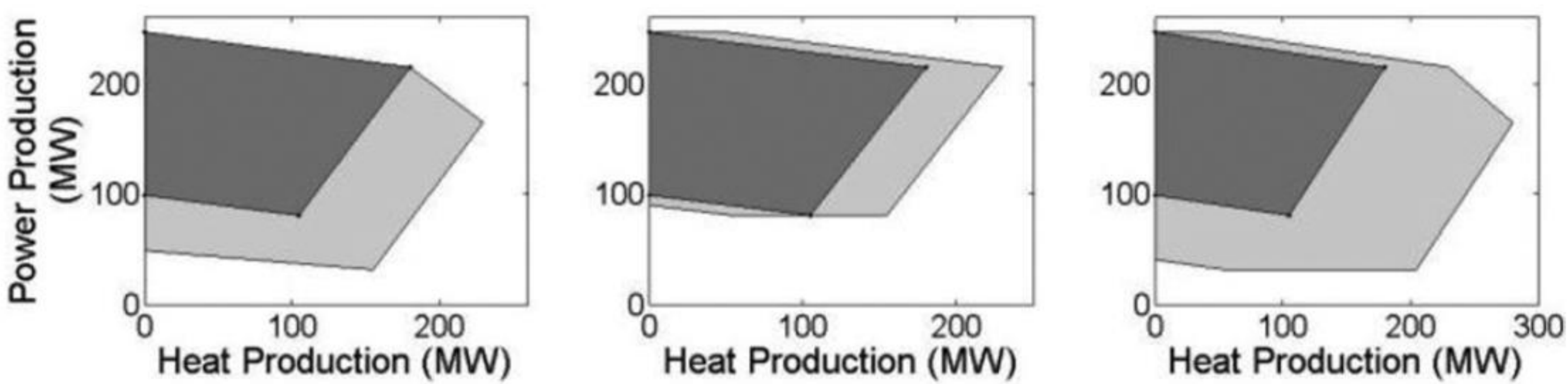

- Large-sized Combined Heat and Power (CHP) units have been installed

- 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




(a) (b) (c)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# Multiple Energy System and Energy Hub

| | Generation | Transmission | Consumption |
|---|---|---|---|
| Electricity | •Centralized primarily<br>•Renewable energy integration | •No delay, less loss<br>•Real time balance, uneconomical storage<br>•Long distance transmission | •Clean consumption, intelligence<br>•Can be transformed into other energy |
| Heat | •Distributed：Low efficiency<br>•Centered：Coupling of electricity and heat | •Have delay， more loss<br>•Easy to stored<br>•Local balance | •Heating and industrial use<br>•Less intelligence |
| Gas | •Central development depending on the distribution of sources. | •Have delay， more loss<br>•Easy to stored<br>•Long distance transmission | •Used for power generation<br>•Low efficiency<br>•Pollution |

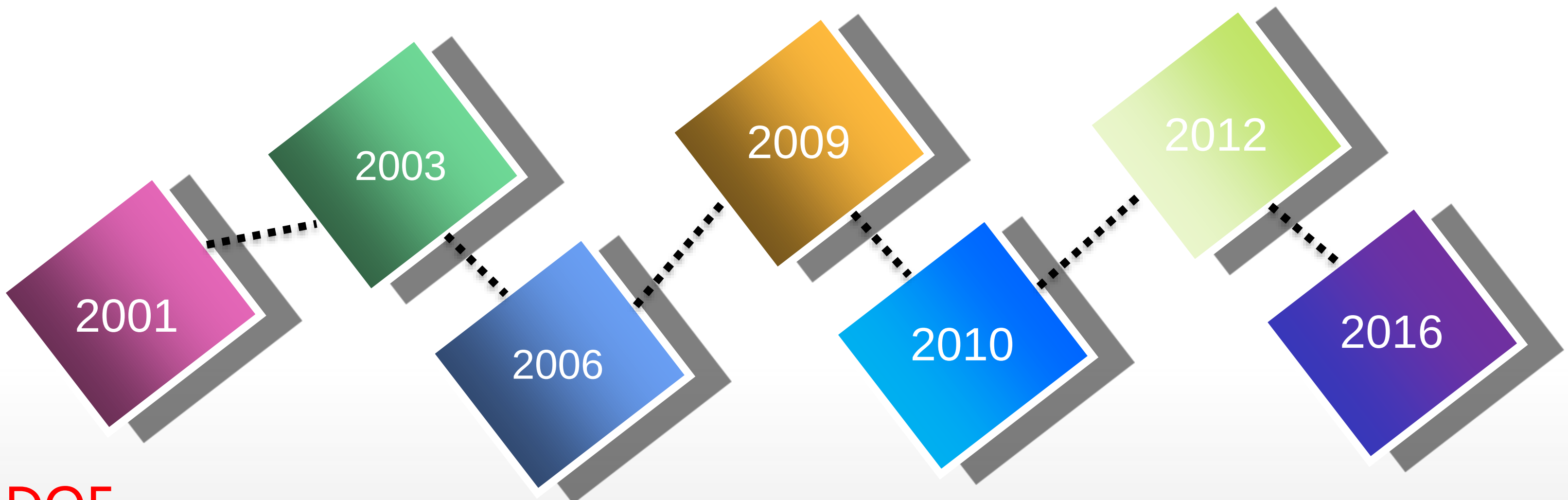
**Energy Internet**

- •Interconnection：Generation-Transmission-Distribution-Consumption in both power and information.
- •Interaction：Source-Network-Load, Multi-energy Supplement
- •Virtual：From real energy system to virtual information system

**Unlocking more flexibility for renewable energy accommodation**
**Efficiency improvement through cascade utilization of energy**

# Multiple Energy Systems and Energy Hub

- Switzerland ETH Vision of Future Energy Networks
- Canada Government report on MES
- Denmark Energy comes together in Denmark




- US DOE integrated energy system，IES Plan
- Japan New national energy strategy
- German Government Draft German Energy Concept
- China The concept of Energy Internet

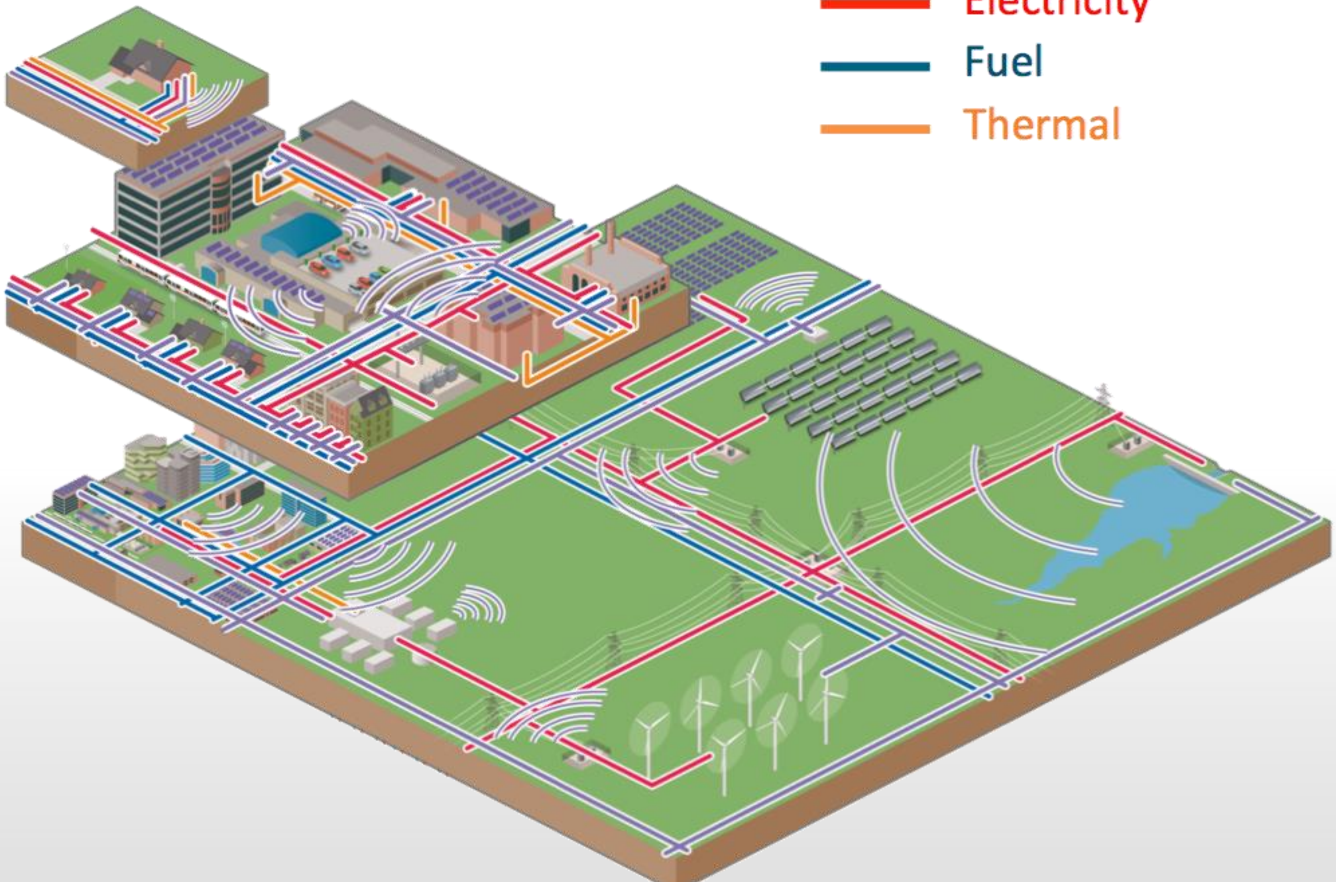
# Multiple Energy Systems

**Energy System Physical Scales**

Buildings

Campus, Fleet, Distribution

Regional



**Energy Grids**

- Electricity
- Fuel
- Thermal

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iiESI International Institute for Energy Systems Integration

# Multiple Energy Systems Modeling

Energy network modeling

- **Electric power grid** — High accuracy linearized AC power flow
- **Gas network** — Linearizing the gas dynamic equation
- **Heat network** — Water flow equation, Heat flow equation based on water flow

**Energy hub modeling**

Standardized model for energy hub based on graph theory

# Modeling Power Grid

# Linearizing Power Flow Equation

## Power flow equation

$$P_i = \sum_{j=1}^{n} G_{ij} V_i V_j \cos\theta_{ij} + \sum_{j=1}^{n} B_{ij} V_i V_j \sin\theta_{ij}$$

$$Q_i = -\sum_{j=1}^{n} B_{ij} V_i V_j \cos\theta_{ij} + \sum_{j=1}^{n} G_{ij} V_i V_j \sin\theta_{ij}$$

$$i = 1, 2, \cdots, n$$

$$Y_{ij} = \begin{cases} -y_{ij} & \text{if } j \neq i \\ y_{ii} + \sum_{k=1,k\neq i}^{n} y_{ik} & \text{if } j = i \end{cases}$$

## Linearization

$$\begin{aligned} P_i &= \sum_{j=1}^{n} G_{ij} V_i V_j \cos\theta_{ij} + \sum_{j=1}^{n} B_{ij} V_i V_j \sin\theta_{ij} \\ &= g_{ii} V_i^2 + \sum_{j=1,j\neq i}^{n} \left(g_{ij} V_i \left(V_i - V_j \cos\theta_{ij}\right) - b_{ij} V_i V_j \sin\theta_{ij}\right) \\ &\approx g_{ii} V_i + \sum_{j=1,j\neq i}^{n} g_{ij} \left(V_i - V_j\right) - \sum_{j=1,j\neq i}^{n} b_{ij} \left(\theta_i - \theta_j\right) \\ &= \left(V_i \sum_{j=1}^{n} g_{ij} + \sum_{j=1,j\neq i}^{n} (-g_{ij}) V_j\right) \\ &\quad - \left(\theta_i \sum_{j=1,j\neq i}^{n} b_{ij} + \sum_{j=1,j\neq i}^{n} (-b_{ij}) \theta_j\right) \qquad (4) \\ &= \sum_{j=1}^{n} G_{ij} V_j - \sum_{j=1}^{n} B'_{ij} \theta_j \end{aligned}$$

$V_i \approx 1 \quad \cos\theta_{ij} \approx 1$

$V_i \approx 1 \quad V_j \approx 1$

$\sin\theta_{ij} \approx \theta_i - \theta_j$

# Linearizing Power Flow Equation

- For the branch flow

$$P_{ij} = g_{ij}\left(V_i - V_j\right) - b_{ij}\left(\theta_i - \theta_j\right)$$

- Similarly for the reactive injection, we have

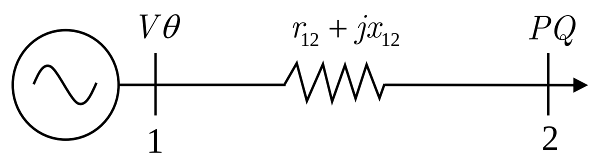
$$Q_i = -\sum_{j=1}^{n} B_{ij} V_j - \sum_{j=1}^{n} G_{ij}\theta_j$$

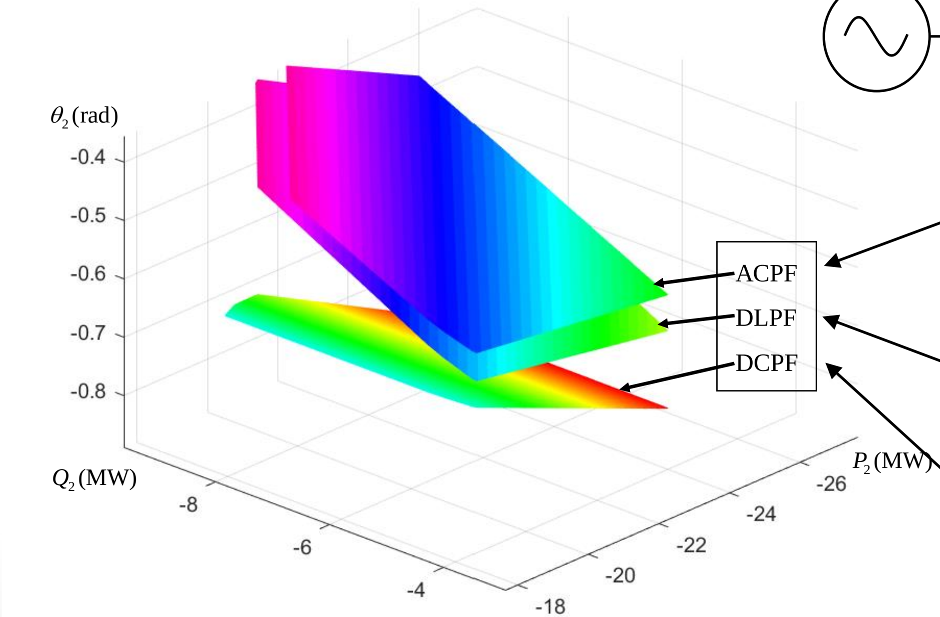
- Matrix form

$$\begin{bmatrix} P \\ Q \end{bmatrix} = -\begin{bmatrix} B' & -G \\ G & B \end{bmatrix}\begin{bmatrix} \theta \\ V \end{bmatrix}$$

# Linearizing Power Flow Equation

Power flow equation of two-bus system:




$$P_i = V_i \sum_{j \in i} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij})$$

$$Q_i = V_i \sum_{j \in i} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij})$$

$$\begin{bmatrix} \mathbf{P} \\ \mathbf{Q} \end{bmatrix} = -\begin{bmatrix} \mathbf{B}' & -\mathbf{G} \\ \mathbf{G} & \mathbf{B} \end{bmatrix} \begin{bmatrix} \boldsymbol{\theta} \\ \mathbf{V} \end{bmatrix}$$

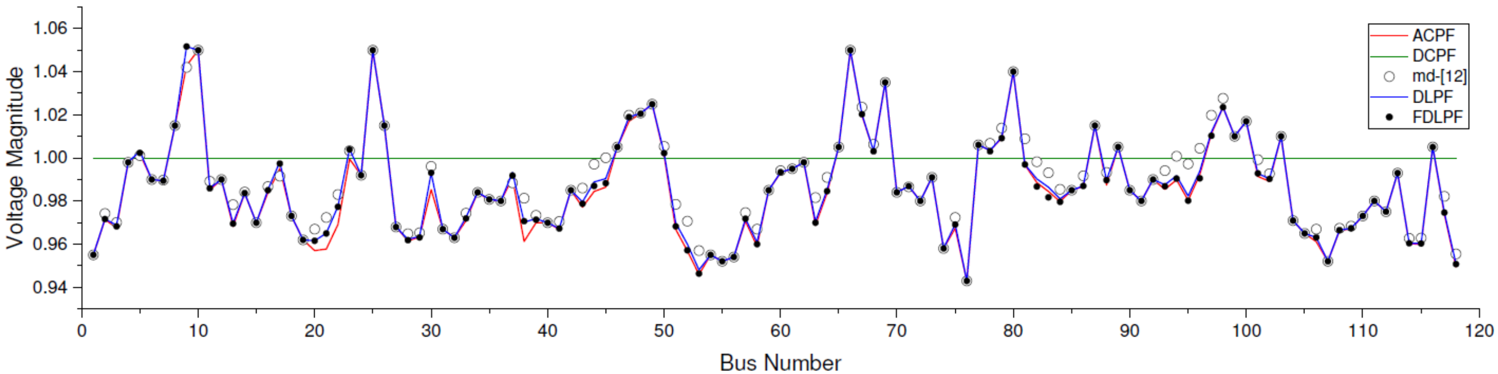
$$\mathbf{P} = \mathbf{B}\boldsymbol{\theta}$$

1) The non-linear ACPF has a high degree of linearity
2) Except DCPF, we develop DLPF which is able to consider reactive power and voltage magnitude

*Yang J, Zhang N, Kang C, et al. A state-independent linear power flow model with accurate estimation of voltage magnitude[J]. IEEE Transactions on Power Systems, 2017, 32(5): 3607-3617.*

# Linearizing Power Flow Equation

*Yang J, Zhang N, Kang C, et al. A state-independent linear power flow model with accurate estimation of voltage magnitude[J]. IEEE Transactions on Power Systems, 2017, 32(5): 3607-3617.*




*Yang Z, Zhong H, Xia Q, et al. A novel network model for optimal power flow with reactive power and network losses[J]. Electric Power Systems Research, 2017, 144:63-71.*

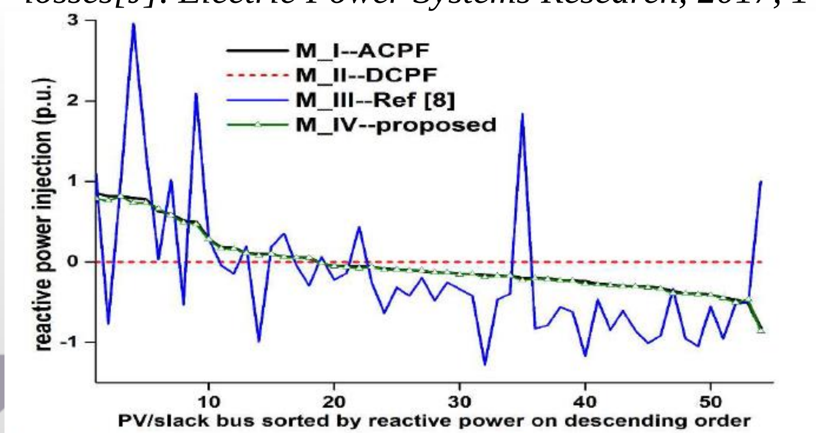



Fig. 3. PV Bus reactive power injections for the IEEE 118-bus system.

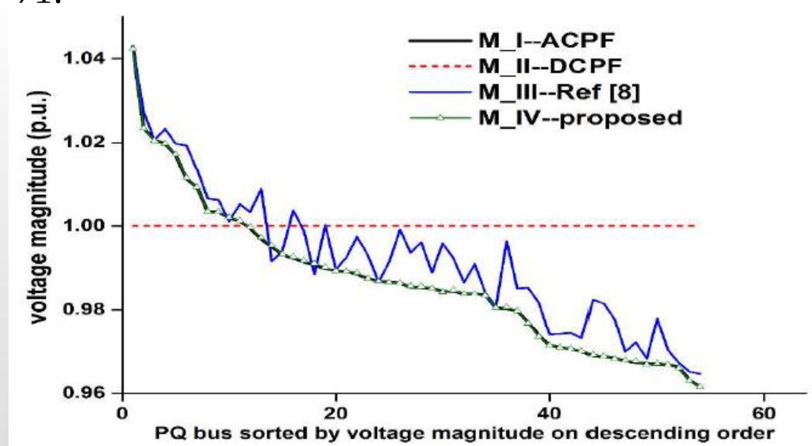


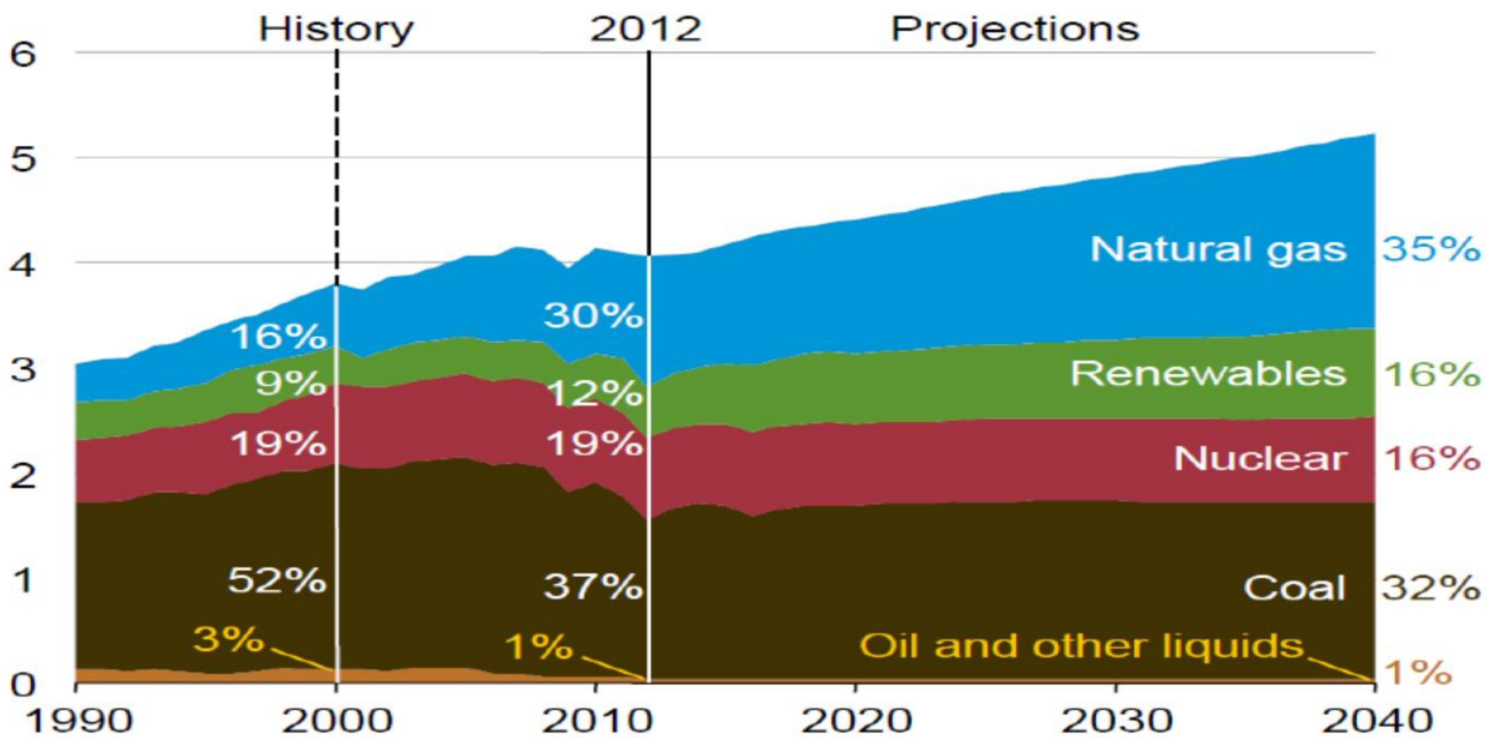

Fig. 2. PQ Bus voltage magnitudes for the IEEE 118-bus system.

# Modeling gas network

# Why is the electric-gas coordination important?

## Change in US Electric Energy Portfolio

Electric energy generation by fuel, 1990-2040 (trillion kW-hrs)




U.S. Gas-fired units in 2014:

-Installed capacity : 42%, largest sector

-Electricity generation : 33%, the same as coal-fired units

# Electric-Gas Coupling

- Problems to look at

**Modelling**

- Modelling the natural gas network
- Modeling the dynamics of natural gas flow

**Operation**

- The uncertainty and security of gas supply system
- Coordinated operation of gas-electricity system

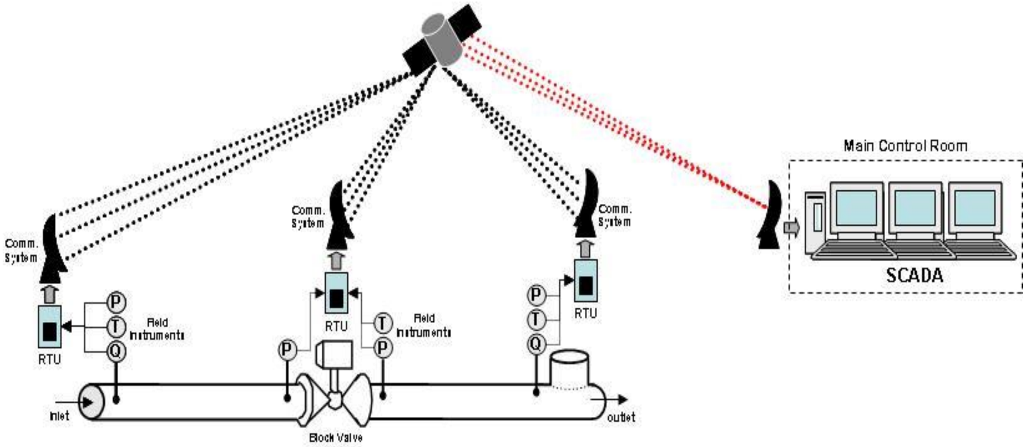
**Planning**

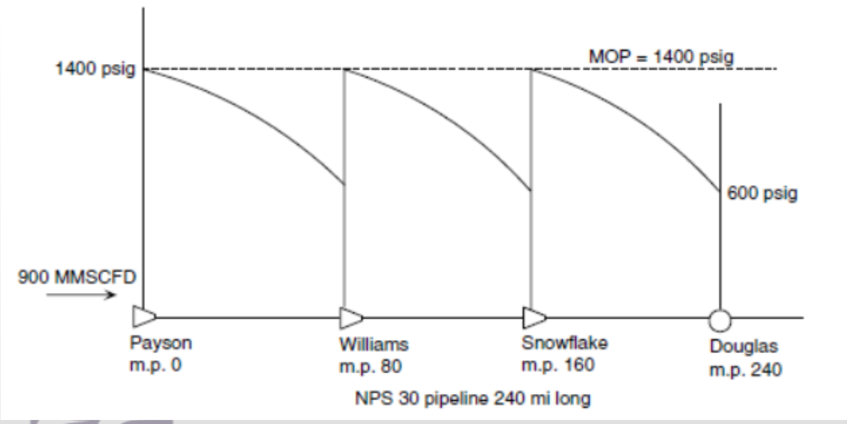
- Co-planning of electric generation, electric transmission and natural gas pipeline

**Market**

- Coordination of day-ahead natural gas and electricity bidding

# Gas Network




- Similar to power grid, gas network can be mashed up to thousands of kilometers.
- Using high pressure to keep the gas moving.
- Several pressure adding stations along the long-distance gas transmission network to maintain pipeline pressure.

# Gas Network Modeling: General Equation

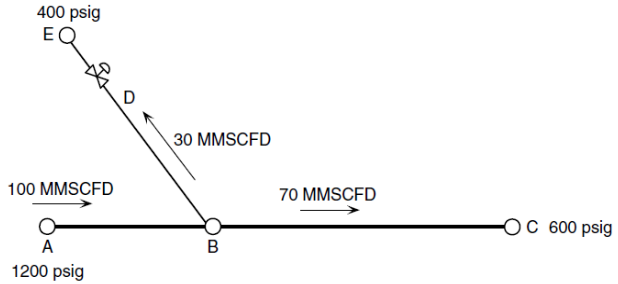
Node:
(1) The source and load of gas network
(2) The junction of different gas pipeline

Branch:
Gas pipeline

Basic variables :
(1) Node variables: node pressure, node gas input
(2) Branch variables : gas flow

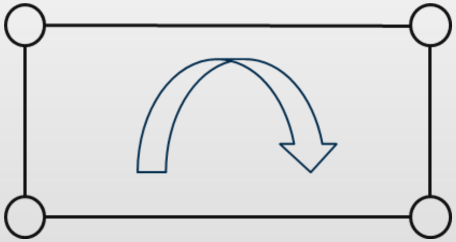
(1) Nodal balance equation: KCL

$$\sum Q = Q_{injection}$$



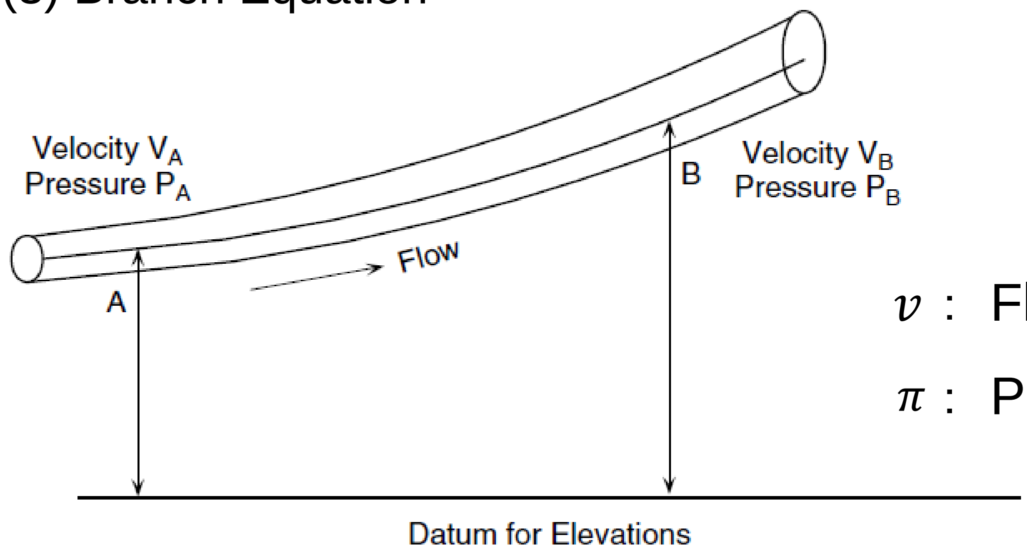

(2) Loop equation: KVL

$$\sum \Delta\pi = 0$$



# Gas Network Modeling: General Equation

(3) Branch Equation




Bernoulli equation for Gas movement

$$v dv + \frac{d\pi}{\rho} + g dH + f\,\frac{dx}{D}\frac{v^2}{2} = 0$$

$v$ : Flow speed $H$ : Height

$\pi$ : Pressure $f$ : Friction coefficient

Neglecting the change of pipe height,
Assuming adiabatic process

$$\begin{cases} \dfrac{\partial \pi}{\partial t} = -C_1 \dfrac{\partial Q}{\partial x} \\ \dfrac{\partial \pi^2}{\partial x} = -C_2 Q^2 \end{cases}$$

$Q$ : Amount of gas flow per time period

# Gas Network Modeling: for Planning

Dynamic branch equation

$$\begin{cases} \dfrac{\partial \pi}{\partial t} = -C_1 \dfrac{\partial Q}{\partial x} \\ \dfrac{\partial \pi^2}{\partial x} = -C_2 Q^2 \end{cases}$$

Neglecting the dynamic part
Assuming the pressure is stable

Steady state branch equation

$$\pi_1^2 - \pi_2^2 = (C_2 L) Q^2$$

$L$ : Length of the pipeline
$C_2$: The feature parameter of the pipeline

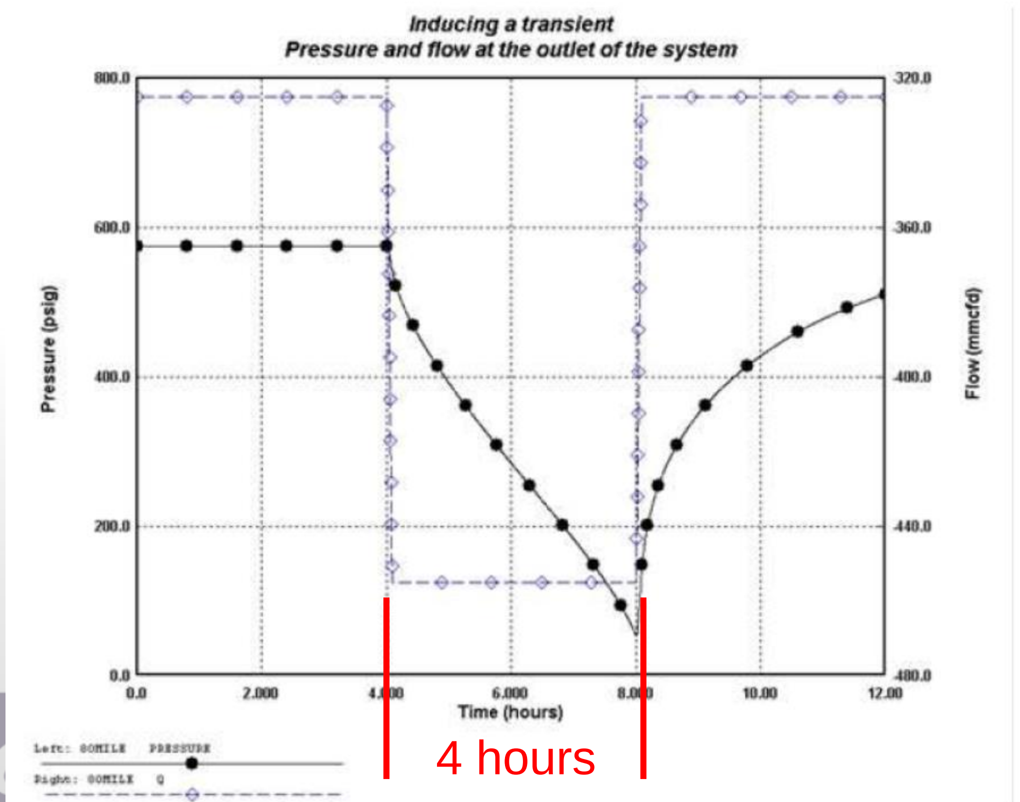
Piecewise linearization

$$Q = \frac{\sqrt{\pi_1^2 - \pi_2^2}}{C_2 L} \quad \Rightarrow \quad Q = \frac{\pi_1 \pi_{10} - \pi_2 \pi_{20}}{C_2 L \sqrt{\pi_{10}^2 - \pi_{20}^2}}$$

# Gas Network Modeling: for Operation

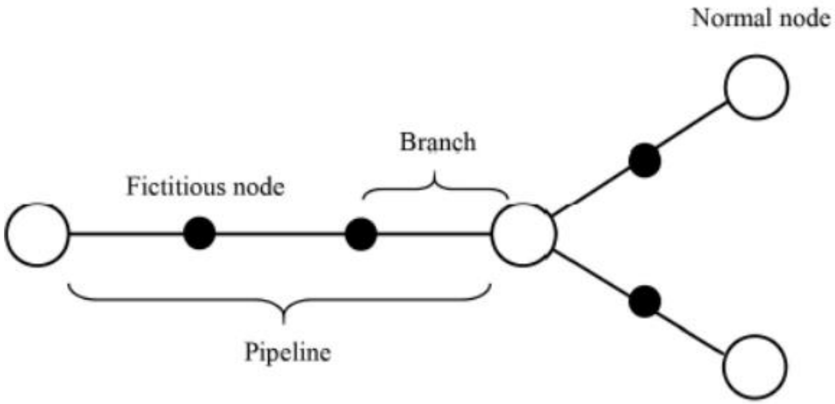
## From steady-state to transient model

- The time constants of natural gas system is several minutes or hours. A steady-state model is not capable to depict the dynamics of gas system.



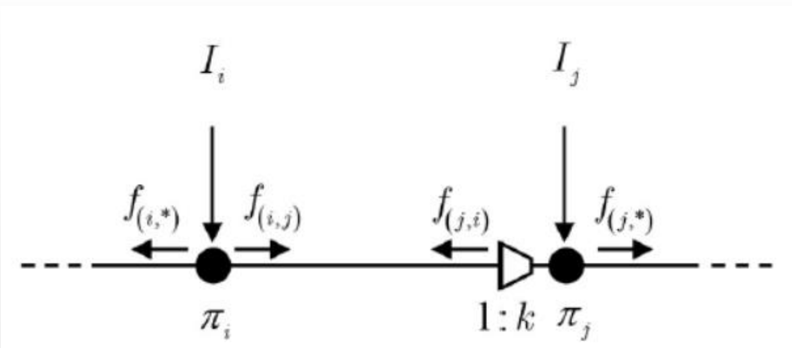

- An example: a typical gas transmission pipeline
- When the gas demand changes abruptly, the nodal pressure changes slowly

# A Transient Node-Branch model




- Step 1: Redefine the Branches and Nodes in gas network

- Step 2: General branch equations




$$\frac{\partial \pi(x,t)}{\partial t} = -C_1 \frac{\partial f(x,t)}{\partial x}$$
$$\frac{\partial \pi^2(x,t)}{\partial x} = -C_2 f^2(x,t)$$

$$\frac{\pi_i(t) - \pi_i(t-\delta t)}{\delta t} = C_1 \frac{f_{(i,j)}(t) + f_{(j,i)}(t)}{l_{(i,j)}}$$
$$\frac{\pi_i^2(t) - \pi_j^2(t)/k^2}{l_{(i,j)}} = C_2 f_{(i,j)}^2(t)$$

Jingwei Yang, Ning Zhang, Chongqing Kang, Qing Xia. Effect of natural gas flow dynamics in robust generation scheduling under wind uncertainty, IEEE Transactions on Power Systems. 2018, 33(2) 2087 - 2097.

# Modeling Heating Network

# Electric-Heating Coupling

- Problems to look at

**Modelling**

- Dynamic modeling of heat network
- Building thermal dynamic modeling

**Operation**

- Coordinated operation of electro thermal coupling system to accommodate renewable energy
- Electro-thermal decoupling operation of cogeneration unit

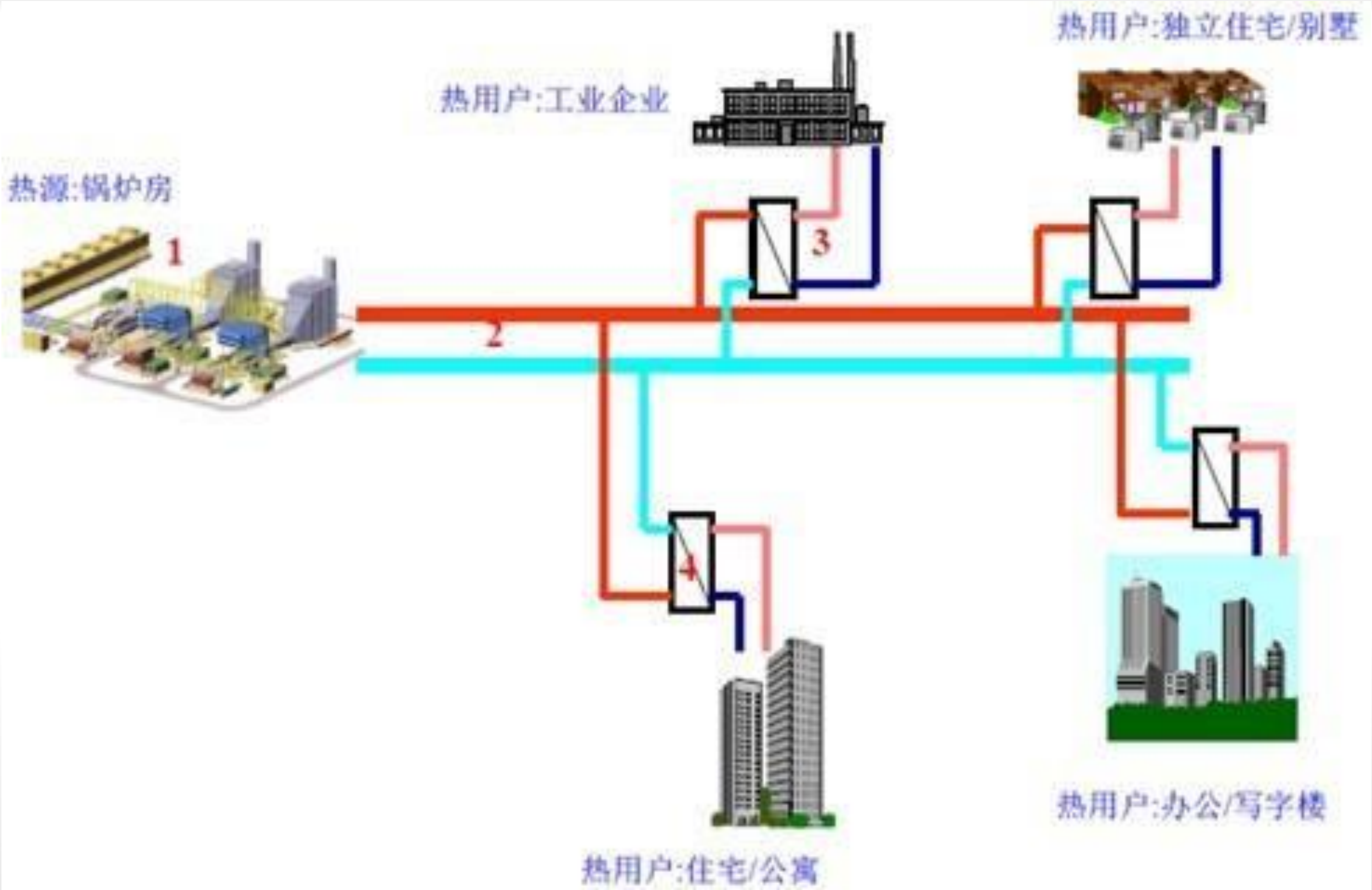
**Planning**

- Co-planning of power and thermal systems

**Flexibility**

- Integrated demand response considering heat storage and thermal inertia
- Electricity thermal coupling consumer providing flexible operation to participate in energy and ancillary service market

# Heating Network Modeling




- Heat network mainly refers to the urban (regional) heat pipe network.
- Generally divided into primary network secondary network, with the heat exchanger in the middle.
- Both the water supply pipe and the backwater pipe are included.

# Heating Network Modeling

The heat network includes water flow network and thermodynamic network

Basic variable of water flow network:

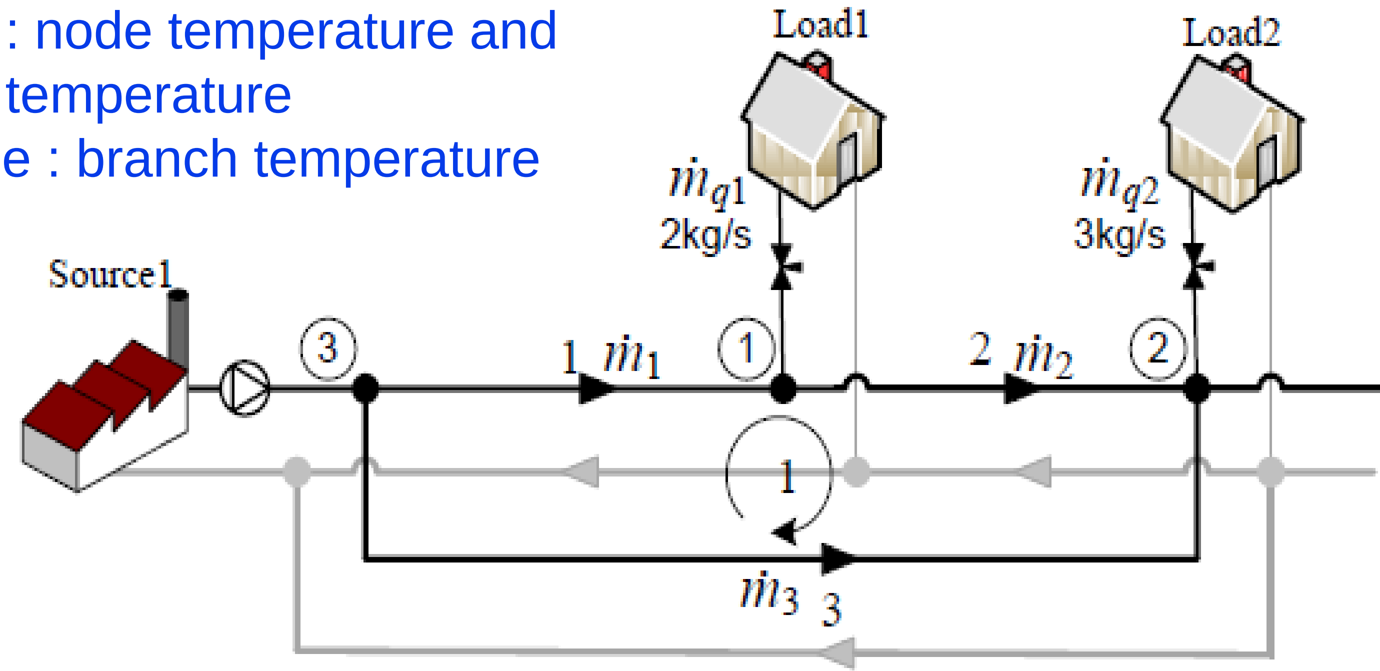
(1) Node variable: node water pressure and node injection flow mass rate.

(2) Branch variable: branch water flow mass rate：

Basic variable of thermodynamic network:

(1) Node variable : node temperature and node injection temperature

(2) Branch variable : branch temperature

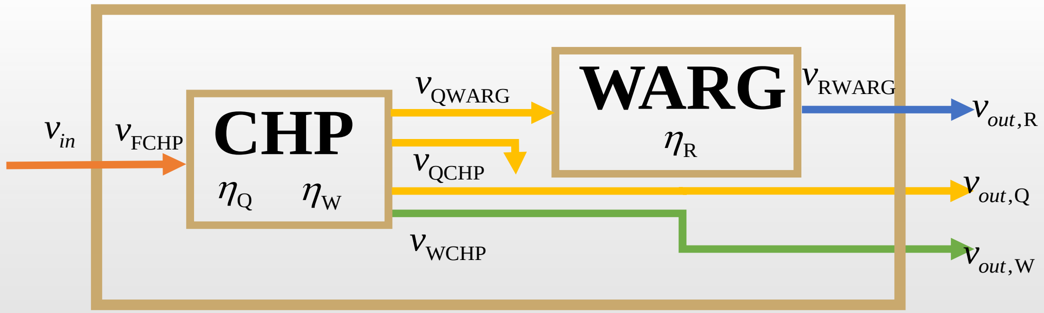



# Standard Modeling of Multiple Energy Systems

# Multiple Energy Systems and Energy Hub

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


$$\boldsymbol{V}_{\text{out}} = \boldsymbol{C}\boldsymbol{V}_{\text{in}}$$

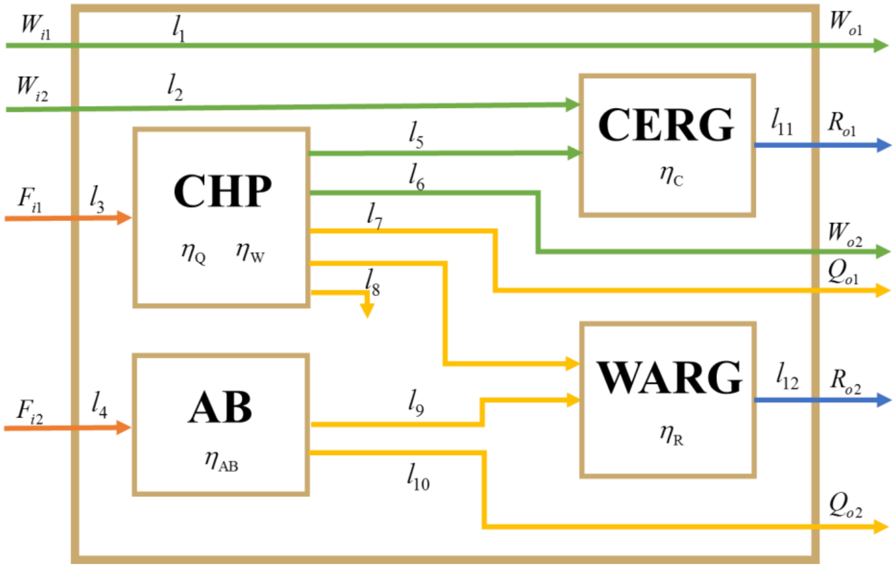



$$\boldsymbol{V}_{in} = \left[ v_{in,\text{F}} \right]$$

$$\boldsymbol{V}_{out} = \left[ v_{out,\text{R}} \;\; v_{out,\text{Q}} \;\; v_{out,\text{W}} \right]^T$$

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

# Multiple Energy Systems and Energy Hub




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

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

Hard to be modeled automatically

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

Introduce high degree nonlinearity

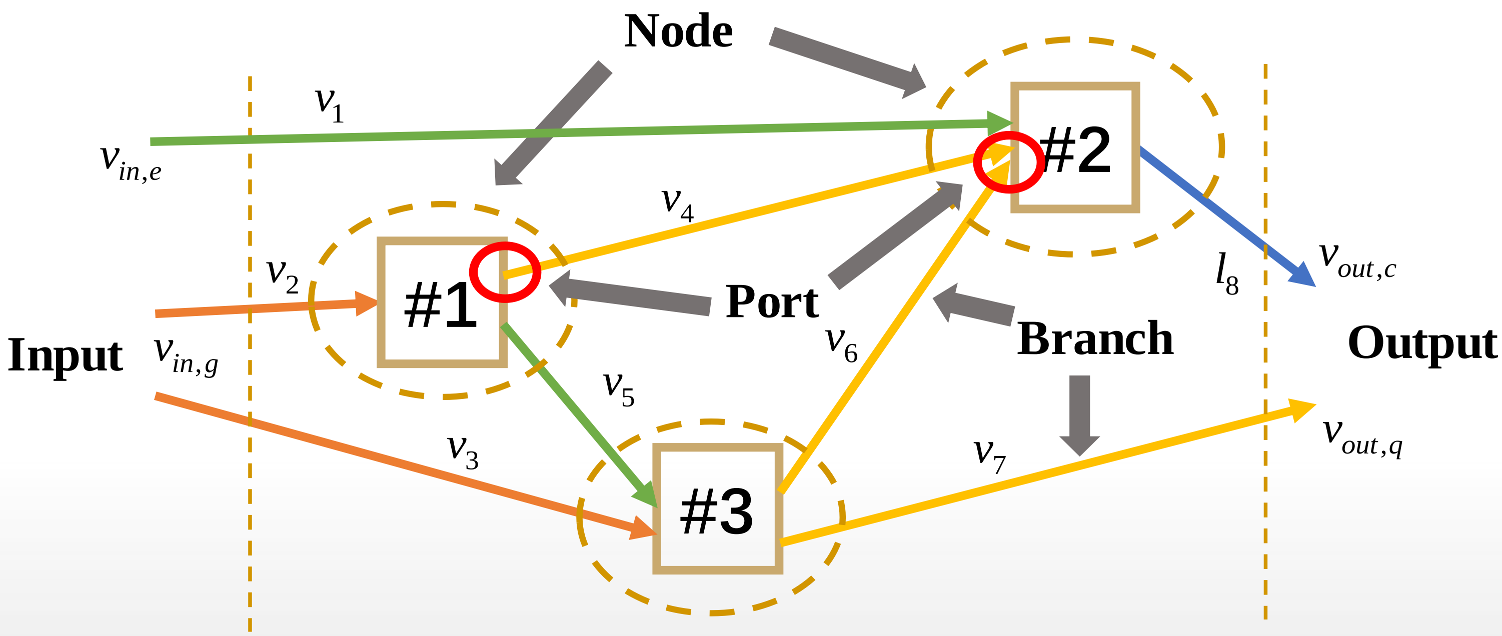

Gianfranco Chicco, Pierluigi Mancarella, Matrix modelling of small-scale trigeneration systems and application to operational optimization, Energy, Volume 34, Issue 3, 2009, Pages 261-273

# Questions

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

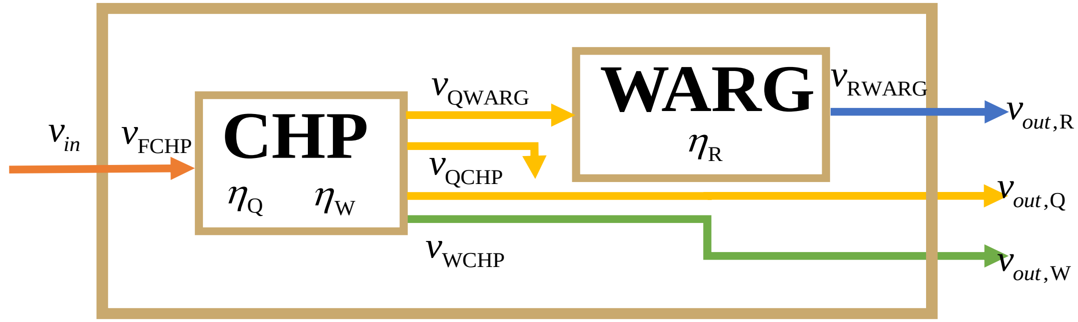
# Standard Modeling of Multiple Energy Systems

◆ 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.

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

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

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

# Basic Model

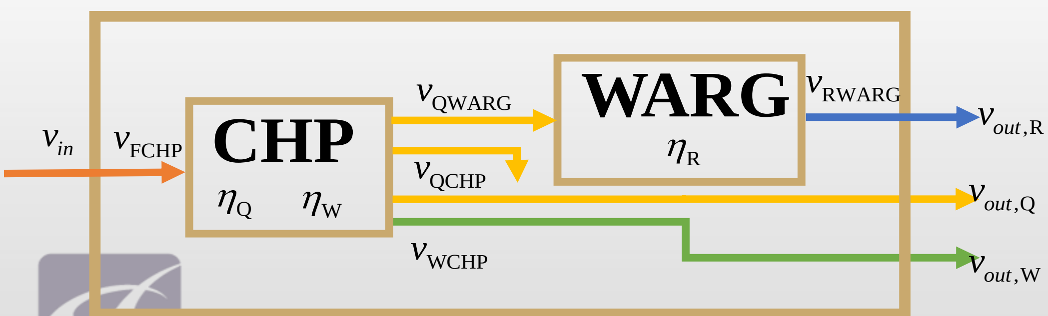
## ◆ Energy Conversion Matrices

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:

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




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

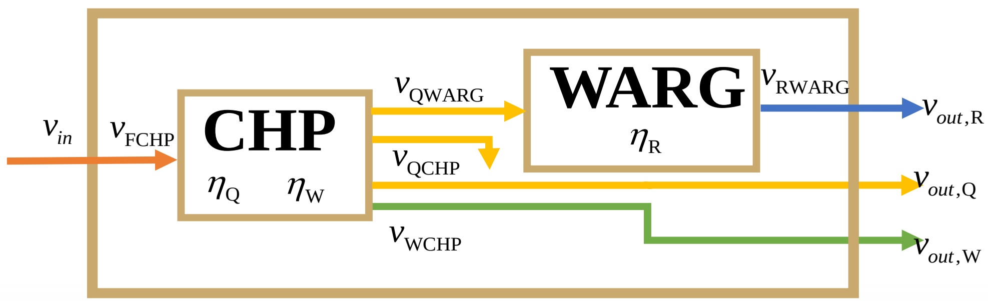
$$\boldsymbol{Z}_2 = \begin{bmatrix} 0 & \eta_{\mathrm{R}} & 0 & 0 & 1 \end{bmatrix}$$

# Standard Modeling of Multiple Energy Systems

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:

$$\boldsymbol{ZV} = \boldsymbol{0}$$

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:

$$\boldsymbol{V}_{in} = \boldsymbol{X}\boldsymbol{V}$$

$$\boldsymbol{V}_{out} = \boldsymbol{Y}\boldsymbol{V}$$

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

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

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 $\Rightarrow$

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

$$V_{out} = -Y Q^{-1} R V_{in}$$

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

$Q$ is not invertible $\Rightarrow$

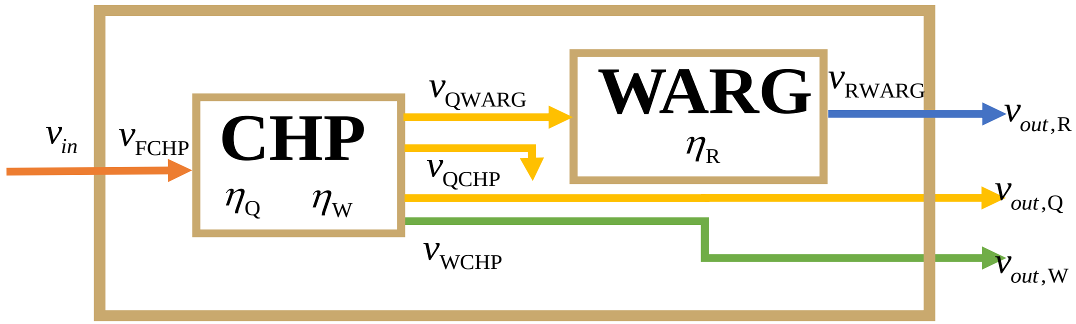
$$R V_{in} + \begin{bmatrix} Q_1 & Q_2 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = 0$$

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

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

# 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 | $\eta_Q$ | $\eta_W$ |
| 2 | 1 | $\eta_{WARG}$ | 0 |

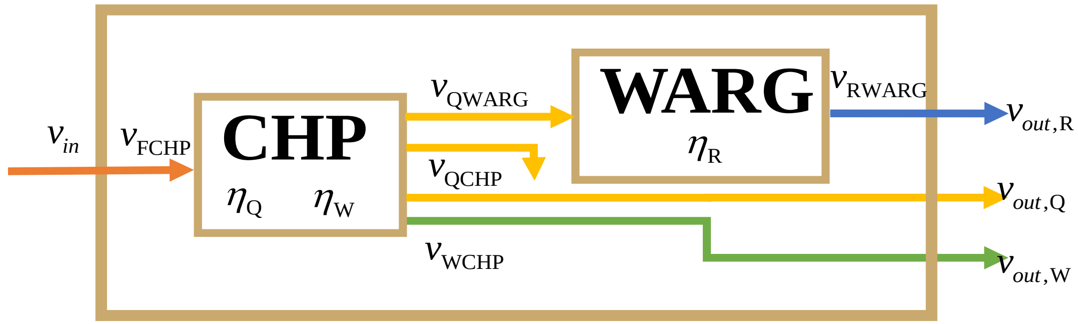
Branch Table

- *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 |

# Case study

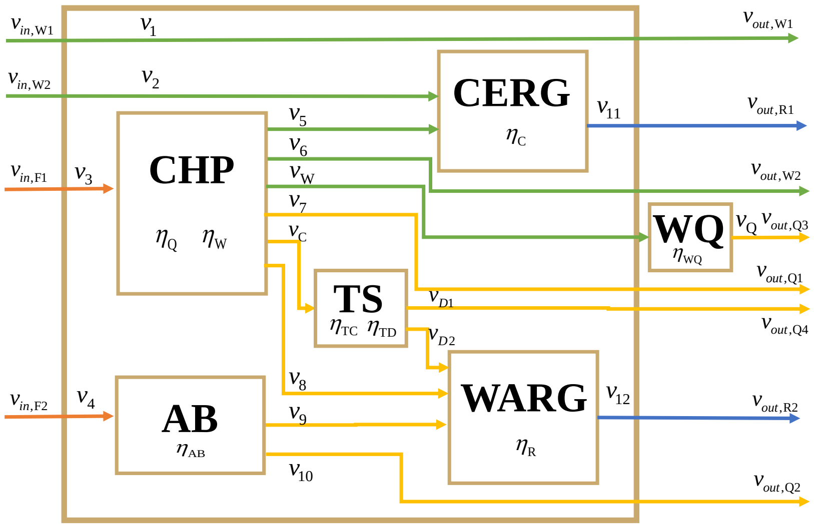


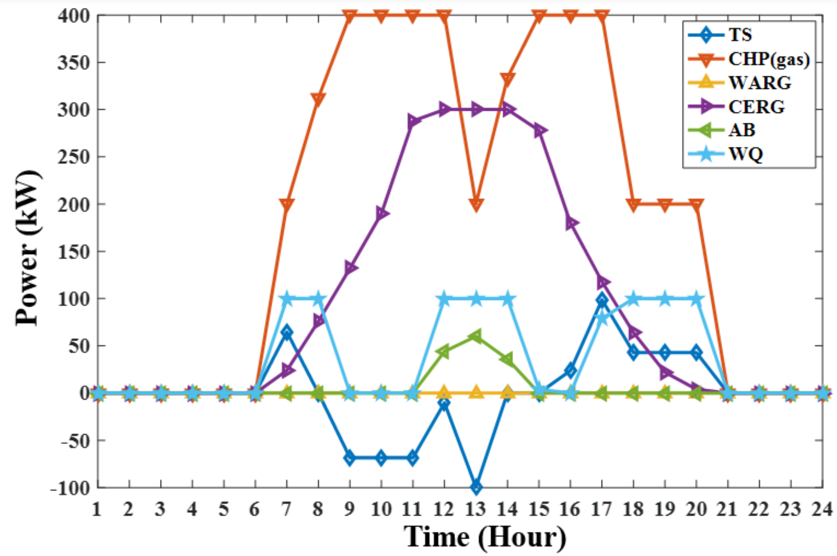

$$\boldsymbol{Q}=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \eta_Q & -1 & -1 & 0 & 0 \\ \eta_W & 0 & 0 & -1 & 0 \\ 0 & \eta_R & 0 & 0 & -1 \end{bmatrix} \Rightarrow \boldsymbol{V}_{out}=\begin{bmatrix} 0 \\ \eta_Q \\ \eta_W \end{bmatrix}\boldsymbol{V}_{in}+\begin{bmatrix} \eta_R \\ -1 \\ 0 \end{bmatrix} v_{QWARG}$$

$$\boldsymbol{Z}=\begin{bmatrix} \eta_Q & -1 & -1 & 0 & 0 \\ \eta_W & 0 & 0 & -1 & 0 \\ 0 & \eta_R & 0 & 0 & -1 \\ 0 & -\alpha_Q & \alpha_R & 0 & 0 \end{bmatrix} \Rightarrow \boldsymbol{C}=-\boldsymbol{Y}\boldsymbol{Q}^{-1}\boldsymbol{R}=\begin{bmatrix} \eta_Q\alpha_R\eta_{WARG} & \eta_Q\alpha_Q & \eta_W \end{bmatrix}^T$$

# Extended Analysis

## ◆ Case Studies

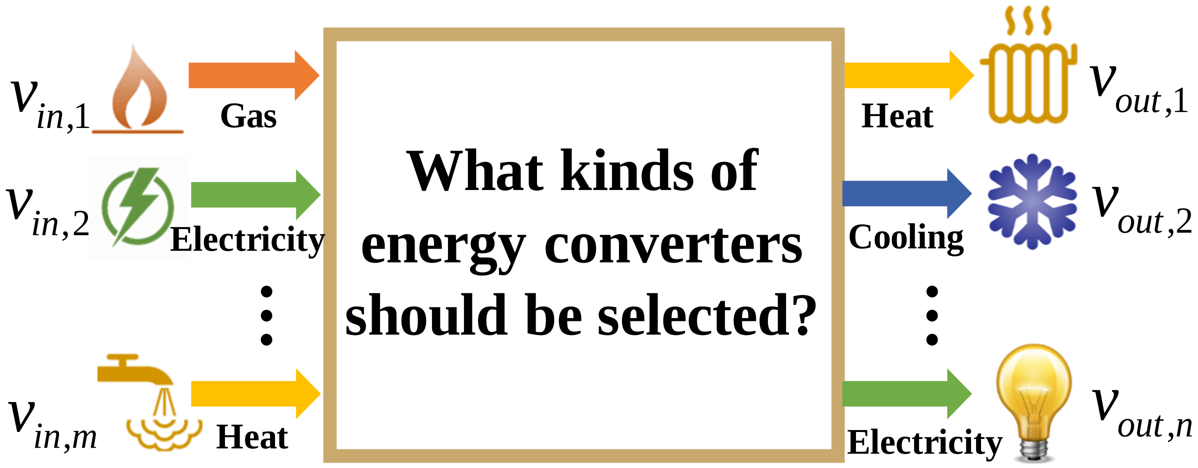



$$
\begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\
-1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0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

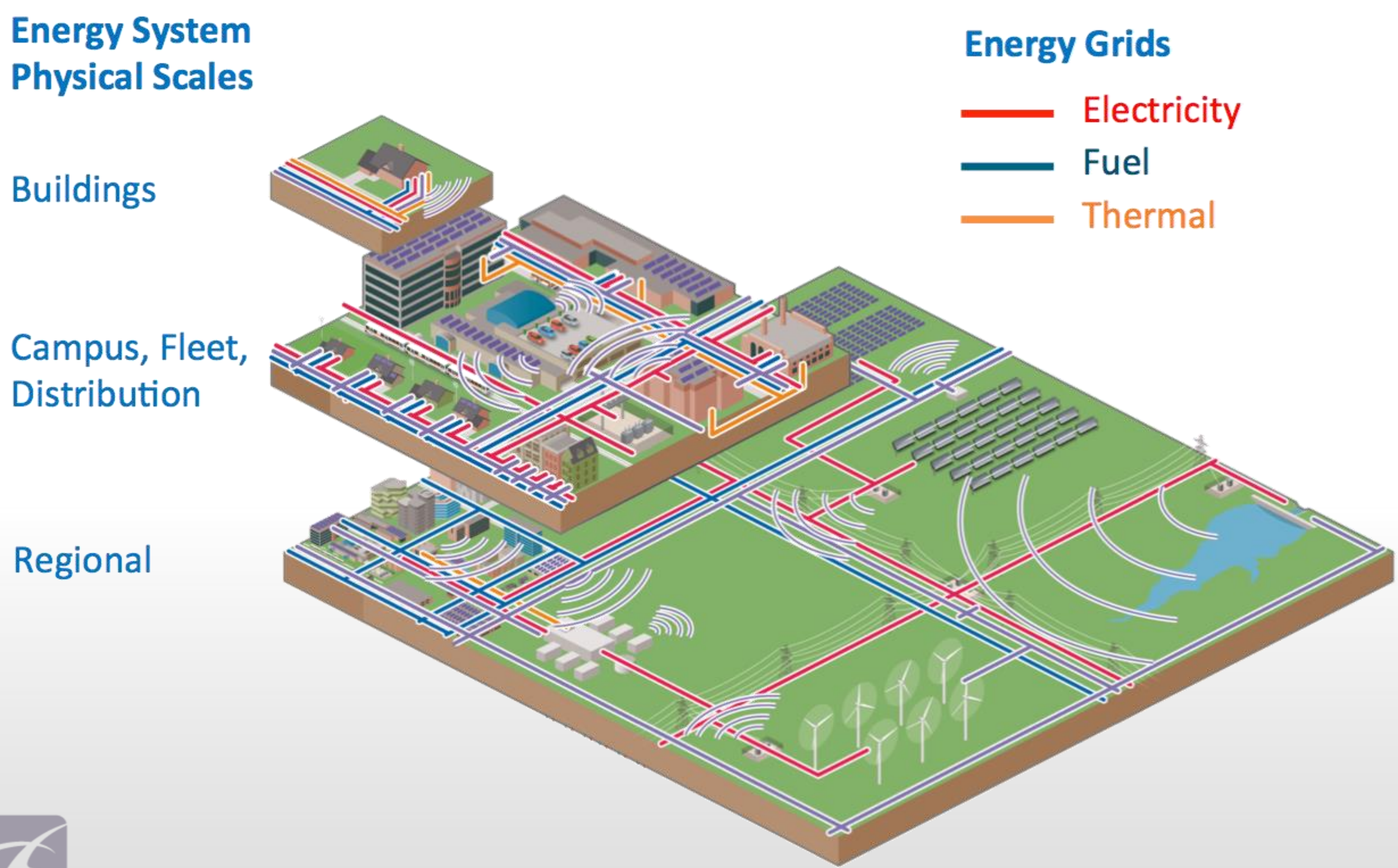
# What to do next?

- Energy Storage ?
- Demand Response ?
- Multiple Energy Networks ?
- Non-linearity of Energy Conversion ?
- General Optimal Energy Flow Model ?



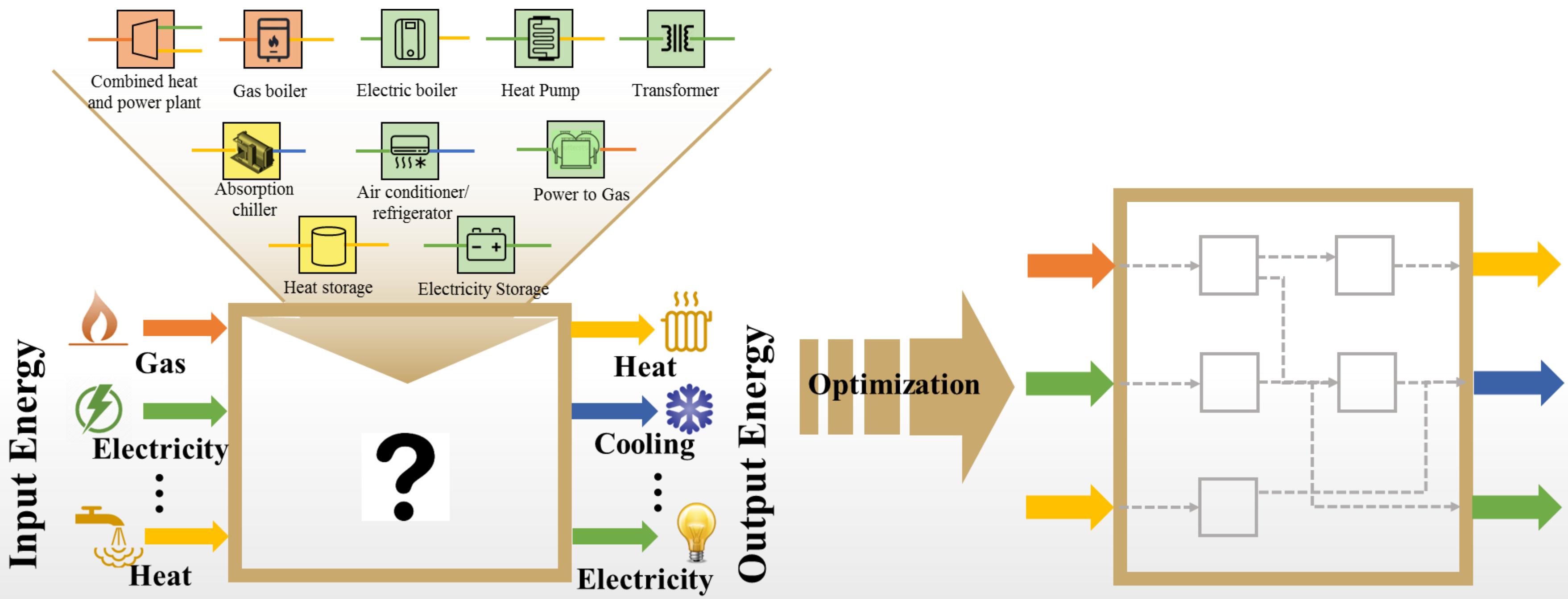

# Planning of Multiple Energy Systems

# Multiple Energy System

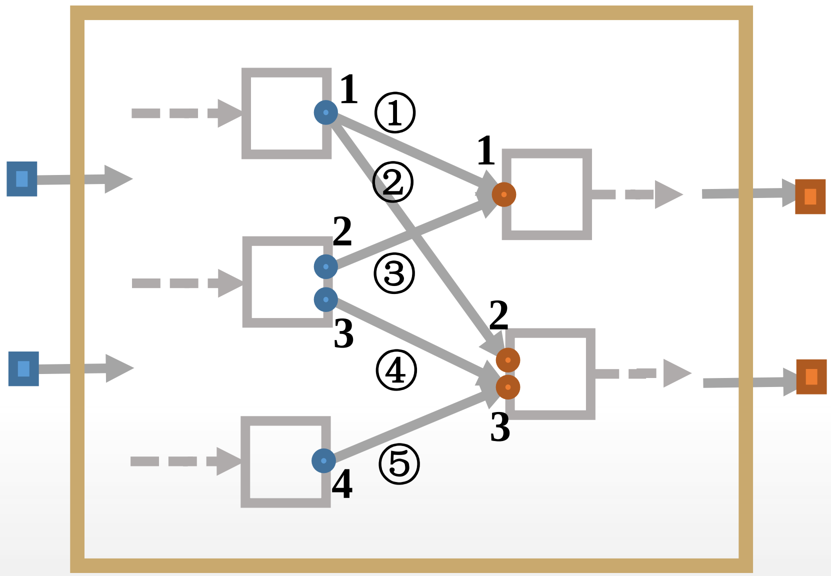


# EH Planning: Starting from Scratch

◆ **Problem Statement**



# Modeling connections of possible components




Output port · Input port · Branch
EH input · EH output

| | #1 | #2 | | #3 | ⋯ | #N | Output | |
|---|---|---|---|---|---|---|---|---|
| Input | $x_{1,1}$ | $x_{1,2}$ | $x_{1,3}$ | $x_{1,4}$ | $\cdots$ | $x_{1,n-2}$ | $x_{1,n-1}$ | $x_{1,n}$ |
| | $x_{2,1}$ | $x_{2,2}$ | $x_{2,3}$ | $x_{2,4}$ | $\cdots$ | $x_{2,n-2}$ | $x_{2,n-1}$ | $x_{2,n}$ |
| #1 | $x_{3,1}$ | $x_{3,2}$ | $x_{3,3}$ | $x_{3,4}$ | $\cdots$ | $x_{3,n-2}$ | $x_{3,n-1}$ | $x_{3,n}$ |
| #2 | $x_{4,1}$ | $x_{4,2}$ | $x_{4,3}$ | $x_{4,4}$ | $\cdots$ | $x_{4,n-2}$ | $x_{4,n-1}$ | $x_{3,n}$ |
| ⋮ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\ddots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| #N-1 | $x_{m-2,1}$ | $x_{m-2,2}$ | $x_{m-2,3}$ | $x_{m-2,4}$ | $\cdots$ | $x_{m-2,n-2}$ | $x_{m-2,n-1}$ | $x_{m-2,n}$ |
| | $x_{m-1,1}$ | $x_{m-1,2}$ | $x_{m-1,3}$ | $x_{m-1,4}$ | $\cdots$ | $x_{m-1,n-2}$ | $x_{m-1,n-1}$ | $x_{m-1,n}$ |
| #N | $x_{m,1}$ | $x_{m,2}$ | $x_{m,3}$ | $x_{m,4}$ | $\cdots$ | $x_{m,n-2}$ | $x_{m,n-1}$ | $x_{m,n}$ |

**Energy flow matrix**

| | #1 | #2 | | #3 | ⋯ | #N | Output | |
|---|---|---|---|---|---|---|---|---|
| Input | $x_{1,1}$ | $x_{1,2}$ | $x_{1,3}$ | $x_{1,4}$ | $\cdots$ | $x_{1,n-2}$ | $x_{1,n-1}$ | $x_{1,n}$ |
| | $x_{2,1}$ | $x_{2,2}$ | $x_{2,3}$ | $x_{2,4}$ | $\cdots$ | $x_{2,n-2}$ | $x_{2,n-1}$ | $x_{2,n}$ |
| #1 | $x_{3,1}$ | $x_{3,2}$ | $x_{3,3}$ | $x_{3,4}$ | $\cdots$ | $x_{3,n-2}$ | $x_{3,n-1}$ | $x_{3,n}$ |
| #2 | $x_{4,1}$ | $x_{4,2}$ | $x_{4,3}$ | $x_{4,4}$ | $\cdots$ | $x_{4,n-2}$ | $x_{4,n-1}$ | $x_{3,n}$ |
| ⋮ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\ddots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| #N-1 | $x_{m-2,1}$ | $x_{m-2,2}$ | $x_{m-2,3}$ | $x_{m-2,4}$ | $\cdots$ | $x_{m-2,n-2}$ | $x_{m-2,n-1}$ | $x_{m-2,n}$ |
| | $x_{m-1,1}$ | $x_{m-1,2}$ | $x_{m-1,3}$ | $x_{m-1,4}$ | $\cdots$ | $x_{m-1,n-2}$ | $x_{m-1,n-1}$ | $x_{m-1,n}$ |
| #N | $x_{m,1}$ | $x_{m,2}$ | $x_{m,3}$ | $x_{m,4}$ | $\cdots$ | $x_{m,n-2}$ | $x_{m,n-1}$ | $x_{m,n}$ |

**Input and output ports incidence matrix**

# MES Planning optimization problem

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

s.t.

**Constraints**

$$\begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{Y} \\ \boldsymbol{Z} \end{bmatrix} \boldsymbol{V} = \begin{bmatrix} \boldsymbol{V}_{in} \\ \boldsymbol{V}_{out} \\ \boldsymbol{0} \end{bmatrix}, \quad \forall l,t,s$$

**Operation constraints under different operation scenario**

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

**The coupling constraints between binary variable and energy flow variable for each branch**

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

**The coupling constraints between binary variables of branch and components**

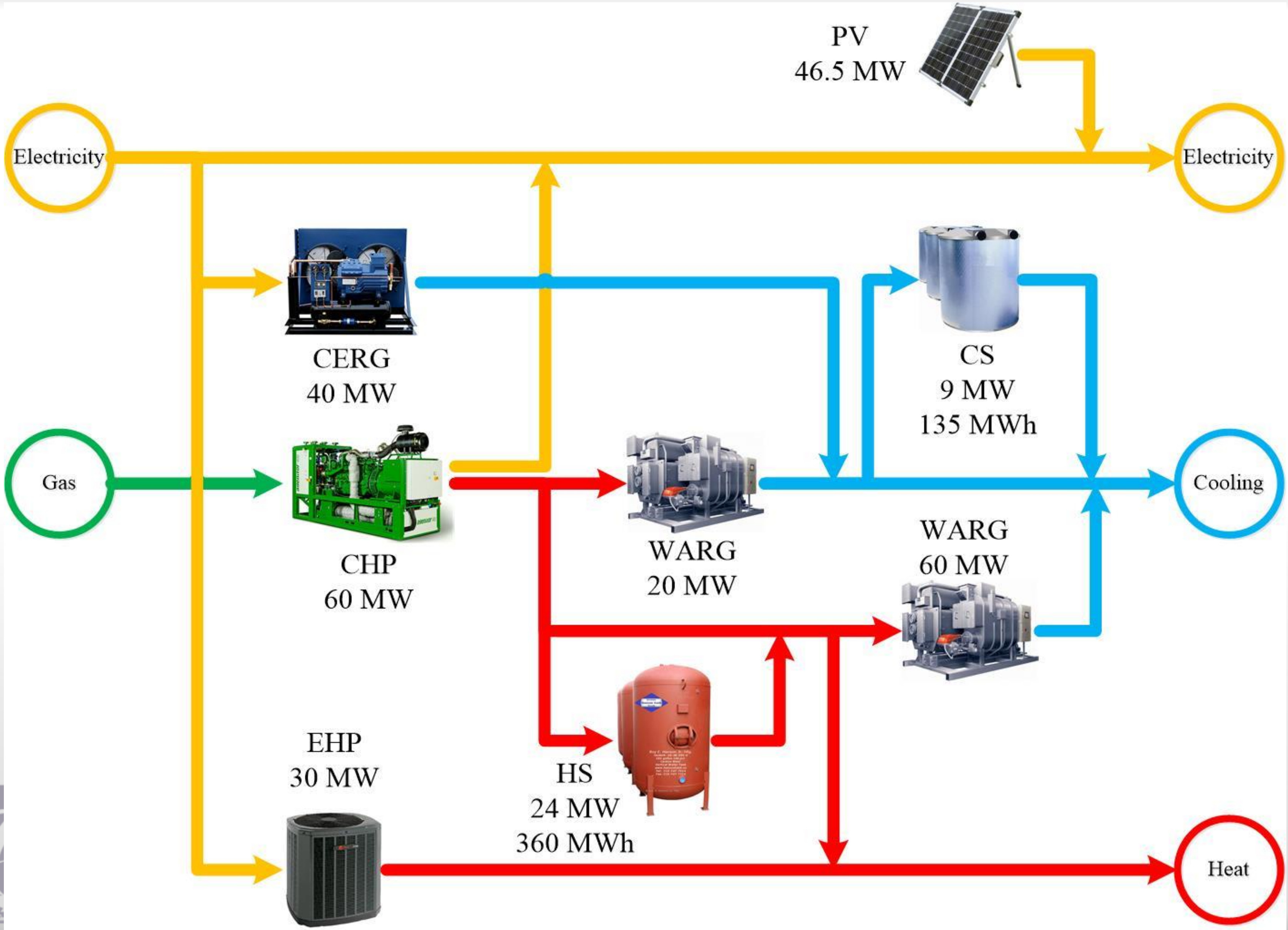
**Large scale MILP problem**

# Planning subsidiary administrative center of Beijing

- 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.

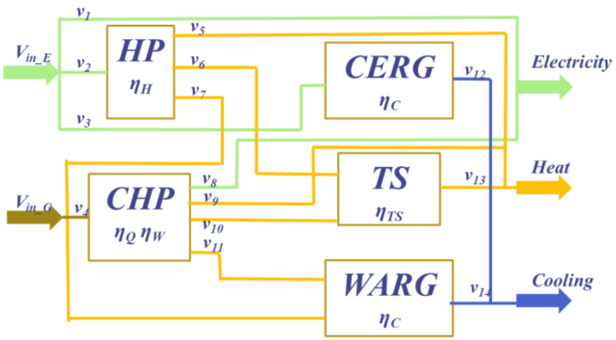
# Optimal Planning



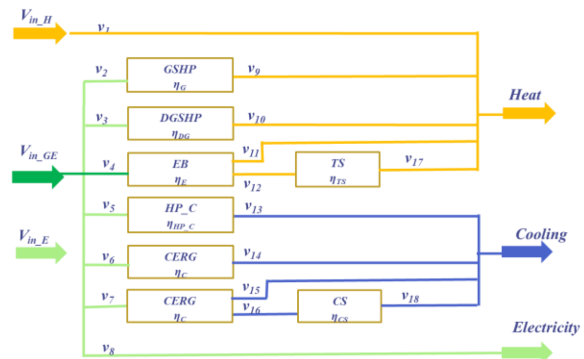
# Planning scheme comparison for Subsidiary administrative center of Beijing

◆ **Potential planning for Tongzhou**

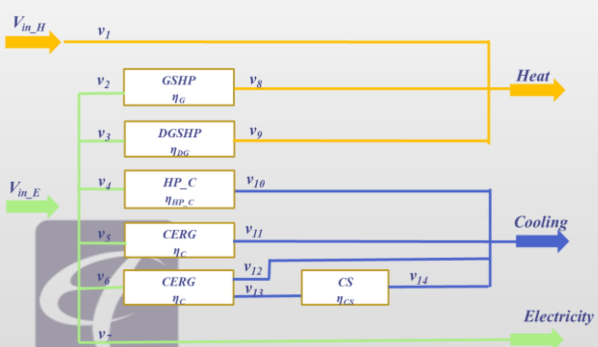
Case 1:
Planning results from the model



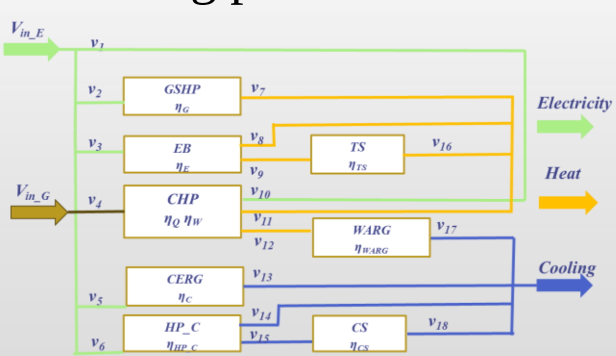

Case 2:
Wind power heating case



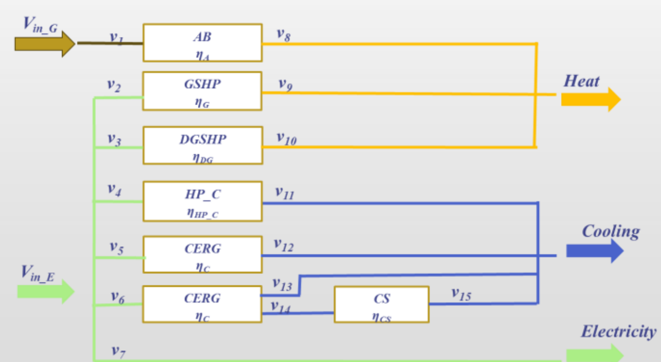

Case 3
Import city heat network plan




Case 4
Combine cooling and heating plan

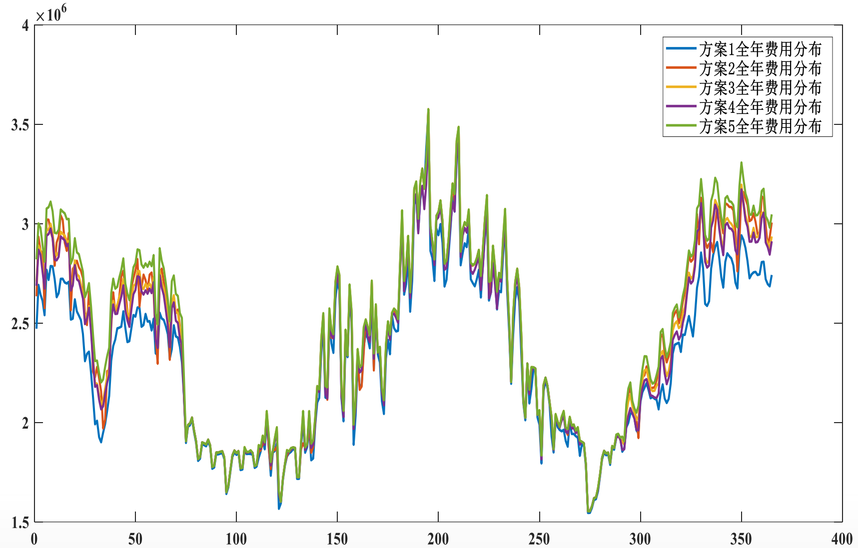


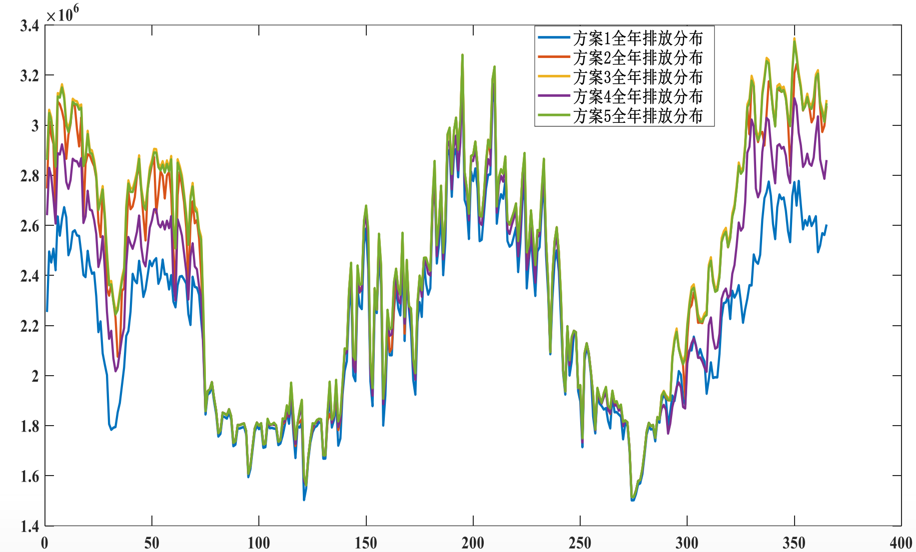

Case 5
Gas boiler plan



# 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

- The presentation provides methodologies of standardized modeling for MES
  - Linear model of power grid, gas network and heat network
  - A standardized matrix modeling method of Energy Hub
- Standardized modeling can:
  - Automated modeling of MES
  - Planning of MES
  - Optimal/stochastic energy flow of MES
  - Reliability/ Resilience of MES

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# Thanks

Q&A