Steady-State Security Region of Energy Hub: Modeling, Calculation, and Applications

Pei Yong, Tsinghua University
PhD Student
Supervisor: Prof. Chongqing Kang
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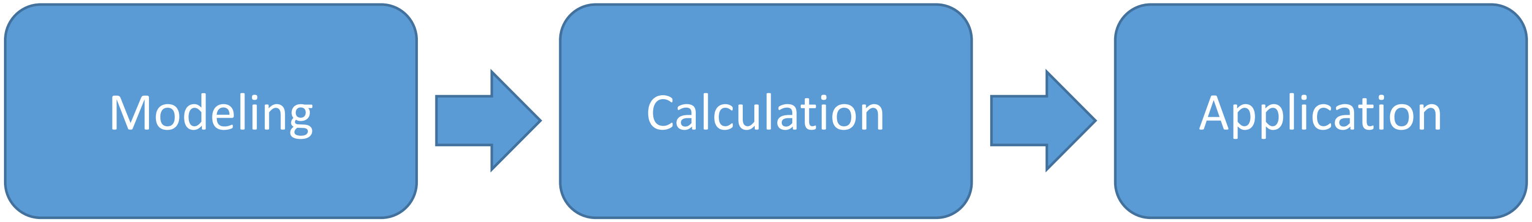
Outline

1. Backgrounds and Motivation
2. Security Region Modeling
3. Calculating Methodology
4. Application in Planning
5. Case Study
6. Conclusion and Future Work

Backgrounds and Motivation

- Multi-energy systems (MES) supply various types of energy by coupling different energy sectors.
- The coupling increases the efficiency and flexibility of the entire energy system, and increases the dependencies of the load carrying capability among different types of load demand.
- It is crucial to identify such mutual effects among different energy sectors when planning the MES.

We model the load carrying capability of MES by proposing a new concept named the Steady-State Security Region of Energy Hub.



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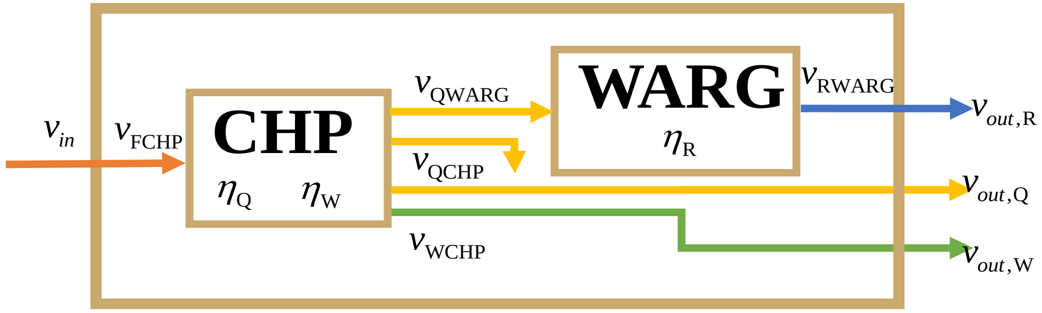
Security Region Modeling

- **Energy hub model formulates the energy conversion in MES as port based unit with multiple inputs and multiple outputs.**

$$\mathbf{V}_{\mathrm{out}} = \mathbf{C}\mathbf{V}_{\mathrm{in}}$$

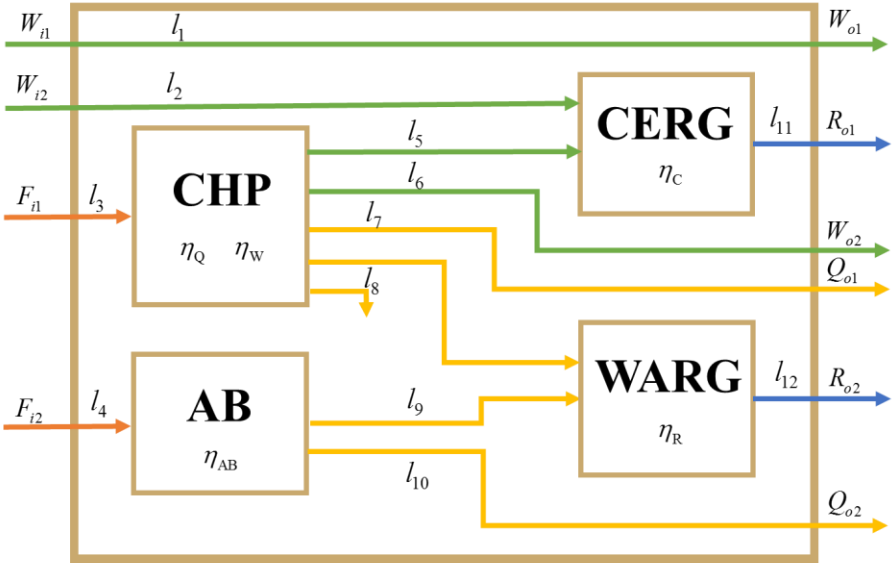


$$\mathbf{V}_{in} = \left[v_{in,\mathrm{F}} \right]$$

$$\mathbf{V}_{out} = \left[v_{out,\mathrm{R}} \quad v_{out,\mathrm{Q}} \quad v_{out,\mathrm{W}} \right]^{T}$$

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

Security Region Modeling



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

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

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

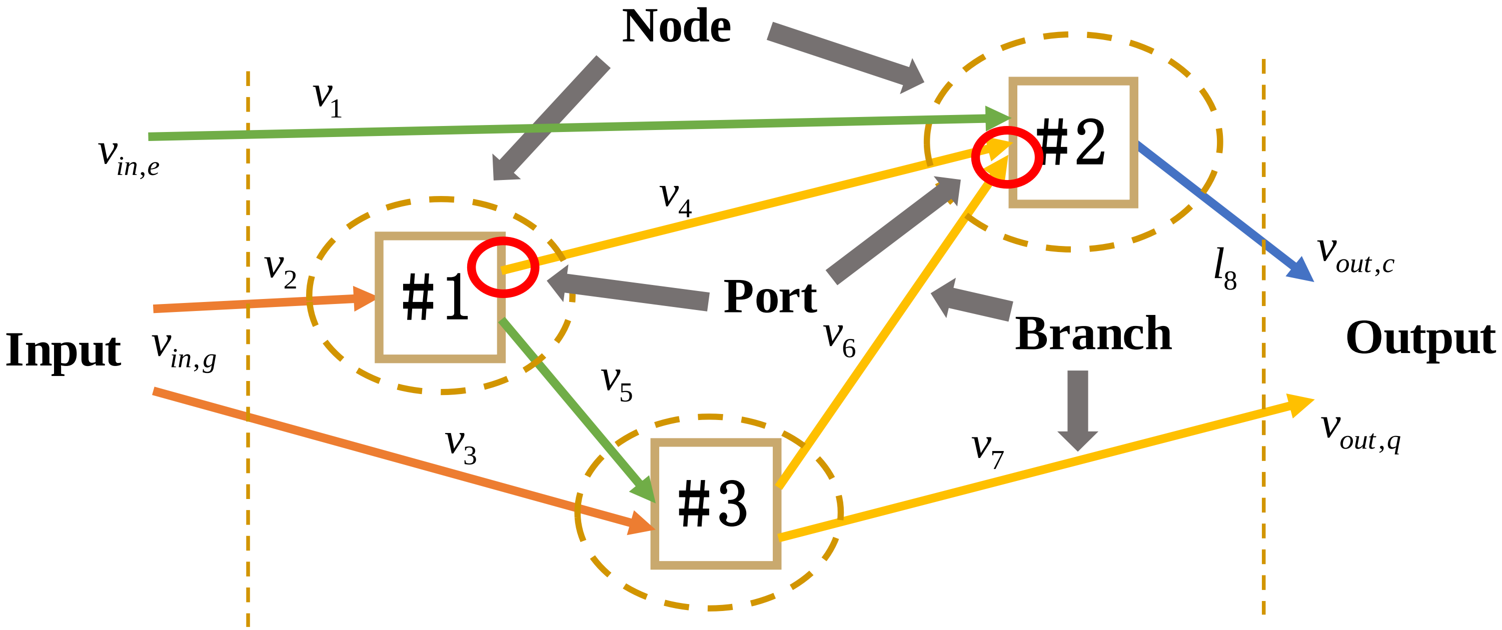
Hard to be modeled automatically

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

Standard Modeling of Energy Hub

- An 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.

Model of the Energy Hub

Several matrices are introduced to describe the topology of the energy hub and energy transfer equations of components.

- **Port-Branch Incidence Matrices A_g**

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

It describes the relationship between the components and energy flow

- **Converter Characteristic Matrices H_g**

It describes the energy transfer equations of component g

- **Energy Conversion Matrices Z_g**

$$Z_g = H_g A_g$$

This matrix combines the energy converter characteristics and the connections between node g and all branches.

Model of the Energy Hub

- Applying these matrices we can get the energy conversion equation of the energy hub:

$$Z \times V = 0$$

where V is the energy flow vector.

- Define the output matrix X and input matrix Y:

$$X(i,b) = \begin{cases} 1 & \text{if input node } i \text{ is source of branch } b \\ 0 & \text{otherwise} \end{cases}$$

$$Y(i,b) = \begin{cases} 1 & \text{if output node } i \text{ is sink of branch } b \\ 0 & \text{otherwise} \end{cases}$$

The input incidence and output incidence equations are:

$$V_{in} = XV$$
$$V_{out} = YV$$

- Operational constraints of energy hub can be modeled by

$$0 \leq V \leq V_{max}$$

Security Region Modeling

Security Region of Energy Hub

Like the steady state security region of power system, the security region of energy hub can be defined as **a set of energy outputs for which the energy conversion equation and the operational constraints can be satisfied.**

$$Z \times V = 0$$

$$0 \le V \le V_{max}$$

$$V_{out} = YV$$

Security Region Ω:

$$\Omega = \{V_{out} | V_{out} = YV, Z \times V = 0, 0 \le V \le V_{max}\}$$

That is to say, for any V_{out} in Ω, there is a V, and $V_{out} = YV$. V satisfies the constraints of the energy hub.

Moreover, if the outage of components are considered, V_{out} should satisfy the energy conversion equation and the operational constraints under all N-1 contingencies.

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Calculating Methodology

The Security Region can be expressed by:

$$\Omega = \{V_{out} | V_{out} = YV, Z \times V = 0, 0 \le V \le V_{max}\}$$

Mathematically, solving Ω is a projection problem. It projects the feasible region of the energy hub constructed by V and V_{out} to the hyperspace of V_{out}. The projection problem can hardly be solved in an analytical way.

However, we can note that the security region have the following characteristics:

- Ω is a convex hull that contains the original point.
- All points V_{out} in Ω satisfy $V_{out} \ge 0$.
- Ω is bounded in hyperspace R^{out}.

Calculating Methodology

According to these characteristics, we can design an algorithm to find the vertexes of the convex hull Ω.

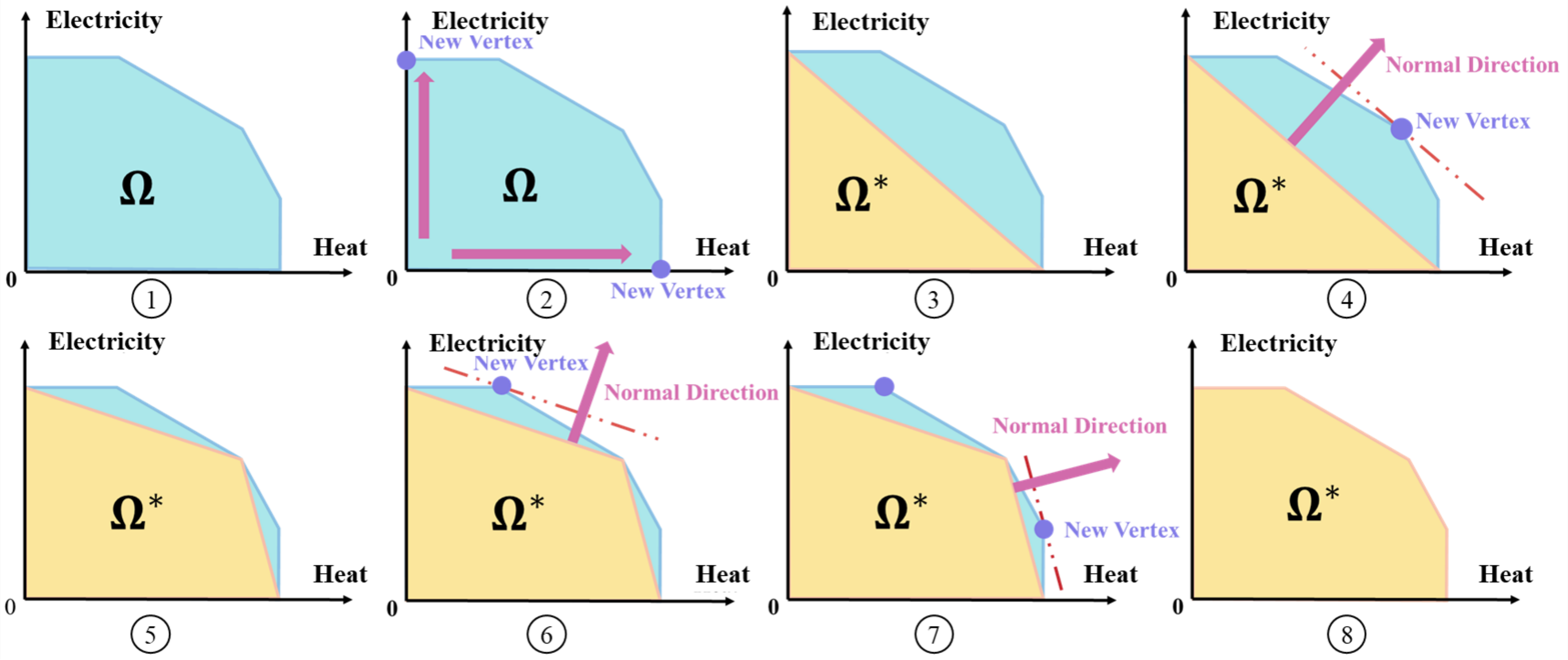
- First, find the vertexes that lie on the axis of hyperspace R^{out}, and build the initial known security region Ω^k. ($\Omega^k \subseteq \Omega$)
- For every surface of the Ω^k, choose its normal direction as the searching direction, and search new vertexes of Ω.
- After a round of searching, update the known security region Ω^k, and repeat the second step. If all vertexes are found, or the security region is accurate enough, then stop the searching process.

Since the Ω only have finite vertexes, the algorithm is convergent and will stop after finite iterations.

Calculating Methodology

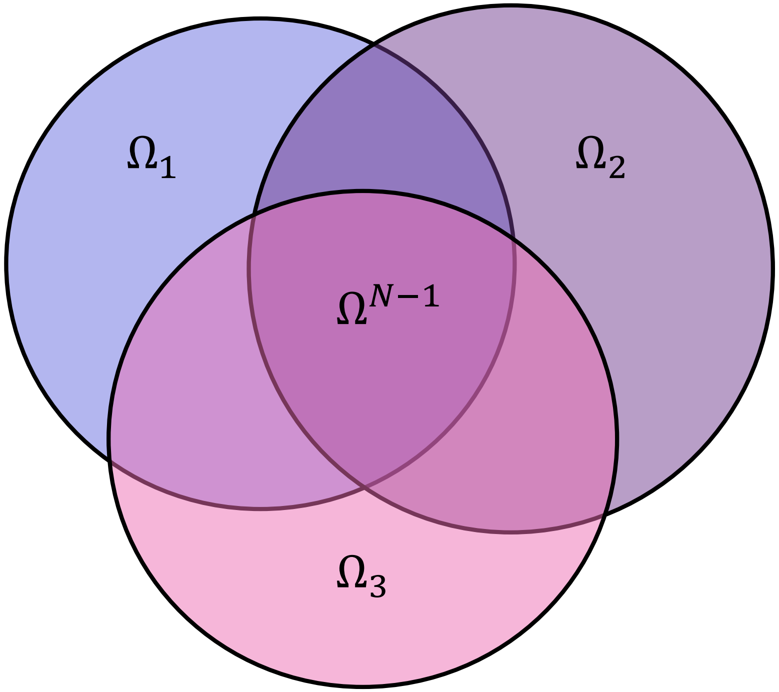
Illustrative Example

- An illustrative example of our method to calculate the security region of energy hubs



N-1 Security Region

- To consider the security region of an energy hub under N-1 contingency, outages of components should be considered.
- For every component *i* in an energy hub, we need to calculate the security region Ω_i under the condition that component *i* is out of service.
- Then calculate the intersection of all Ω_i, $\Omega^{N-1} = \Omega_1 \cap \Omega_2 \cap \cdots \cap \Omega_N$



Outline

Application in Planning

The EH steady-state security region can be applied in the planning stage to analyze the load carrying capability of MES

➢ Volume of the Security Region (VSR)

$$S_{\Omega} = \int_{\Omega} dv = \int \cdots \int_{\Omega} dx_1 dx_2 \cdots dx_k$$

- The volume of the security region measures the size of the load demand space that the EH can deliver.
- The absolute value of the VSR does not have a direct physical meaning, but can be used to make comparisons among different planning schemes of the same MES.

➢ Load-Weighted Volume (LWV)

$$L_{\Omega} = \int_{\Omega} p_d \, dv \times 100\% = \int \cdots \int_{\Omega} p_d \, dx_1 dx_2 \cdots dx_k$$

- Compared with the VSR, the LWV takes the distribution of the load demand into consideration.
- A higher LWV indicates a greater probability of serving all kinds of loads.

Application in Planning

The EH steady-state security region can be applied in the planning stage to analyze the load carrying capability of MES

The components in an EH hold different positions, and their contributions to the load carrying ability vary.

- ➢ Important Degree of volume (IDV) and Important Degree of Load (IDL)

$$IDV_i = (1 - \frac{VSR_i}{VSR_0}) \times 100\%$$

$$IDL_i = (1 - \frac{LWV_i}{LWV_0}) \times 100\%$$

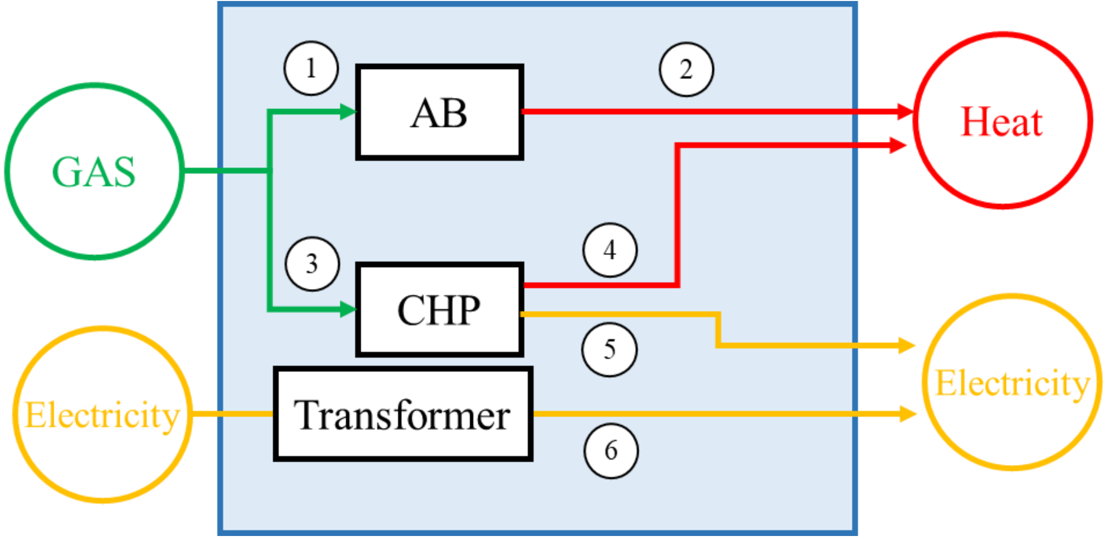
we define two indices to identify the critical components. The important degree of volume (IDV) measures a component's influence on the VSR, and the important degree of load (IDL) measures its influence on the LWV.

Outline

Case Study

Case Study No.1

- Topology of Test System



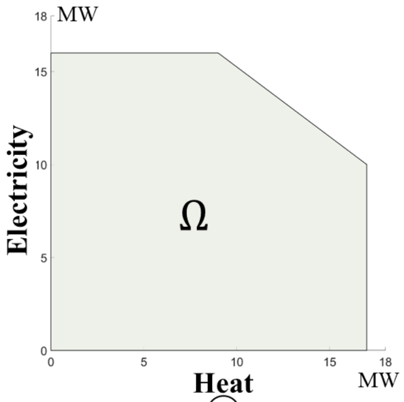
- Parameters of Components

Component	Capacity	Efficiency
AB	10MW	0.9
CHP	6MW	Ele: 0.3 Therm: 0.4
Transformer	10MW	—

Case Study

Case Study No.1

- Security Region Analysis



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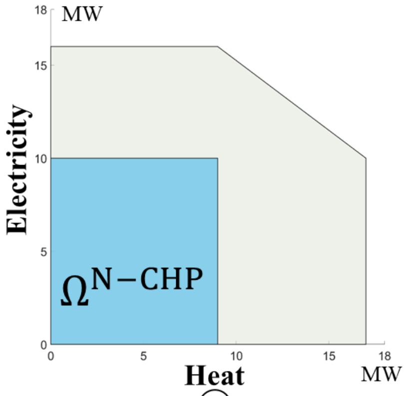

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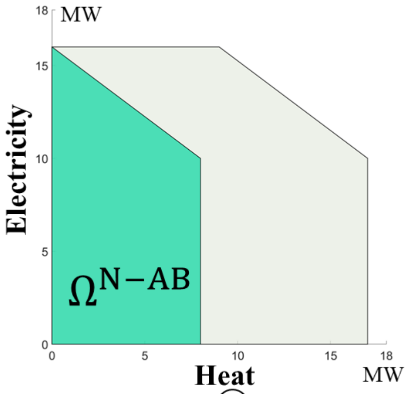

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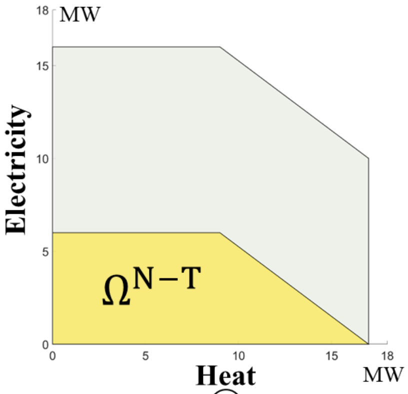

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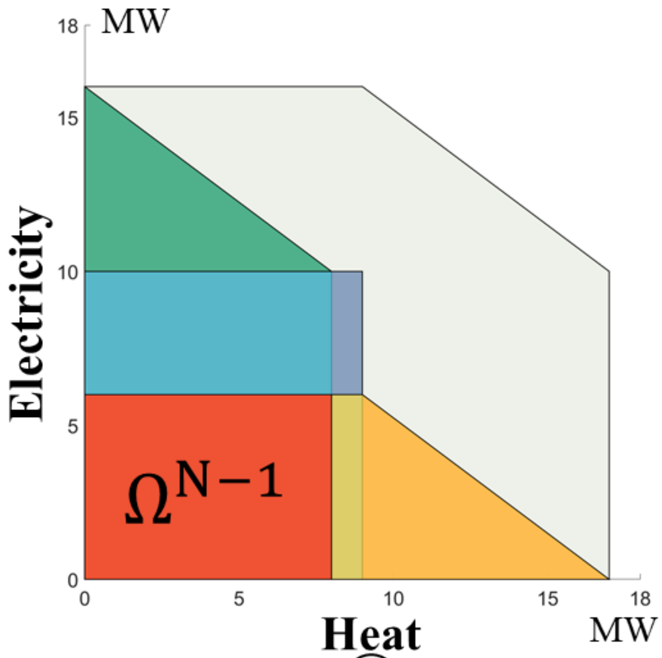
- N-1 Security Region



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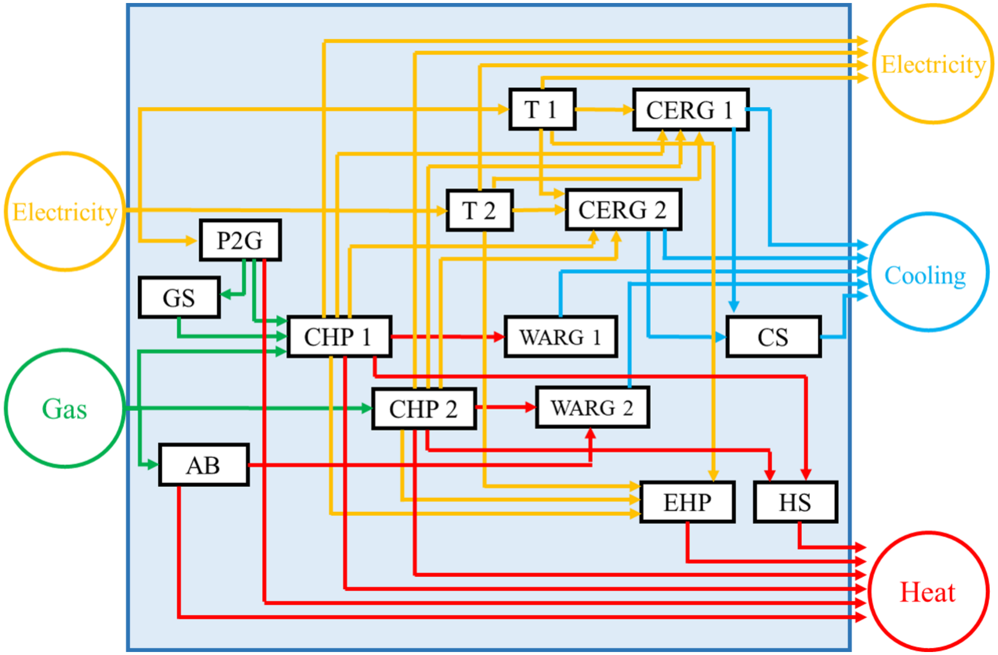
Case Study

Case Study No.2

- Topology of Test System

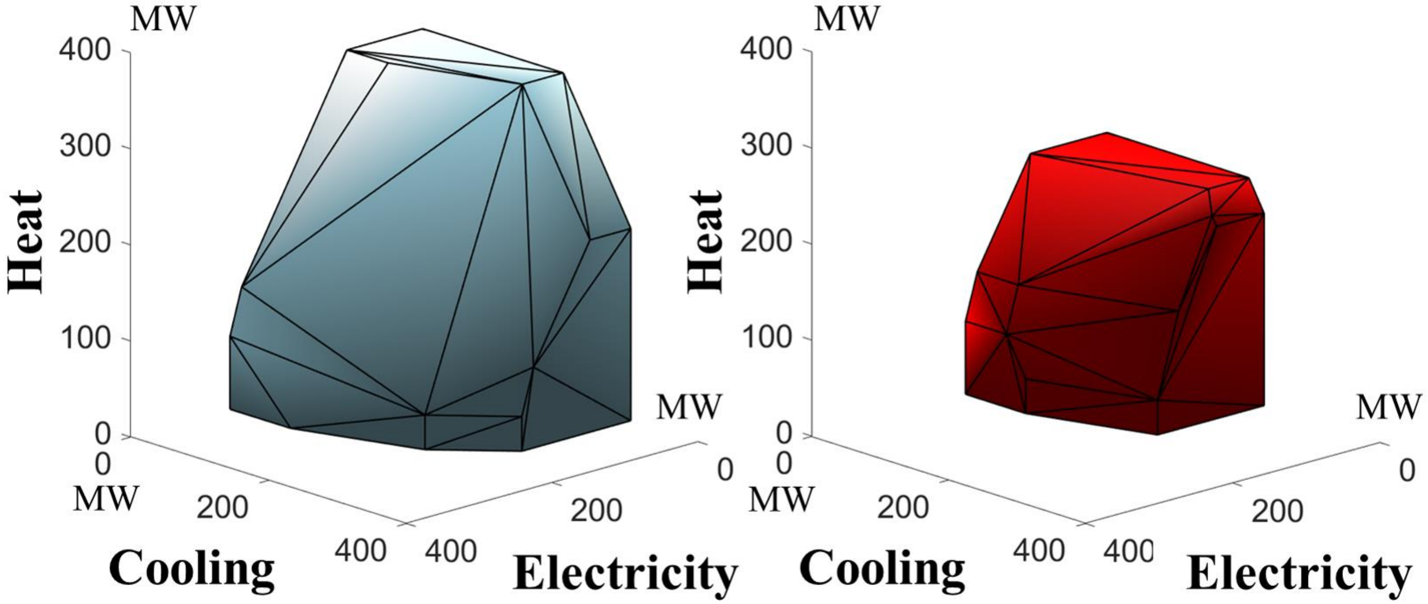


- Parameters of Components

Component1.	Capacity	Efficiency
AB	50MW	0.8
CHP	240MW	Ele: 0.3 Therm: 0.45
CERG	24MW	3
WARG	70MW	0.7
EHP	16MW	3
Transformer	70MW	—
P2G	50MW	Gas:0.58 Therm:0.12
HS	30MW	0.9
CS	60MW	0.9
GS	30MW	1

Case Study

Case Study No.2



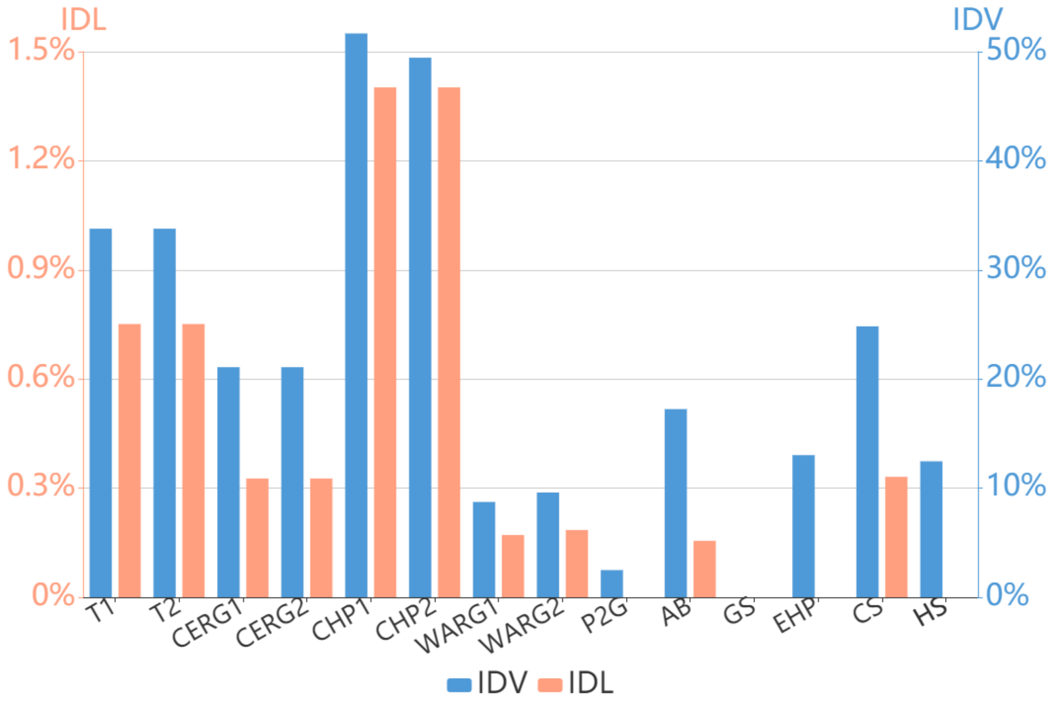
without Consideration of Outages Considering N-1 Contingency

- The VSR without considering outages is $1.70 \times 10^7 MW^3$, while the VSR considering N-1 contingency is $5.73 \times 10^6 MW^3$. When the N-1 contingency is considered, the VSR is shrunk by 66.3%.

Case Study

Case Study No.2

We do critical component identification on Test System 2.



- The results show that for this system, CHP1 and CHP2 are the most critical components.
- If we adjust the planning scheme by removing CHP1 and adding two CHPs, the VSR considering N-1 contingency will increase by 30.5%

Conclusion

- We provide insights on load carrying capability of MES by the concept of the EH steady-state security region.
- It is able to systematically formulate the load carrying capability under both normal operation and contingency.
- The MES is formulated using standardized matrix modeling.
- An effective vertex-based algorithm is proposed to calculate the security region as a polyhedron in a hyperspace.
- The proposed method is able to find critical component that affect load carrying capability of an district MES.

Thanks!

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