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Operational Reliability Evaluation of Distributed Multi-Energy Systems Considering Optimal Control of Energy Storages

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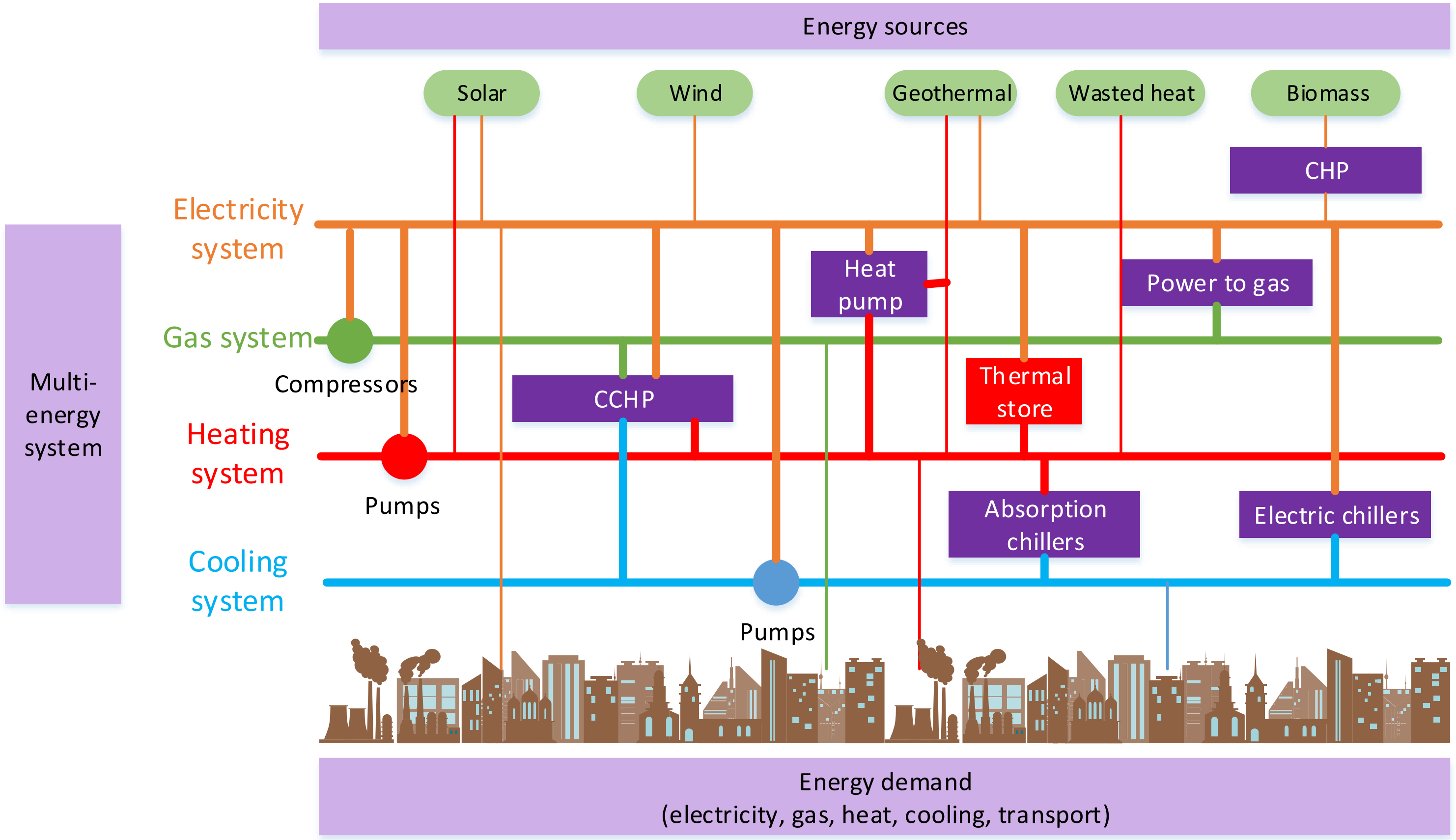
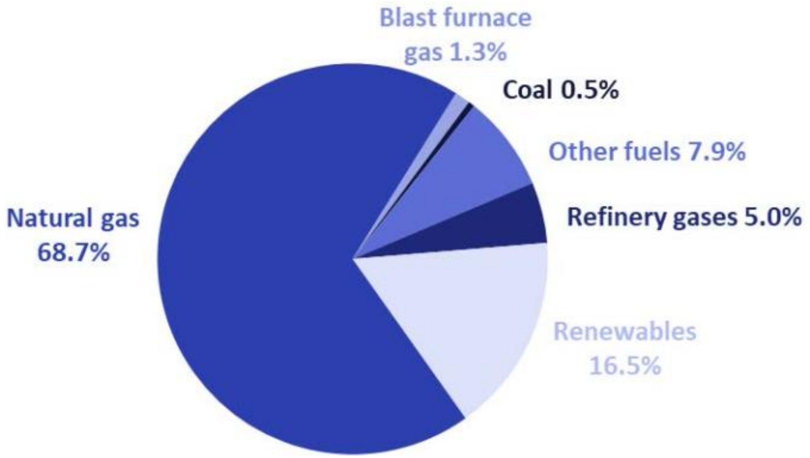
Introduction





- **68.7%** of the fuel used in CHP schemes in 2017 was natural gas in UK [1].
- In China, the heat demand of nearly 9×109 m2 area is supplied by centralized heating supply, 51% of which is met by CHP

Multiple energy sources, transmission and distribution systems and energy demands are organized for production, delivery and consumption, especially **electricity**, **gas** and **heat** in demand side.

[1] GOV.UK:Department for Business EIS. Digest of UK Energy Statistics (DUKES): combined heat and power 2018 July. <https://www.gov.uk/government/statistics/combined-heat-and-power-

Introduction

Reliability issues

2017.08

Taiwan, China

- Human error in Datan gas fired power plant
- Interruption of gas supply
- 4 GW electricity shortage

2020.12

Shanxi, China

- Freeze of the coal handling belt of the heating and power plant
- interruption of the heat supply for the urban district of 11 km^2 for three days

2021.02

Texas, US

- Freeze of the gas well valves
- 20 GW load shedding, interruption of over 4.8 million users

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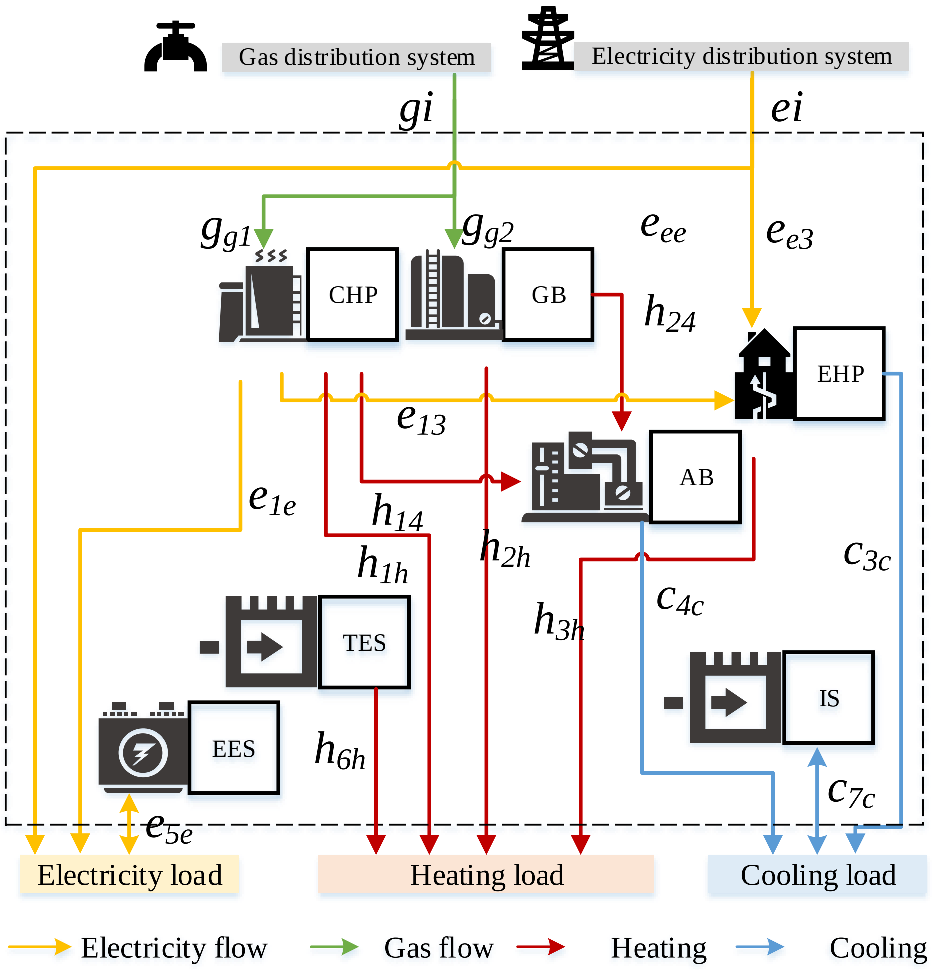
Our work

Long-term

Short-term

- Time-varying load curve
- Time-varying state probability
- Optimal control actions

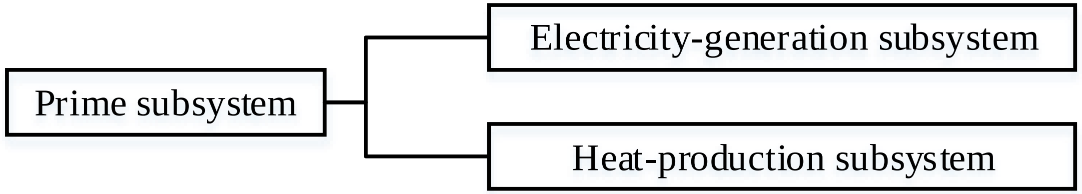
Structure of the studied DMES



- Combined heat and power plant (CHP)
- gas boiler (GB)
- electric heat pump (EHP)
- absorption chiller (AB)
- electric energy storage (EES)
- thermal energy storage (TES)
- ice storage (IS)

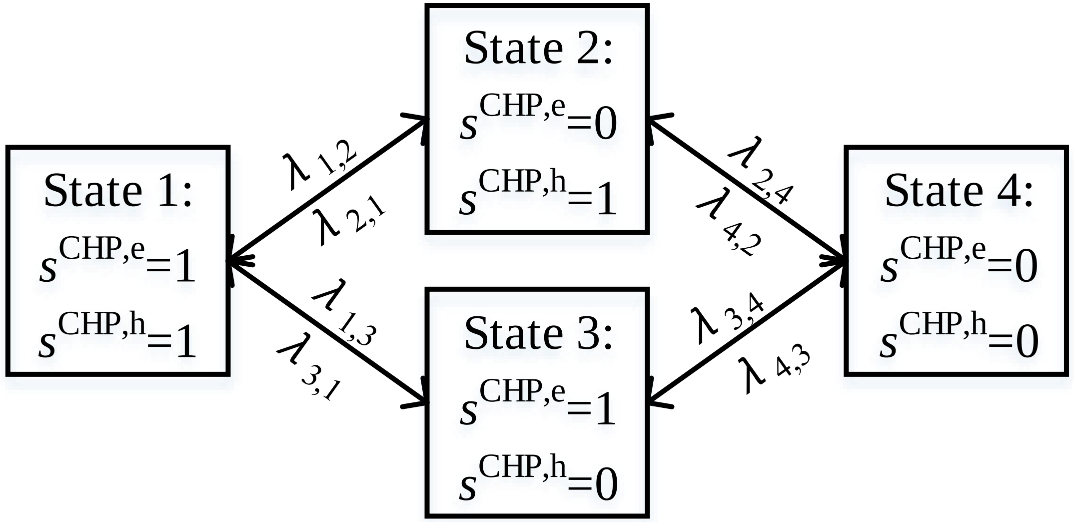
Operational reliability of the components

Structure



$$s^{CHP,h} = s^p s^h, s^{CHP,e} = s^p s^e$$

State transition



- State transition rate

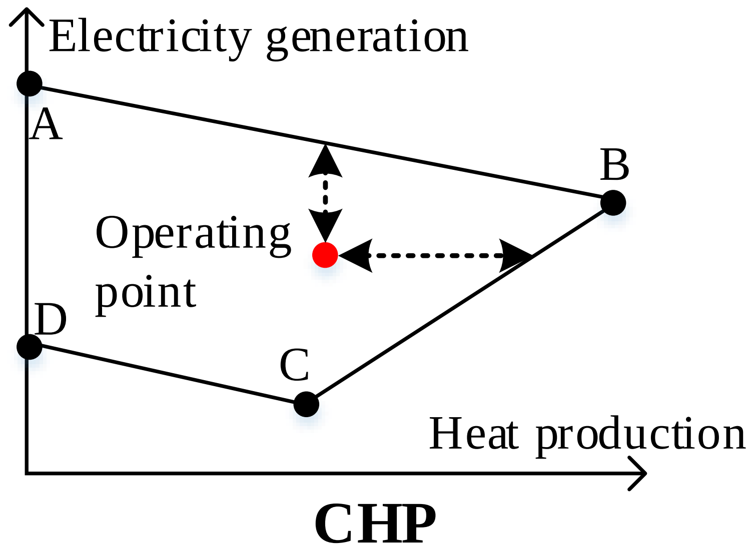
$$\lambda_{1,2} = \lambda^e, \lambda_{2,1} = \mu^e \quad \lambda_{1,3} = \lambda^h, \lambda_{3,1} = \mu^h \quad \lambda_{2,4} = \lambda^h + \lambda^p, \lambda_{3,4} = \lambda^e + \lambda^p$$

$$\lambda_{4,2} = \left(\begin{array}{l} \Pr\{s^p = 1, s^e = 0, s^h = 0\}\mu^h \\ + \Pr\{s^p = 0, s^e = 0, s^h = 1\}\mu^p \end{array} \right) \Big/ \left(\begin{array}{l} \Pr\{s^p = 1, s^e = 0, s^h = 0\} \\ + \Pr\{s^p = 0, s^e = 0, s^h = 1\} \end{array} \right)$$

$$\lambda_{4,3} = \left(\begin{array}{l} \Pr\{s^p = 1, s^e = 0, s^h = 0\}\mu^e \\ + \Pr\{s^p = 0, s^e = 1, s^h = 0\}\mu^p \end{array} \right) \Big/ \left(\begin{array}{l} \Pr\{s^p = 1, s^e = 0, s^h = 0\} \\ + \Pr\{s^p = 0, s^e = 1, s^h = 0\} \end{array} \right)$$

Operational reliability of the components

Operating constraints



In the normal state

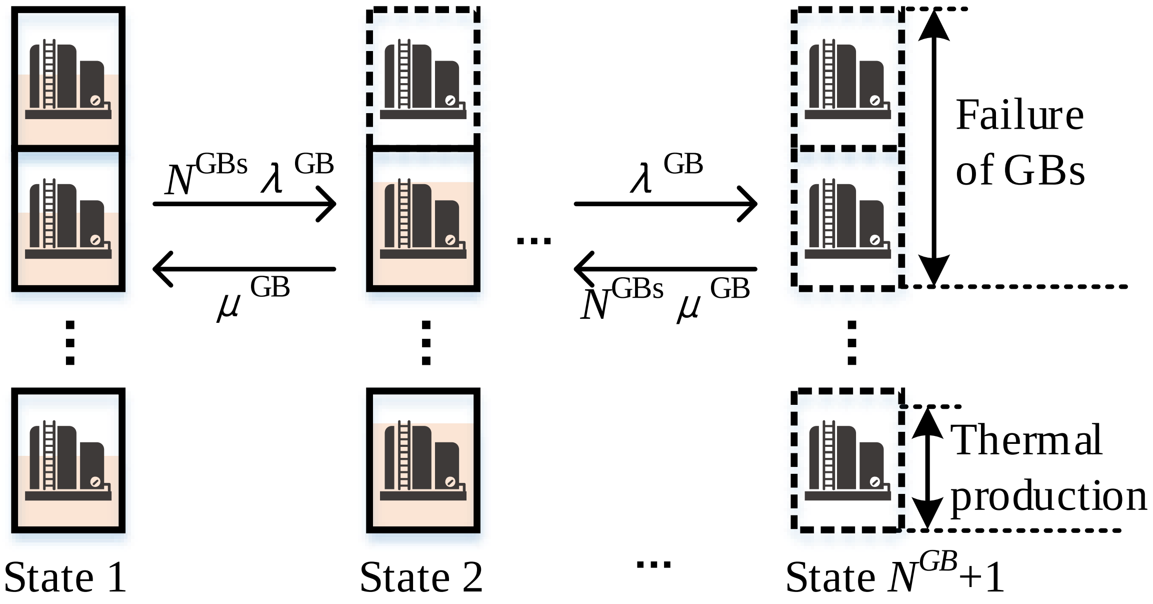
$$\begin{cases} h_{1h}+h_{14}\ge 0 \\ e_{13}+e_{1e}-E_A-(E_A-E_B)/(H_A-H_B)(h_{1h}+h_{14})\le 0 \\ e_{13}+e_{1e}-E_B-(E_B-E_C)/(H_B-H_C)(h_{1h}+h_{14}-H_B)\ge 0 \\ e_{13}+e_{1e}-E_D-(E_C-E_D)/(H_C-H_D)(h_{1h}+h_{14})\ge 0 \end{cases}$$

In the failure state

$$\begin{cases} s^{CHP,h}=1, s^{CHP,e}=0 \\ e_{13}+e_{1e}=0 \\ \min\{H_A,H_B,H_C,H_D\}\le h_{1h}+h_{14}\le \max\{H_A,H_B,H_C,H_D\} \\ s^{CHP,h}=0, s^{CHP,e}=1 \\ h_{1h}+h_{14}=0 \\ \min\{E_A,E_B,E_C,E_D\}\le e_{13}+e_{1e}\le \max\{E_A,E_B,E_C,E_D\} \end{cases}$$

Operational reliability of the components

Gas boilers



- Operating constraints

$$0 \le h_{24} + h_{2h} \le \frac{N^{GBs} + 1 - s^{GBs}}{N^{GBs}} ho_2^+$$

- State transition rates

$$\lambda^{GBs}_{s^{GBs},s^{GBs}+1} = (N^{GBs} + 1 - s^{GBs})\lambda^{GB}$$

$$\lambda^{GB}_{s^{GB},+1s^{GB}} = s^{GBs}\mu^{GB}$$

Optimal control during the component failure

Objective function

$$Min\ \ C = \sum_{k\in K} \rho_k^g (g_{g1,k} + g_{g2,k}) + \rho_k^e (e_{ee,k} + e_{e3,k}) + \sum_{l\in\{el,th,cl\}} CDF^l (T_{s_k}) lc_k^l$$

Control variables

$$g_{g1},\ g_{g2},\ e_{ee},\ e_{e3},\ e_{1e},\ e_{13},\ h_{1h},\ h_{14},\ h_{2h},$$
$$h_{24},\ c_{3c},\ h_{3h},\ c_{4c}, e_{5e}, h_{6h}, c_{7c}, es_5, es_6, es_7$$

Constraints

- CHP constraints
- Energy conversion constraints:

$$\mathbf{H}\begin{bmatrix} ei & gi & \mathbf{u}\end{bmatrix}^T =$$
$$\begin{bmatrix} d^{el} - lc^{el} & d^{th} - lc^{th} & d^{cl} - lc^{cl} & \mathbf{0}\end{bmatrix}^T$$

- Operating constraints of GBs, EHPs, and ABs

$$0 \le c_{4c} \le co_4^+ (N^{ABs} + 1 - s^{ABs})\ \ /N^{ABs}$$
$$0 \le h_{3h} \le \gamma ho_3^+ (N^{EHPs} + 1 - s^{EHPs})\ \ /N^{EHPs}$$
$$0 \le c_{3c} \le (1-\gamma) co_3^+ (N^{EHPs} + 1 - s^{EHPs})\ \ /N^{EHPs}$$
$$\mathbf{u}_k \ge 0$$

- Operating constraints for energy storages

$$|e_{5e}| \le eo_5^+ (N^{EESs} + 1 - s^{EESs})\ \ /N^{EESs}$$
$$|e_{5e}| \le eo_5^+ (N^{EESs} + 1 - s^{EESs})\ \ /N^{EESs}$$
$$|c_{7c}| \le co_7^+ (N^{ISs} + 1 - s^{ISs})\ \ /N^{ISs}$$
$$es_{5,k} = es_{5,k-1} + e_{5e}\Delta t$$
$$es_{6,k} = es_{6,k-1} + h_{6h}\Delta t$$
$$es_{7,k} = es_{7,k-1} + c_{7c}\Delta t$$
$$0 \le es_{5,k} \le es_5^+ (N^{EESs} + 1 - s^{EESs})\ \ /N^{EESs}$$
$$0 \le es_{6,k} \le es_6^+ (N^{TESs} + 1 - s^{TESs})\ \ /N^{TESs}$$
$$0 \le es_{7,k} \le es_7^+ (N^{ISs} + 1 - s^{ISs})\ \ /N^{ISs}$$

Reliability evaluation procedures

- Reliability indices

$$EDNS^{l}(k)=\sum_{i=1}^{NS} lc_{k}^{l}\ /\ NS$$

$$LOLP^{l}(k)=\sum_{i=1}^{NS} flag(lc_{k}^{l})\ /\ NS$$

- Convergence criterion

$$\sqrt{Var(EDNS^{l}(k))}\ /\ EDNS^{l}(k)\le\xi$$

Step 1
- input data. Including the physical characteristics of the DMES, the reliability parameters, and the load profile.
- Set the duration of the operation horizon.

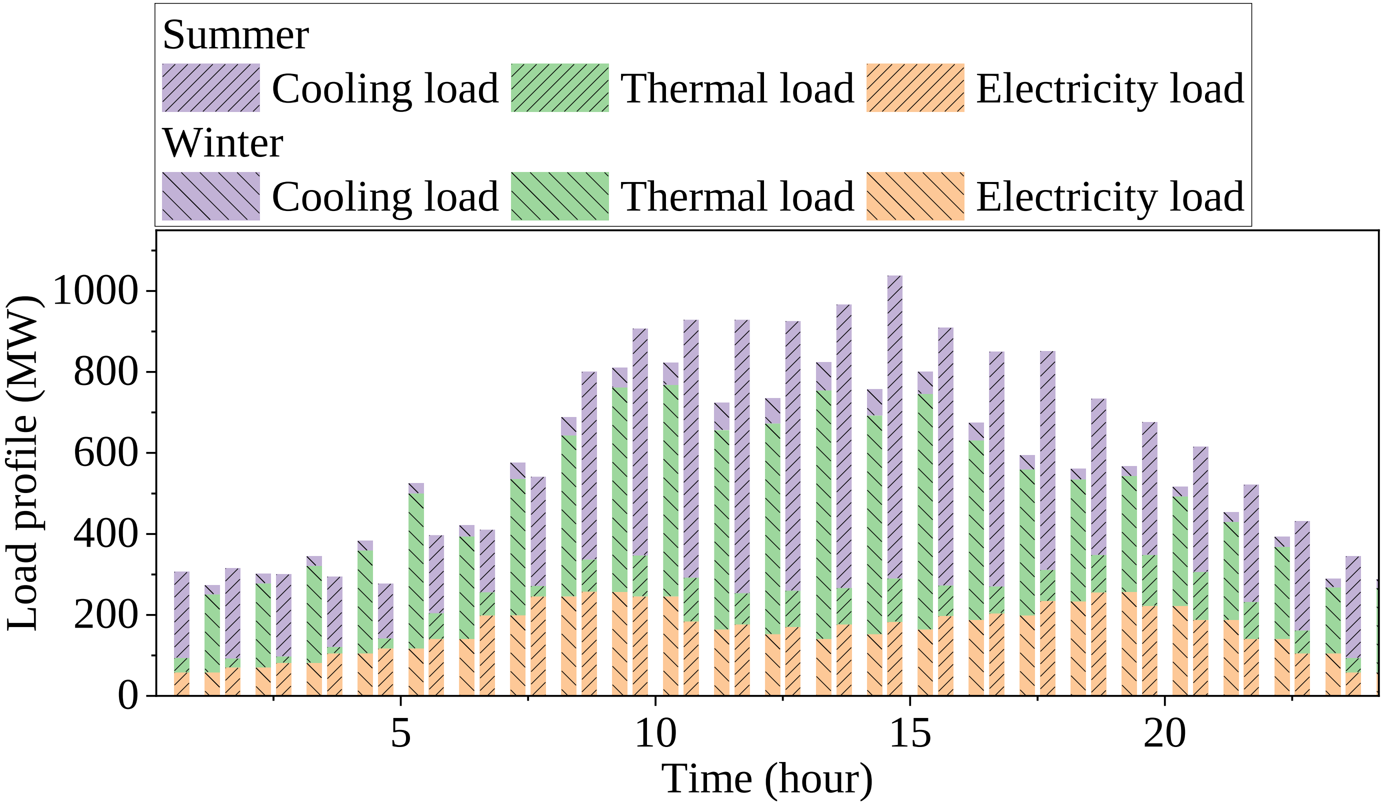
Step 2
- simulate the state sequence of each component using TSMCS.
- Combine them into the system state sequence.

Step 3
- formulate the optimal control problem over the operational horizon.
- Solve the linear optimal control problem using the Gurobi solver, and obtain the load curtailment for each energy.

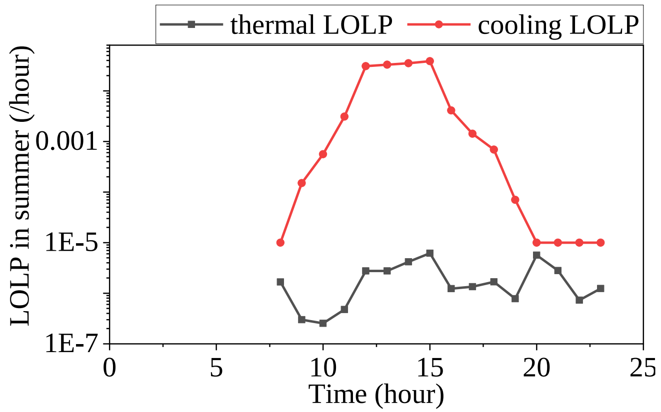
Step 4
- Calculate the reliability indices.
- Check for convergence. If satisfies, then output the operational reliability indices. Otherwise, repeat from step 2 for the next simulation.

Case studies

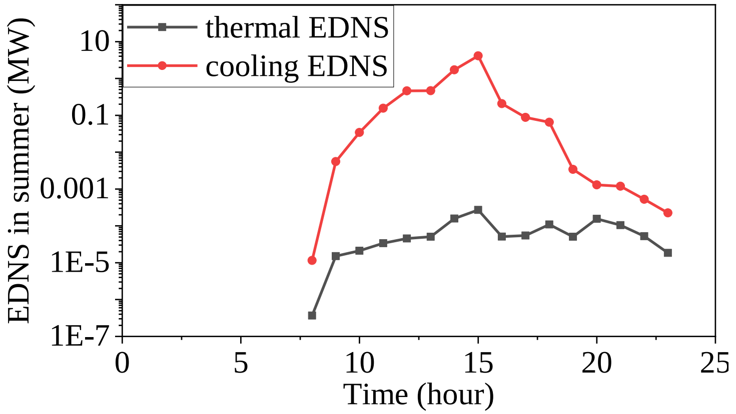
load profiles



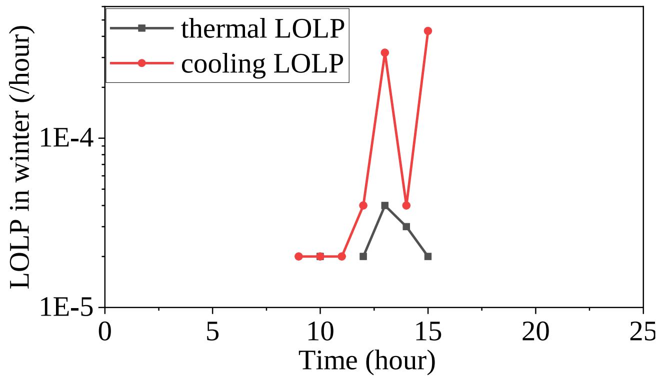
Case studies



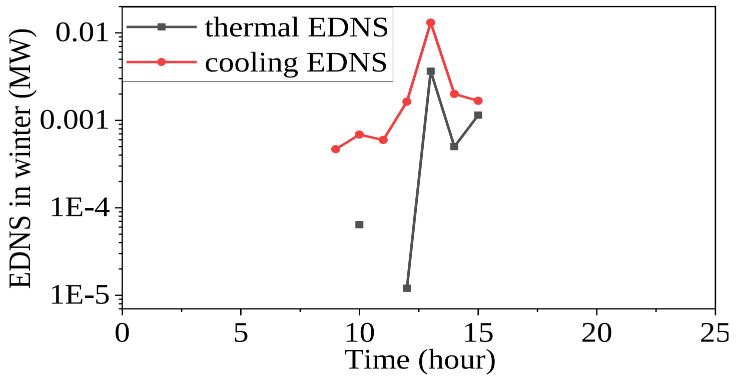
LOLP in summer



EDNS in summer



LOLP in winter



EDNS in winter

- In both seasons, the EDNS and LOLP of electricity remains 0.
- Other two energies remain zero until 8：00. The EDNS and LOLP emerge during 8:00-23:00.
- In summer, the LOLP and EDNS of cooling are higher than those in winter.
- the LOLP and EDNS of thermal load are lower than those in winter.

Thank you