Resilience Oriented Planning of Urban Multi-Energy Systems With Generalized Energy Storage Sources

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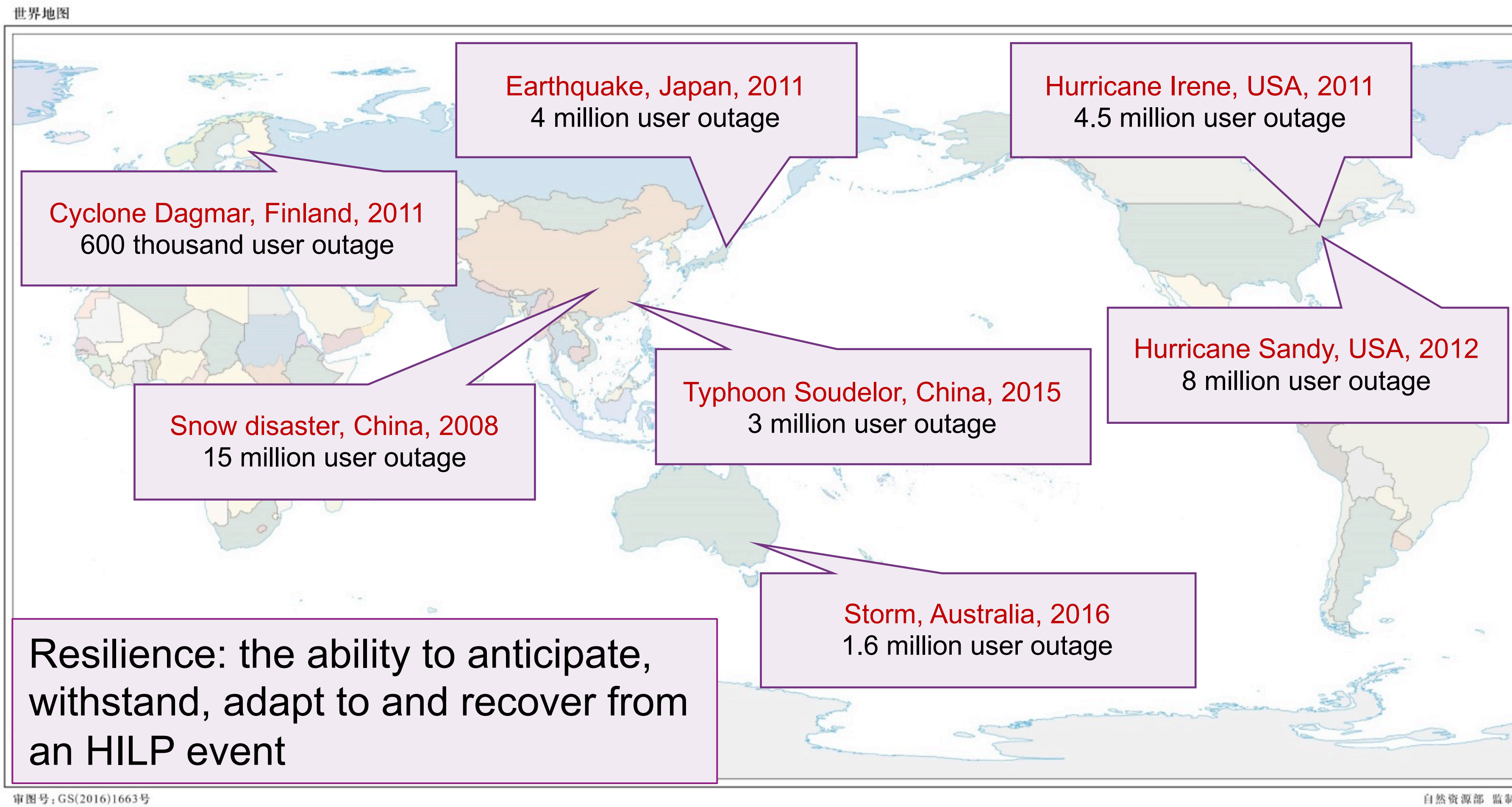
Outline

Introduction

Introduction

- Extreme natural disasters highlight the need for rethinking current planning principles and expanding the classical reliability-oriented view.
- In addition to being reliable to low-impact and high-probability outages, urban energy systems should also have high level of resilience to withstand high-impact and low-probability (HILP) events.

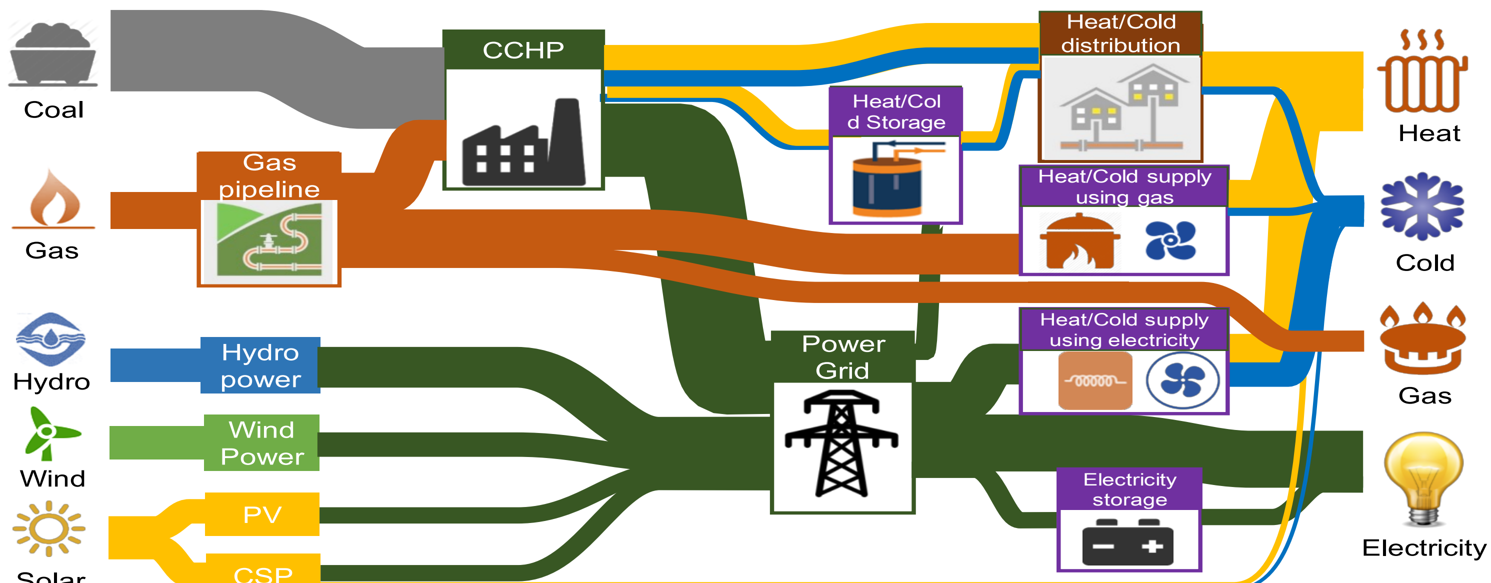


Resilience: the ability to anticipate, withstand, adapt to and recover from an HILP event

Introduction

Compared with power system, multi-energy systems (MES) has three main advantages in improving resilience:

- **Supply side:** The flexibility of energy supply is unlocked because energy shifting across multiple energy sectors is realized by various types of energy converters.
- **Network side:** A variety of centralized, distributed and equivalent energy storage resources provide adequate reserve during HILP events. In particular, the hot water and gas pipes in heat and gas networks store considerable energy, which can continue to be used during a certain time period after the heat and gas sources fail.
- **Demand side:** The thermal inertia of heat load, e.g., space heating for buildings, relaxes the constraint of instantaneous power balance. The user experience will not be greatly affected in a certain time after the failure of supply, which provides a buffer.



Introduction

- **Considered aspects in the planning:** Current research on the resilience of distribution level MES mainly considers the energy shifting in the planning or operation model. The resilience resources in the gas, heat and cooling sectors, besides the electricity sector, are not fully utilized to support the resilience-oriented planning of MES.

- A resilience-oriented planning method to determine optimal configuration of distribution level MES is proposed. Resilience resources from supply, network and demand sides in MES are all taken into consideration to support the resilient energy supply of MES in HILP events of different intensities.

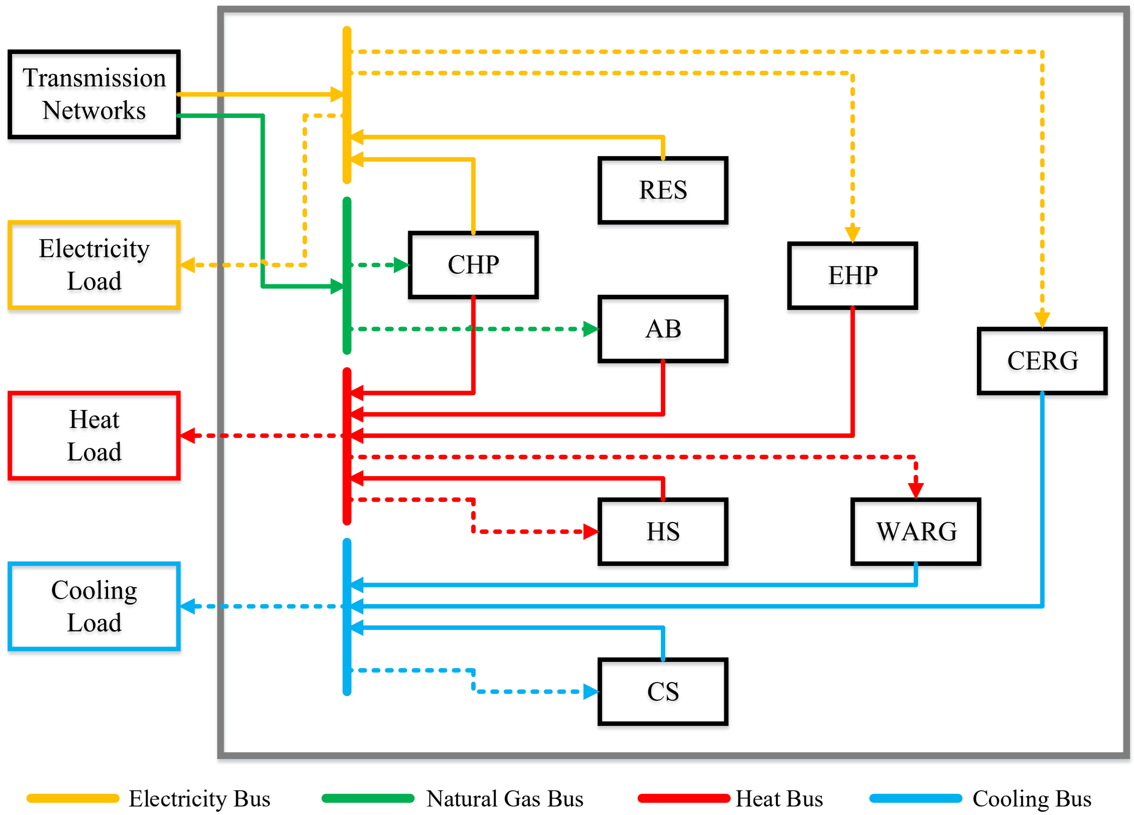
- **Methodology:** To avoid directly embedding the nonlinear models of pipe network and heat/cooling load in the planning model,

- A generalized energy storage model is proposed to facilitate an efficient resilience-oriented planning of energy resources in MES. The impacts of energy shifting at supply side, pipe storage at network side and thermal inertia at demand side are described in the same linear modeling framework using energy hub (EH) model.

Model Of Distribution Level MES

Modeling Energy Conversion Configuration

The used energy hub (EH) model, i.e., energy bus-based EH model, is a variant of the original EH model.

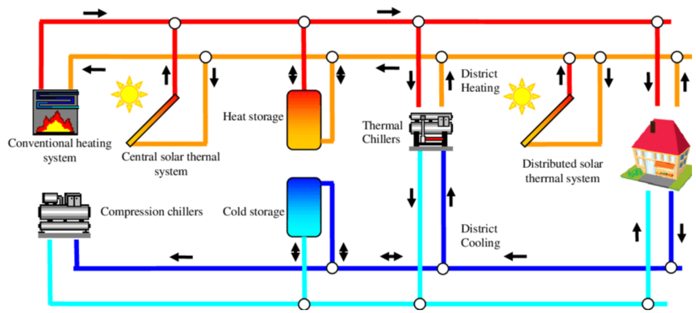


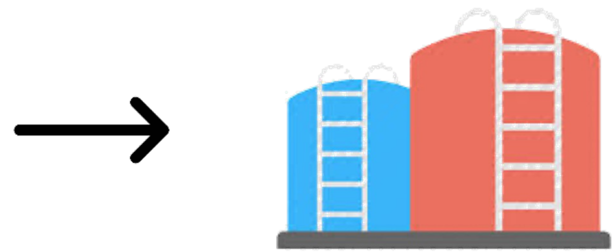
- **Bus:** A junction that concentrates the energy flows from different sources upstream, and distributes the total energy to downstream loads.
- **Node:** 1) Equipment nodes (inside EH) represent different energy converters and energy storage devices. 2) Interface nodes (outside EH) represent external energy infrastructures and loads.
- **Branch:** A direction of energy flow, which connects nodes to buses in EH.

Modeling Discharging of Energy Stored in Pipe Network

In contrast to power networks, natural gas, heat and cooling networks always store a certain amount of energy in their pipelines during daily operation.

If a heat source fails and its downstream hot water pipelines survive in an HILP event, the heat stored in these pipelines would not immediately lose with the disconnection of heat source. As a result, the downstream hot water pipe network can be equivalent to a heat storage tank for emergency heat supply.





The hot water pipe network discharges the stored heat like other real heat storage devices until the temperature of water decreases to ambient temperature.

The model of discharging of pipe network equivalent storage is:

$$E_l \cdot (SOC_l(t+1) - SOC_l(t)) = -P_l(t) / \eta_l \cdot \Delta t$$

energy capacity　　state-of-charge　　discharging power　　discharging efficiency

Modeling Discharging of Energy Stored in Pipe Network

$$E_l \cdot (SOC_l(t+1) - SOC_l(t)) = -P_l(t) / \eta_l \cdot \Delta t$$

energy capacity: the stored heat of pipe network *l* at the onset of the HILP event

$$E_l = c_p m_l \cdot (T_l(0) - T_a)$$

c_p —— Specific heat capacity of water
m_l —— Mass of water held in pipe network *l*
$T_l(0)$ —— Temperature of water in pipe network *l* at the onset of the HILP event
T_a —— ambient temperature

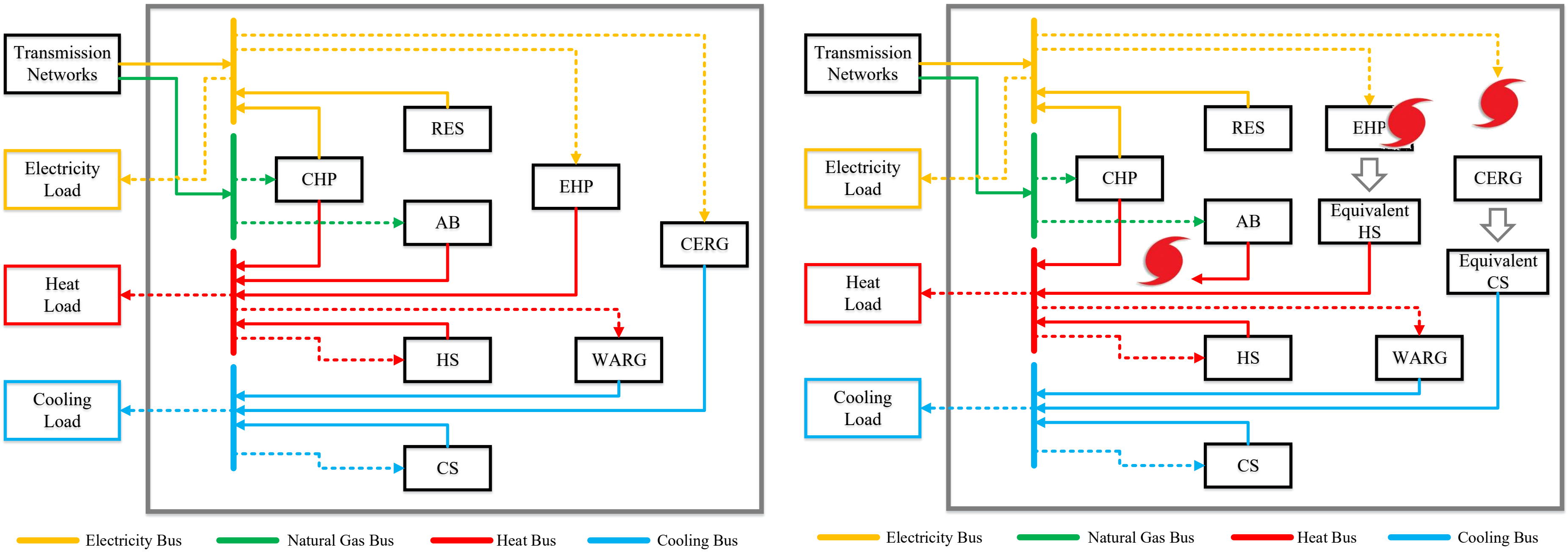
- SOC decreases to zero if the temperature of water in pipe network l decreases to ambient temperature:

$$0 \le SOC_l(t) \le 1, \quad \forall t$$

- P_l can be adjusted by controlling the volumetric flow rate of water in pipe network to obtain an optimal discharge strategy.
- However, the energy stored in pipe network is considered to be unavailable if a failure happens in pipe network.

Modeling Discharging of Energy Stored in Pipe Network

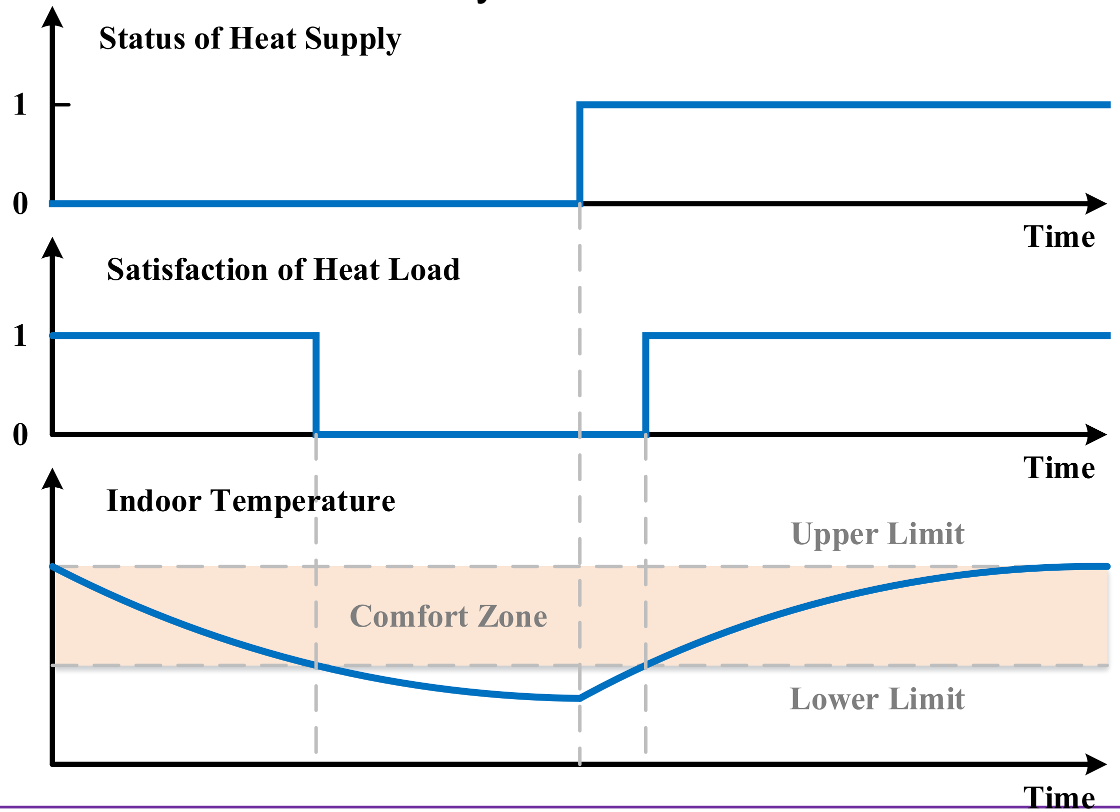
The equivalent of EH encountering a HILP event and considering hot/cold water pipe network storage for emergency supply.



- Three components in EH fail in this HILP event: 1) a node representing EHP, 2) a branch representing power distribution network between electricity bus and CERG, and 3) a branch representing heat distribution network between AB and heat bus.
- Equivalent HS and CS are introduced to model the energy storage of pipe network in the downstream of EHP and CERG, respectively. While the heat stored in pipe network in the downstream of AB is unavailable.

Modeling Thermal Inertia of Heat/Cooling Load

- Some heat/cooling loads, e.g., space heating/cooling for buildings, have thermal inertia toward the change of heat/cooling supply, that is, it takes some time for these loads to be unserved after the heat/cooling supply fails.
- The comfort temperature for users has a certain zone and the user experience will not be significantly affected until the indoor temperature is beyond the comfort zone. This lag between the failure of energy supply and load shedding offers a buffer for MES to effectively survive a HILP event.



Modeling Thermal Inertia of Heat/Cooling Load

- Quantitatively, the model of space heating for a building is

$$
\begin{aligned}
Q(t+1)-Q(t) &= C_b \cdot (T_b(t+1)-T_b(t)) \\
&= (P_{in}(t)-P_{load}(t)) \cdot \Delta t
\end{aligned}
$$

Q —— Heat stored in the interior space of building
C_b —— Heat capacity of the interior space of building
T_b —— Indoor temperature of building
P_{in} —— Thermal power provided by heat supply system
P_{load} —— Heat load of building

- When the heat supply fails,

$$
\begin{aligned}
P_{load}(t) \cdot \Delta t &= P_{disch}(t) \cdot \Delta t \\
&= Q(t)-Q(t+1) = C_b \cdot (T_b(t)-T_b(t+1))
\end{aligned}
$$

Modeling Thermal Inertia of Heat/Cooling Load

$$
\begin{aligned}
P_{load}(t)\cdot\Delta t &= P_{disch}(t)\cdot\Delta t \\
&= Q(t)-Q(t+1) = C_b\cdot(T_b(t)-T_b(t+1))
\end{aligned}
$$

- The thermal inertia of heat/cooling load is modeled by an equivalent heat/cooling storage device, which begins to discharge thermal/cooling power to supply heat/cooling load when heat/cooling supply system fails to satisfy the required demand:

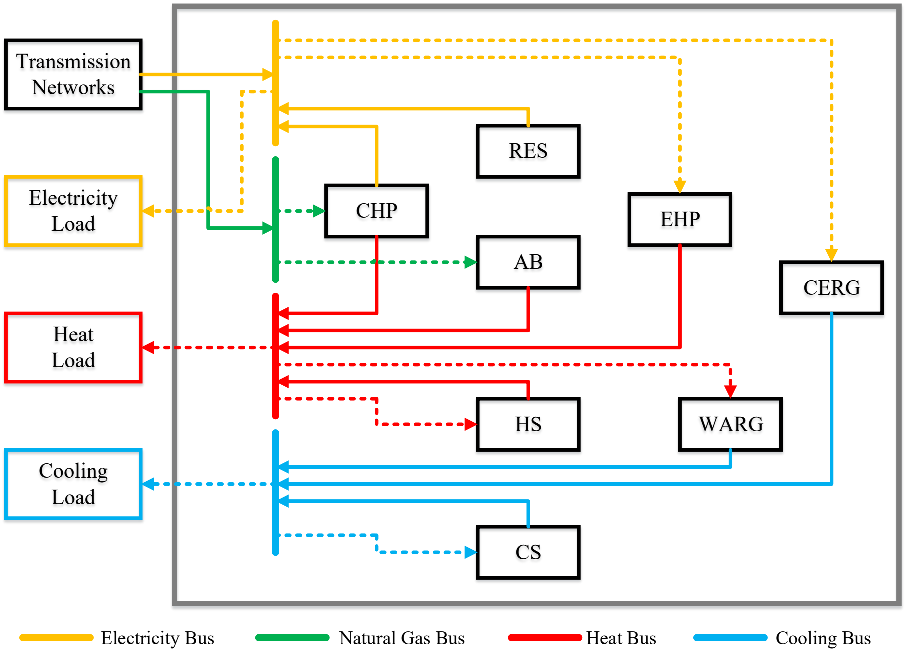
$$E_b\cdot(SOC_b(t+1)-SOC_b(t)) = -P_{disch}(t)\cdot\Delta t$$

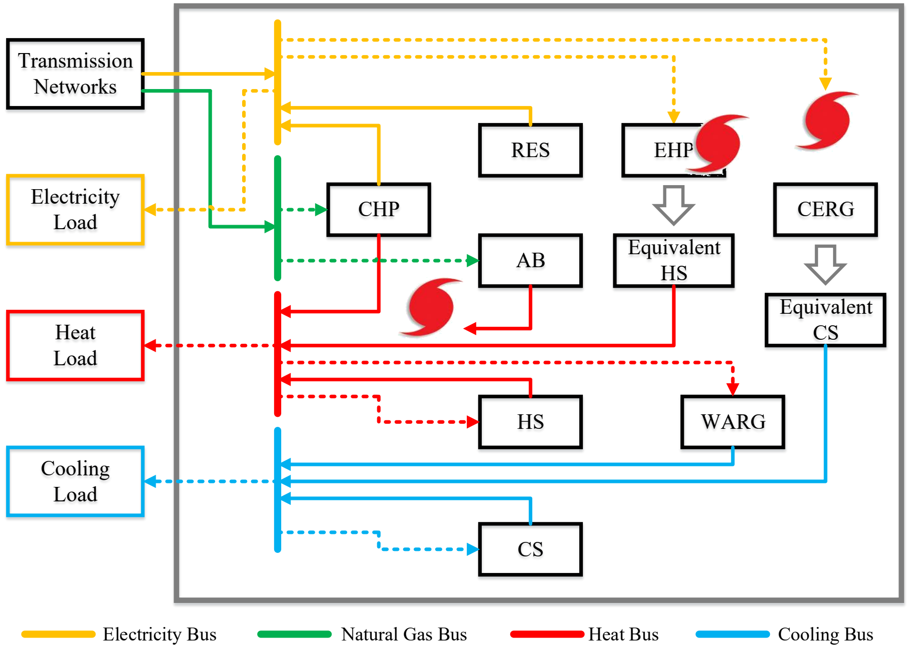
- Considering that the heat/cooling load is totally unserved when the indoor temperature is beyond the comfort zone, E_b here only models the temperature variation within the comfort zone:

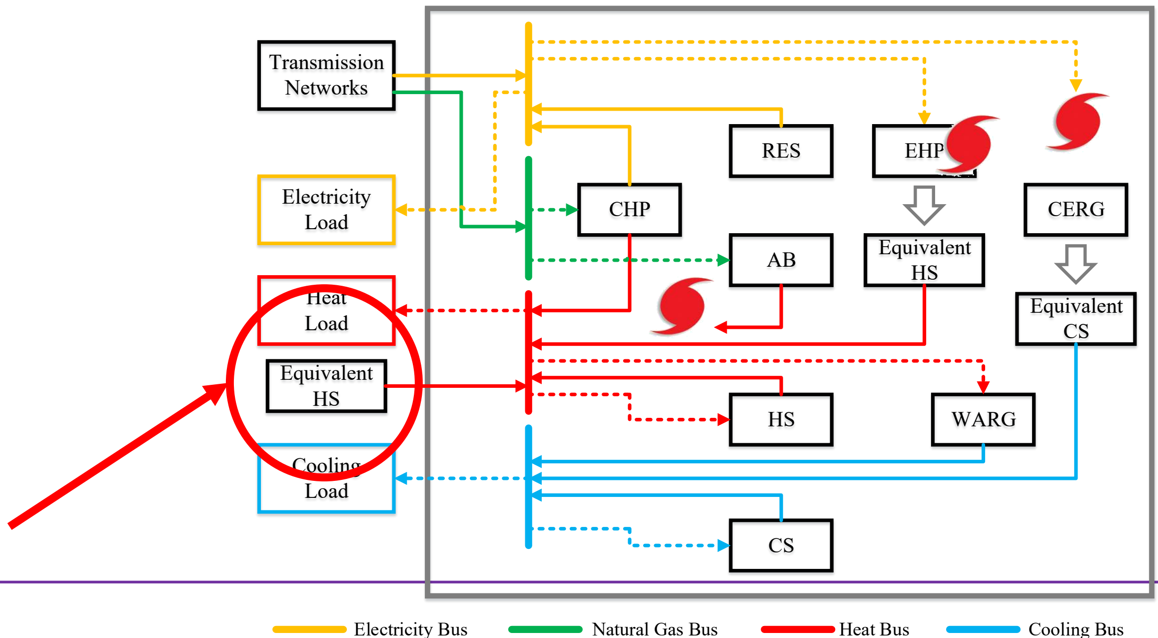
$$E_b = C_b\cdot\left|T_b(0)-T_{\text{limit}}\right|$$

$T_b(0)$ —— Indoor temperature at the onset of the HILP event
T_{limit} —— Limit of comfort temperature (using lower limit for heat load while upper limit for cooling load)

Modeling Thermal Inertia of Heat/Cooling Load

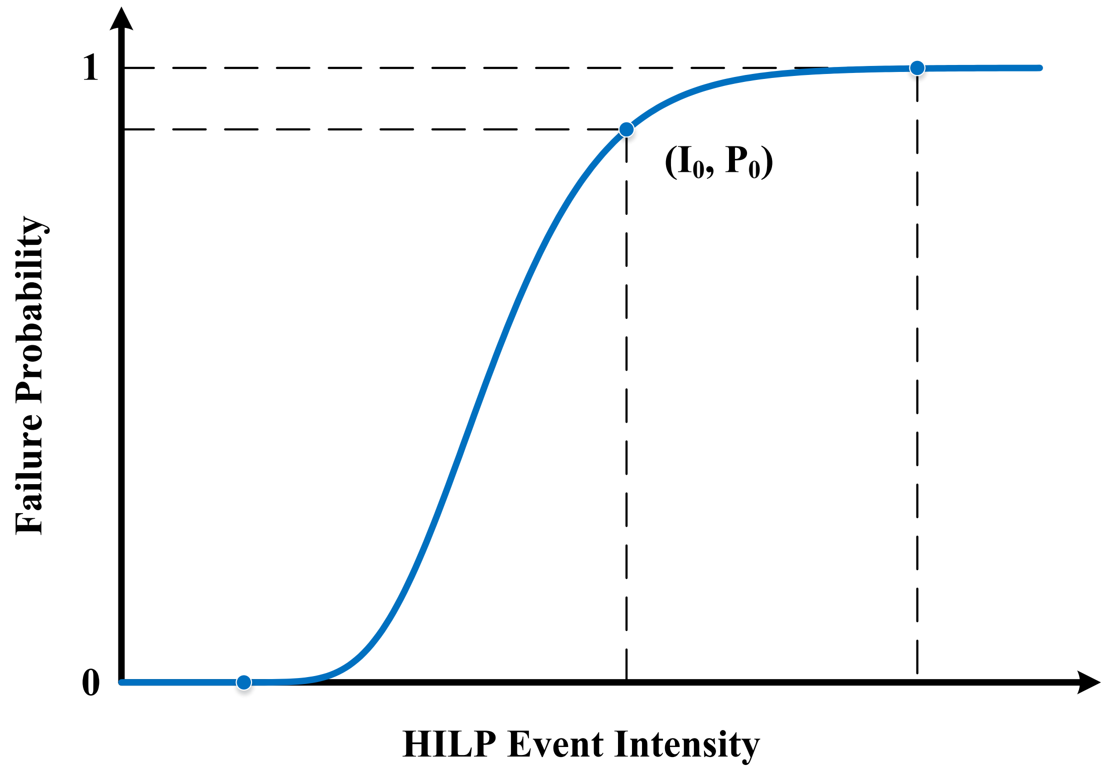






Component Fragility and Restoration

- In a HILP event, each component in MES has a certain probability of failure. The failure probability is obtained by the fragility curve of each component, which presents the relationship between the failure probability of component and the intensity of a HILP event. The component fragility curves are usually represented using lognormal distributions and fitted using empirical data.

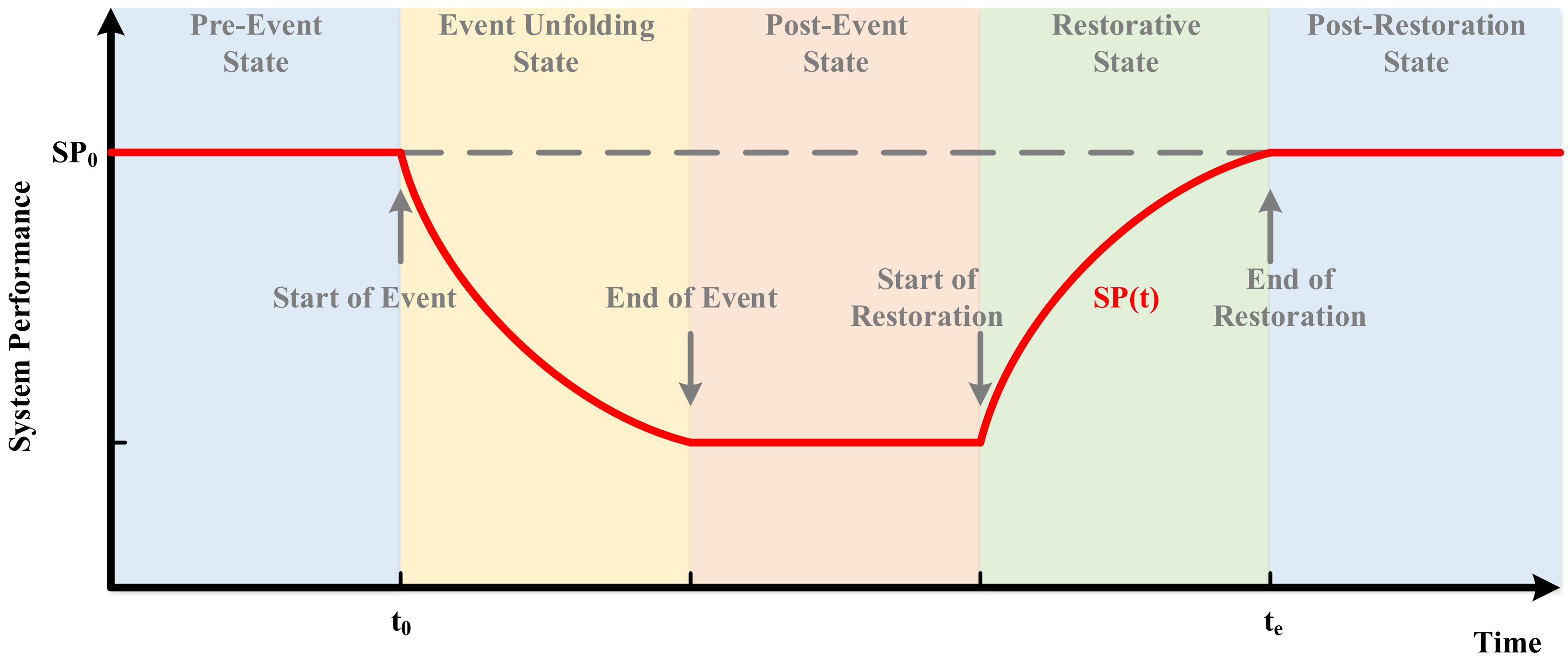


- The downtime of each component is considered to be normally distributed. The parameters of distribution of component downtime is decided by the type of component and its damage stage.

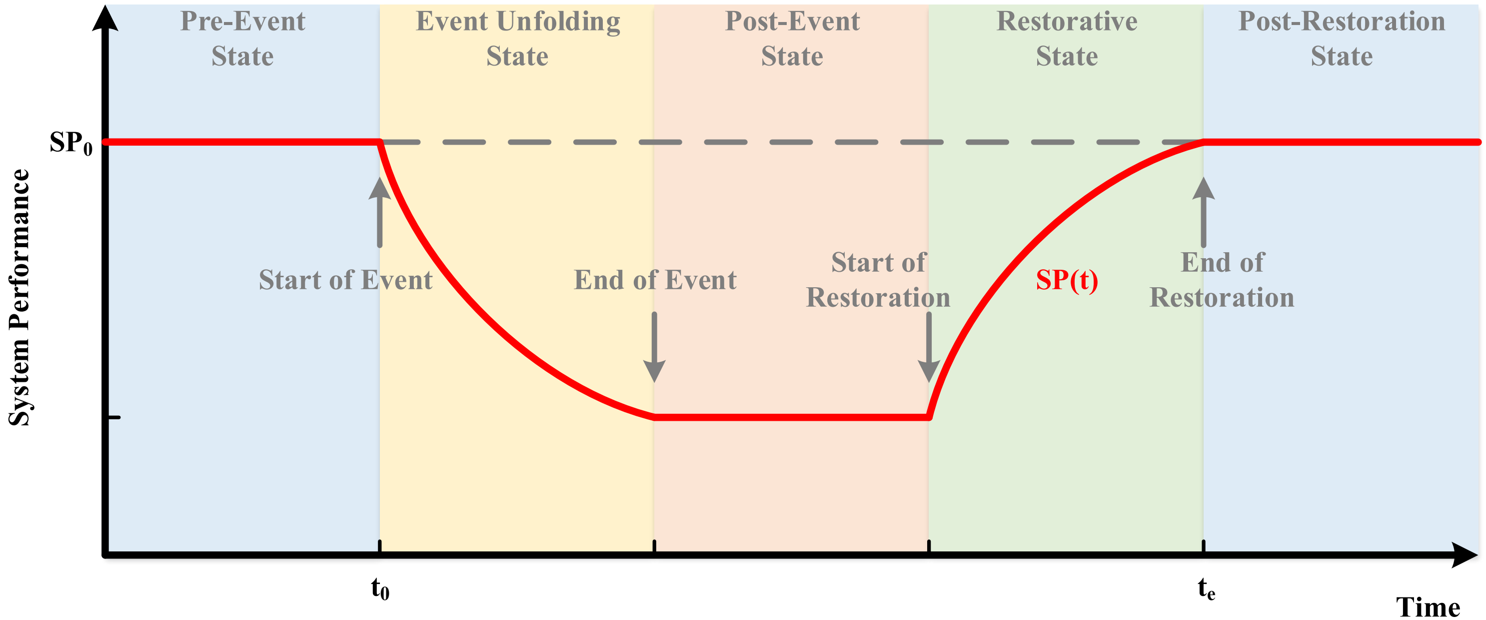
Resilience Oriented Planning Method

Quantification of Resilience

- Analysis of resilience puts particular emphasis on not only the extreme events having high impact on system performance but also the time-varying characteristics of system performance. The concept of resilience covers multiple states before, during and after a HILP event
- A system resilience curve across multiple states is described by the time-varying characteristics of system performance before, during and after a HILP event.



Quantification of Resilience



- The total loss of system performance across multiple states during and after a HILP event is used to quantify the resilience of energy supply in MES:

$$\text{Resilience Index} = \int_{t_0}^{t_e} (SP_0 - SP(t))\, dt$$

- The amount of load actually served is used to describe the system performance in this paper; therefore, the resilience index is equal to the total energy-not-served (ENS) during and after a HILP event:

$$\text{Resilience Index} = \text{ENS} = \int_{t_0}^{t_e} LS(t)\, dt$$

Scenario Generation

1) Normal Operation Scenarios **—— Estimate the operating cost of MES**

The normal operation scenarios are represented by several typical scenarios of different seasons. The method of scenario reduction, e.g., k-means clustering, is used to characterize load scenarios and RES output scenarios by different patterns for several selected days belonging to different seasons.

2) HILP Event Scenarios **—— Calculate the resilience index**

A number of scenarios representing different HILP events are generated beforehand to support the quantification of system resilience. The main steps of scenario generation are:

Step 1: Decide the greatest intensity of the studied HILP events, e.g., a once-in-a-century event is considered at most, which depends on the budget of decision makers.
Step 2: Calculate the failure probability of each component in MES according to its fragility curve and the greatest intensity of HILP events decided in Step 1.
Step 3: Sample the status of each component, i.e., operating or failure, in the HILP event according to its failure probability obtained in Step 2.
Step 4: Sample the downtime (restoration time) of each failed component from its corresponding normal distribution of downtime.
Step 5: Combine the sampling results of all components in MES to form a complete HILP event scenario. The total time of a scenario is decided by the longest downtime of failed components.
Step 6: Repeat Step 3 to Step 5 until the number of generated scenarios reaches a preset amount.

Optimization Problem

- A stochastic optimization problem is solved to determine the optimal configuration of distribution level MES.
- **Decision variables:** capacities of energy converters, energy storage devices, renewable energy sources and energy feeders (e.g., power feeder lines, gas pipelines and hot water pipelines).
- **Objective:** to minimize the sum of equivalent annual capital cost and annual operating cost of the studied MES:

$$\min \left\{ \begin{array}{l} \sum_{i \in \Omega_c} \left[C_i \cdot p_i^c \cdot \dfrac{r \cdot (1+r)^{\tau_i}}{(1+r)^{\tau_i} - 1} \right] + \\ \sum_{s \in \Omega_s} D \cdot \omega(s) \cdot \left\{ \sum_{k \in \Omega_k} \sum_{t=1}^{T} \left[P_k^{in}(t) \cdot \Delta t \cdot c_k^o(t) \right] \right\} \Big|_s \end{array} \right\}$$

- **The first line: Equivalent annual capital cost**, which is calculated by multiplying the net present value of capital cost by a capital recovery factor,
- **The second line: Annual operating cost**, which is proportional to the weighted mean of operating cost of each scenario. The calculated annual operating cost is only contributed by normal operation scenarios, that is, it does not include the operating costs in HILP events and restorative periods.

Optimization Problem

- The constraints of the proposed planning problem consist of two categories, i.e., 1) normal operation constraints, 2) resilient operation constraints in HILP events.

1) Normal Operation Constraints

This category of constraints is applied to normal operation scenarios where all of the components (including energy converters, energy storage devices, renewable energy sources and energy feeders) in the system are in normal operating state.

Power Conservation Constraint $$\sum_{j \in \Omega_b^{in}} P_j^{l,in}(t) = \sum_{j \in \Omega_b^{out}} P_j^{l,out}(t), \quad \forall b \in \Omega_b, \forall t$$

Energy Converter Operating Characteristics $$P_i^{out}(t) = P_i^{in}(t) \cdot \eta_i, \quad \forall i \in \Omega_{uc}, \forall t$$

Energy Storage Device Operating Characteristics $$E_i \cdot (SOC_i(t+1) - SOC_i(t)) = (P_i^{char}(t) \cdot \eta_i^{char} - P_i^{disch}(t) / \eta_i^{disch}) \cdot \Delta t, \quad \forall i \in \Omega_{us}, \forall t$$

Energy Feeder Power Loss $$P_j^{l,out}(t) = P_j^{l,in}(t) \cdot \eta_j^l, \quad \forall j \in \Omega_l$$

Component Capacity Constraint $$0 \le P_i(t) \le C_i, \quad \forall i \in \Omega_c / \Omega_{ur}, \forall t$$

Energy Purchase Constraint $$0 \le P_k^{buy}(t) \cdot \Delta t \le P_k^{buy,\max}(t) \cdot \Delta t, \quad \forall k \in \Omega_k, \forall t$$

Optimization Problem

2) Resilient Operation Constraints in HILP Events

This category of constraints is applied to HILP event scenarios. It should be noted that power conservation constraint and energy purchase constraint are also applied to HILP event scenarios; Constraints of component operating characteristics are also applied to normally operating components in HILP event scenarios.

Power Conservation Constraint	***Component Failure Constraint***
Energy Converter Operating Characteristics	***Model of Pipe Energy Storage***
Energy Storage Device Operating Characteristics	***Model of Thermal Inertia of Load***
Energy Feeder Power Loss	***Resilience Index Constraint***
Component Capacity Constraint	
Energy Purchase Constraint	

Classification of HILP Events

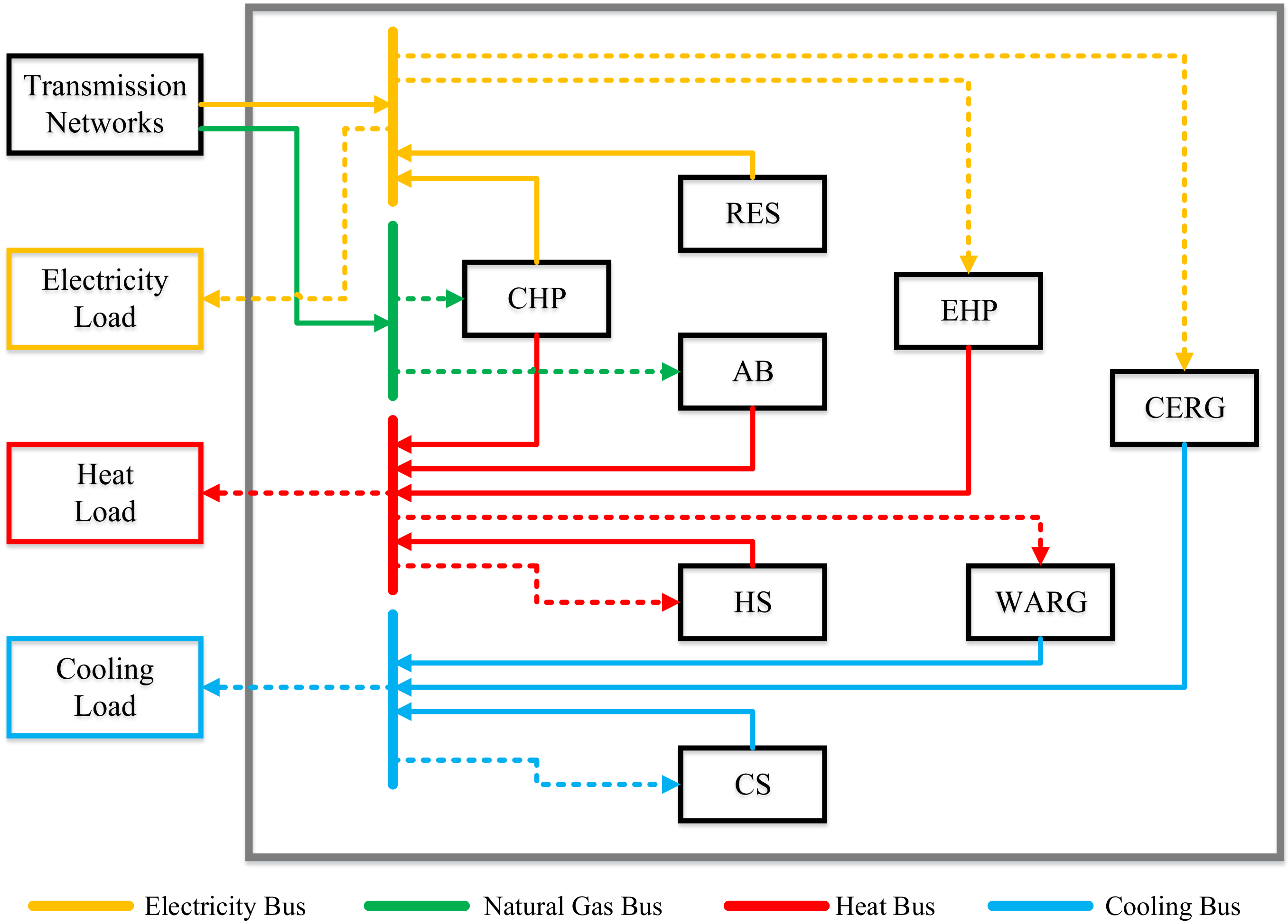
- One single preset maximum ENS is not adequate and not proper to cover all HILP events of different degrees. A stricter limit can be set for a less severe HILP event, while a looser limit can be set for a more severe HILP event.
- The severity of a HILP event can be judged by the number of failed units or disconnected units that it causes.

Level	Impact
I	Medium Scale: one of heat sources[a] fails
II	Large Scale: part of heat sources fail
III	Extra Large Scale: all of heat sources fail; only heat storage device works for emergency

Case Study

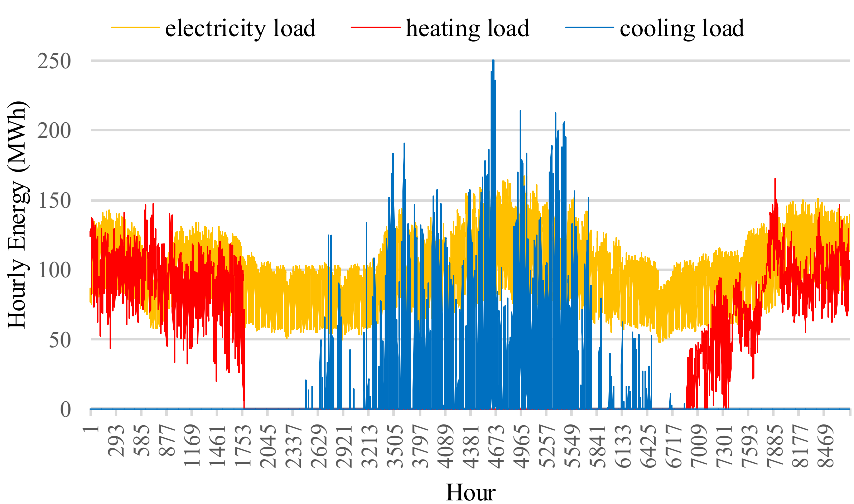
Basic Settings

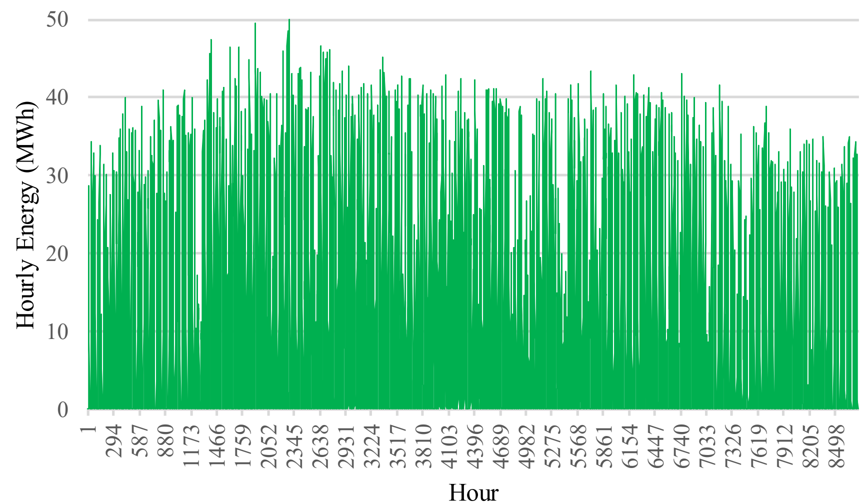
- The proposed planning method is used to determine the configuration of the typical distribution level MES.



Basic Settings

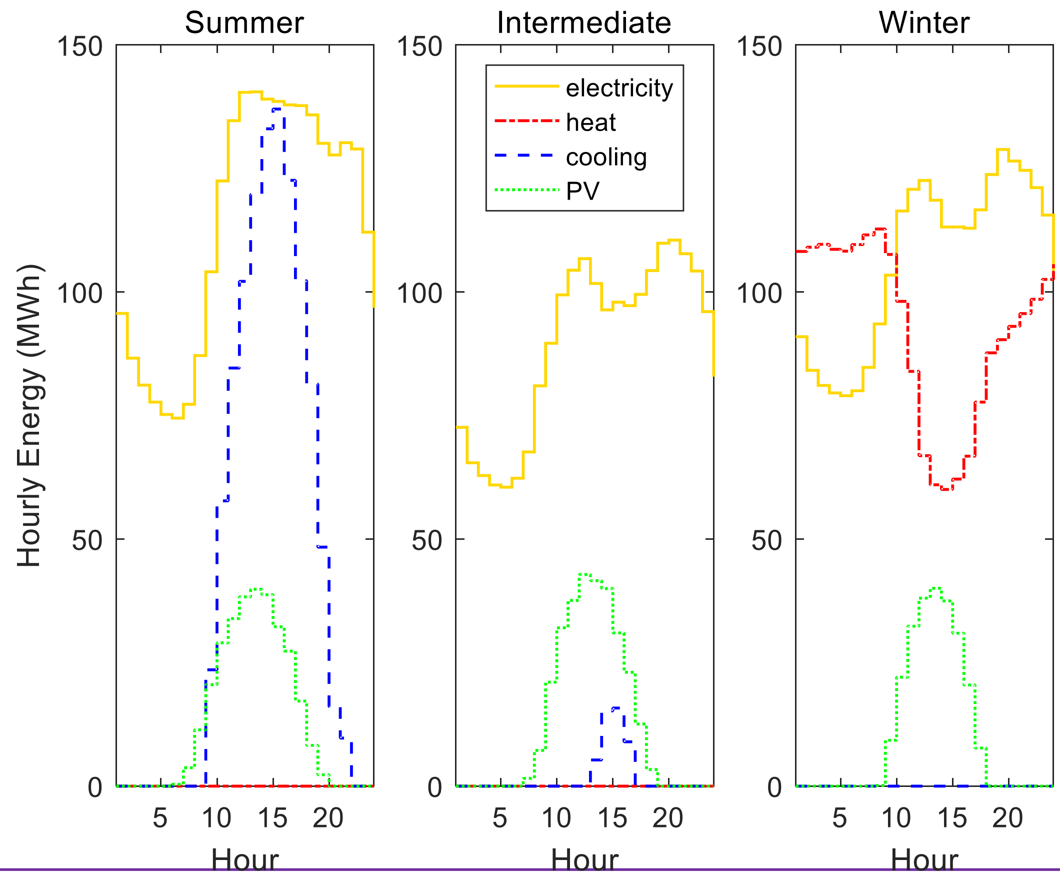
- **Load:** The studied MES operates to satisfy electricity load with a peak load of 168 MW, heat load with a peak load of 166 MW, and cooling load with a peak load of 251 MW. The annual electricity, heat and cooling load profiles refer to Tongzhou subsidiary administrative center, Beijing, China.
- **Renewable energy:** Roof photovoltaic (PV) system, one kind of RES, is considered as an alternative electricity resource of the studied MES besides main grid electricity. The maximum installed capacity of roof PV system within the area of the studied MES is 50 MW. The hourly PV system output data in Beijing are obtained from the National Renewable Energy Laboratory (NREL).





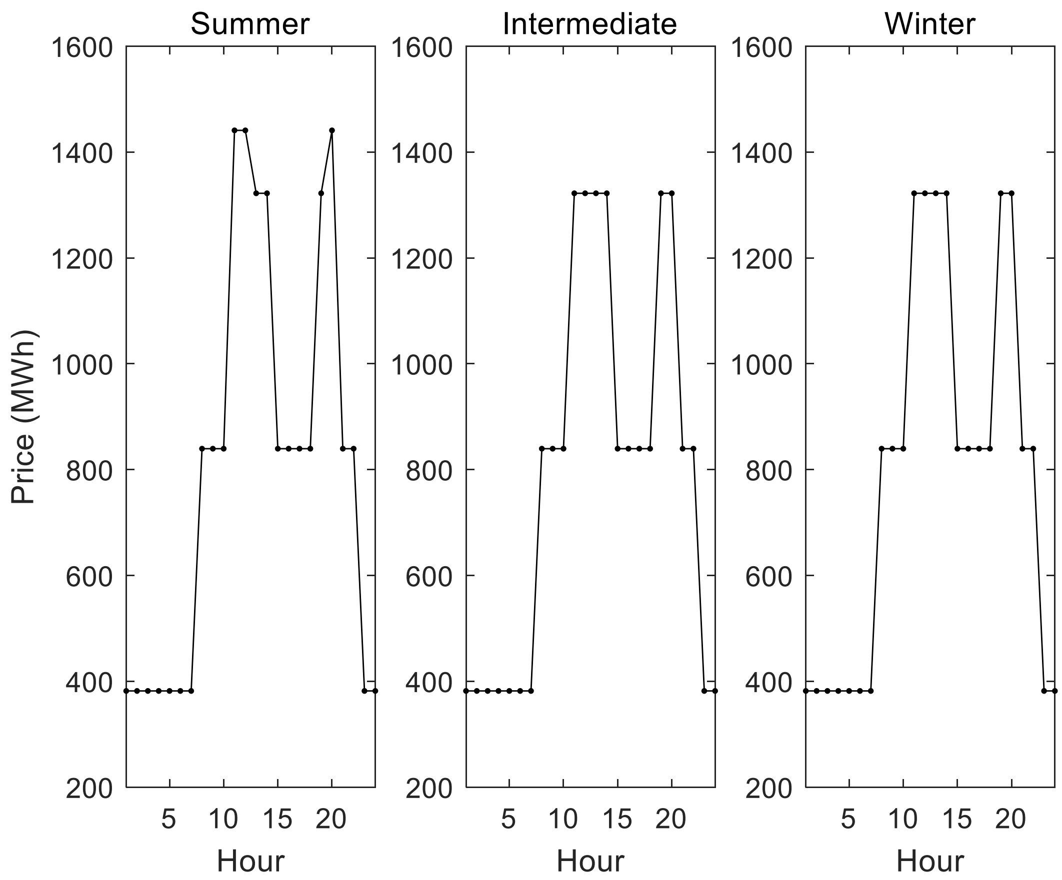
Basic Settings

- **Scenario reduction:** The normal operation scenarios are represented by several typical scenarios of different seasons to estimate the annual operating cost of the studied MES. Using method of scenario reduction, e.g., k-means clustering, load scenarios and PV system output scenarios are characterized by different patterns for three selected days belonging to summer, intermediate and winter seasons, respectively.



Basic Settings

- **Energy price:** The price of main grid electricity in Beijing is categorized into peak, flat and valley time prices. In summer, critical peak price is applied to three hours (11:00~13:00 and 20:00~21:00) each day. The price of natural gas for industrial and commercial use in Beijing is 300 CNY/MWh.



Basic Settings

- The technological and economic parameters of candidate components, including energy efficiency, unit investment cost and lifetime.

	Energy efficiency	Unit investment cost	Lifetime
CHP	El.: 0.3 Therm.: 0.45	7900 CNY/kW	30 year
AB	0.8	851 CNY/kW	20 year
EHP	3	1200 CNY/kW	20 year
CERG	3	1200 CNY/kW	20 year
WARG	0.7	1228 CNY/kW	20 year
HS	Char./ Disch.: 0.9	90 CNY/kWh	20 year
CS	Char./ Disch.: 0.9	190 CNY/kWh	20 year
PV	-	7215 CNY/kW	30 year
Power feeder	0.9	400 CNY/kW	30 year
Water pipeline	0.9	4800 CNY/kW[a]	30 year

Basic Settings

- 500 HILP scenarios are considered in the planning to ensure the resilience of the obtained configuration of the studied MES. The expectation of repair time of failed nodes and branches is 48 hours and 24 hours, respectively, with a standard deviation of 4 hours.
- The table presents the resilience requirement, i.e., maximum ENS, of each load under HILP events of different levels.

Load	Level	Resilience requirement
Electricity load	-	10 MWh
Heat load	I	10 MWh
	II	200 MWh
	III	500 MWh
Cooling load	I	10 MWh
	II	100 MWh

Results and Discussion

- To show and analyze the impact of energy storage of pipe network and thermal inertia of heat/cooling load, another three planning methods besides the proposed one are used to determine the configuration of MES. Specifically:

① **The proposed planning method.** Both energy storage of pipe network and thermal inertia of heat/cooling load are considered.

② **Alternative planning method I.** Energy storage of pipe network is considered; Inertia of heat/cooling load is neglected.

③ **Alternative planning method II.** Energy storage of pipe network is neglected; Inertia of heat/cooling load is considered.

④ **Alternative planning method III.** Both energy storage of pipe network and thermal inertia of heat/cooling load are neglected.

Results and Discussion

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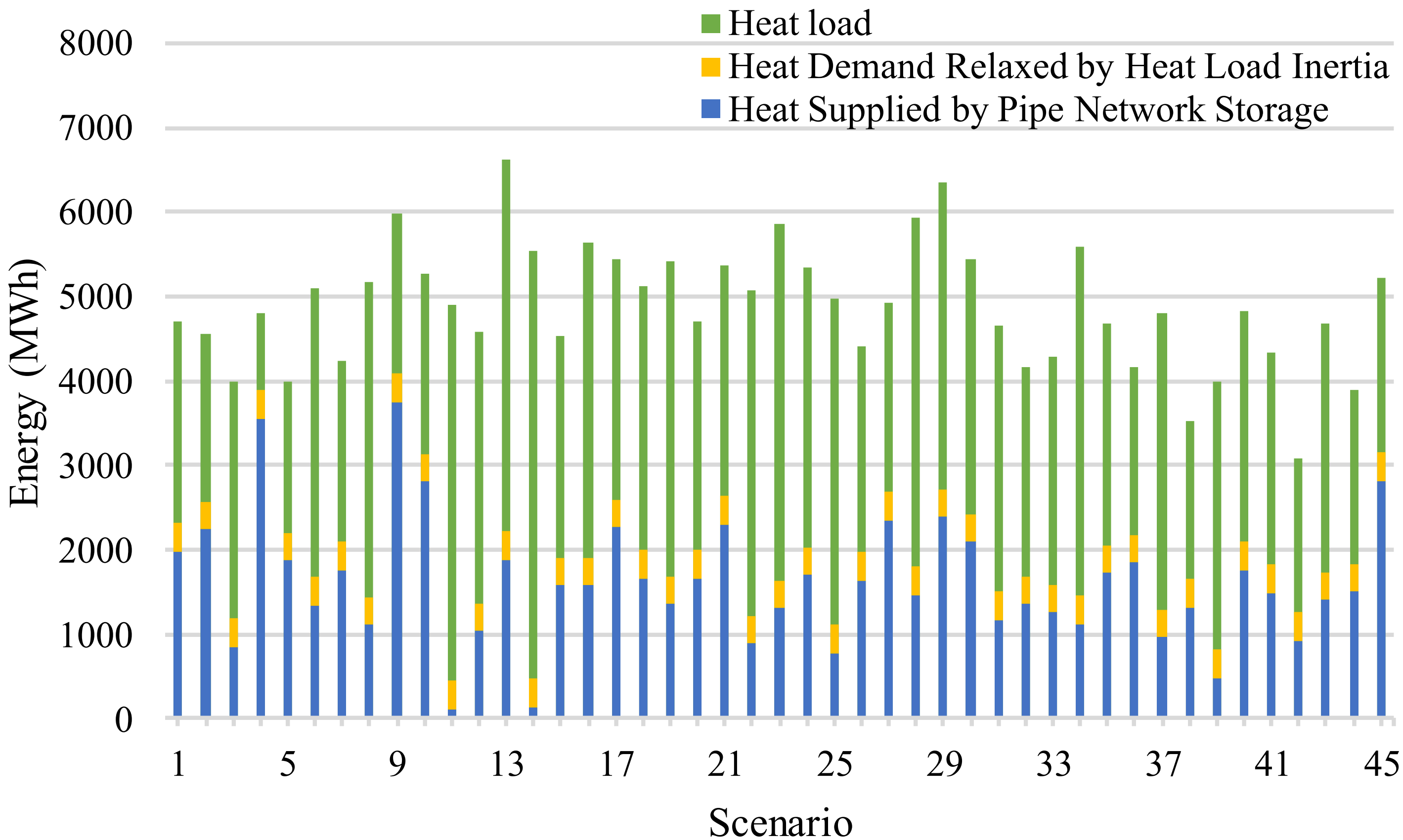
① The proposed planning method. Both energy storage of pipe network and thermal inertia of heat/cooling load are considered.
② Alternative planning method I. Energy storage of pipe network is considered; Inertia of heat/cooling load is neglected.
③ Alternative planning method II. Energy storage of pipe network is neglected; Inertia of heat/cooling load is considered.
④ Alternative planning method III. Both energy storage of pipe network and thermal inertia of heat/cooling load are neglected.

	The Proposed Planning Method	Alternative Planning Method I	Alternative Planning Method II	Alternative Planning Method III
CHP	225 MW	225 MW	No Feasible Solution	No Feasible Solution
AB	280 MW	356 MW		
EHP	137 MW	117 MW		
CERG	110 MW	92 MW		
WARG	199 MW	309 MW		
HS	235 MWh	300 MWh		
CS	3 MWh	89 MWh		
PV	50 MW	50 MW		
Annual Cost	2.01 Billion CNY	2.14 Billion CNY		

Results and Discussion

- On average, the heat provided by pipe network storage accounts for 33.0% of heat load in 45 HILP events in winter season.
- The heat demand relaxed by heat load inertia accounts for 6.8% of heat load in these HILP events.



Results and Discussion

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- To further conduct a comparison among the four planning methods, the resilience requirement is relaxed.

Load	Level	Resilience requirement
Electricity load	-	100 MWh
Heat load	I	100 MWh
	II	4000 MWh
	III	5000 MWh
Cooling load	I	2000 MWh
	II	2500 MWh

Results and Discussion

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④ Alternative planning method III. Both energy storage of pipe network and thermal inertia of heat/cooling load are neglected.

	The Proposed Planning Method	Alternative Planning Method I	Alternative Planning Method II	Alternative Planning Method III
CHP	150 MW	133 MW	207 MW	203 MW
AB	73 MW	92 MW	100 MW	148 MW
EHP	18 MW	26 MW	70 MW	99 MW
CERG	53 MW	58 MW	86 MW	84 MW
WARG	43 MW	59 MW	169 MW	241 MW
HS	0	0	298 MWh	323 MWh
CS	0	20 MWh	55 MWh	118 MWh
PV	50 MW	50 MW	50 MW	50 MW
Annual Cost	1.41 Billion CNY	1.44 Billion CNY	1.83 Billion CNY	1.99 Billion CNY

Results and Discussion

- The advantages of classification of HILP events in the proposed planning method is proved.

	With Classification of HILP Events	Without Classification of HILP Events	Comparison[a]
CHP	225 MW	225 MW	0
AB	280 MW	213 MW	-24%
EHP	137 MW	155 MW	+13%
CERG	110 MW	115 MW	+4%
WARG	199 MW	179 MW	-10%
HS	235 MWh	235 MWh	0
CS	3 MWh	3 MWh	0
PV	50 MW	50 MW	0
Annual Cost	2.012 Billion CNY	2.006 Billion CNY	-0.3%
$EENS_e$	9 MWh	9 MWh	0
$EENS_h$	108 MWh	187 MWh	+73%
$EENS_c$	19 MWh	34 MWh	+74%

Thanks!