Contingency Management in Integrated Electricity and Gas Systems Considering Gas Flow Dynamics

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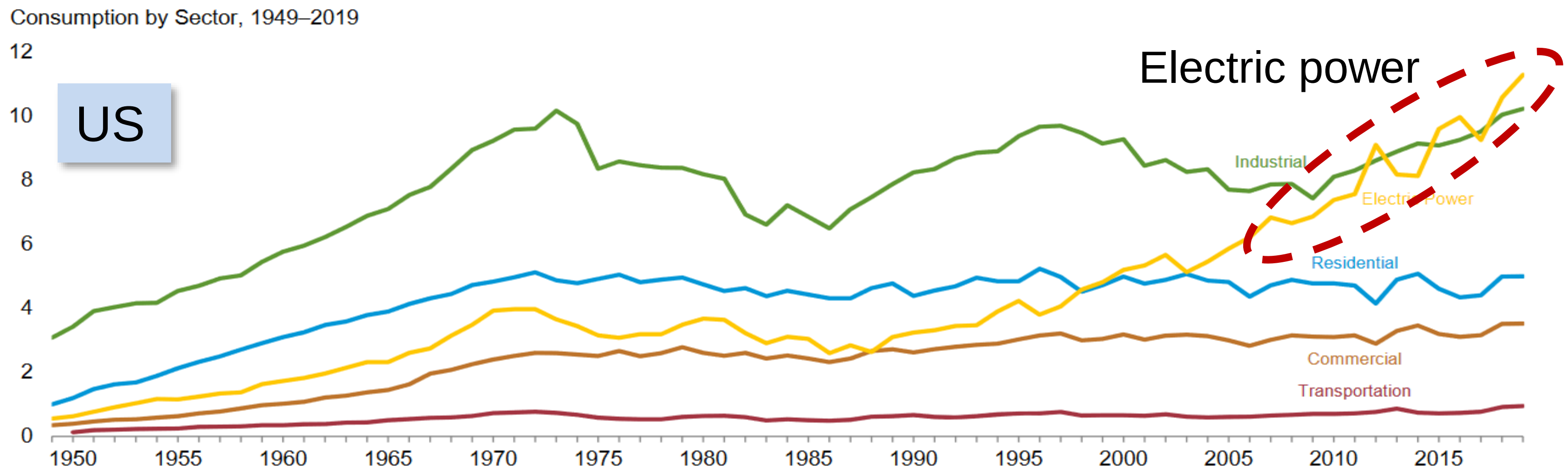
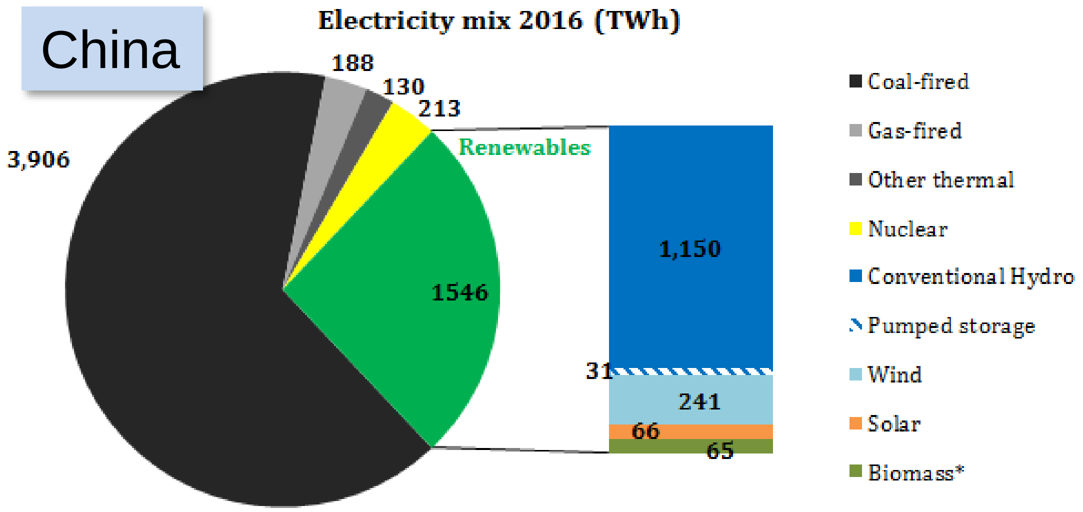
1.1 Integration of electricity and gas systems



- In the US, the gas consumption from the electric power sector has increased by 22.03% in the last three years

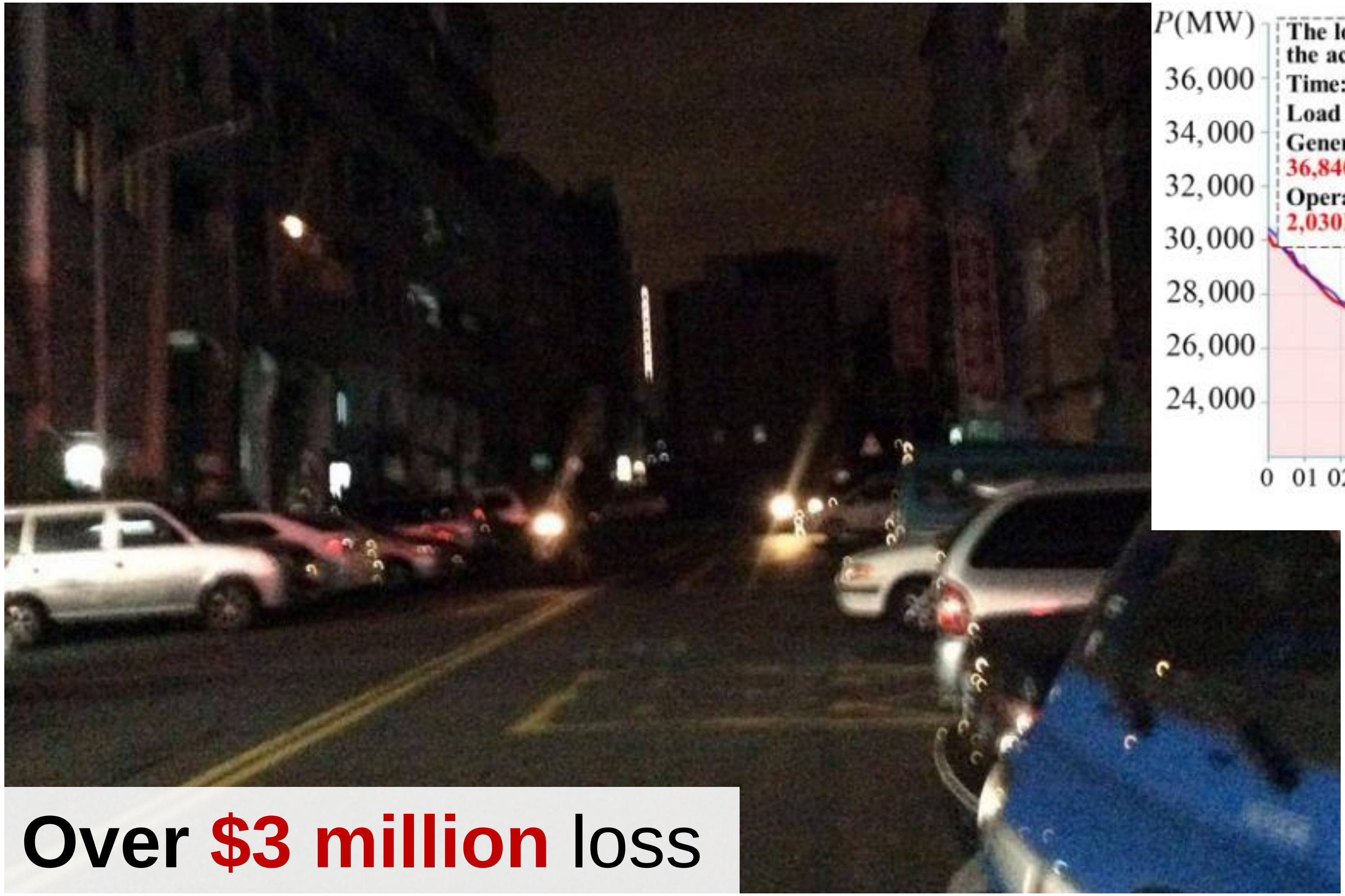


- Until 2016, the generation from natural gas reaches to 188.1 TWh in China, with year-on-year growth of 12.7%

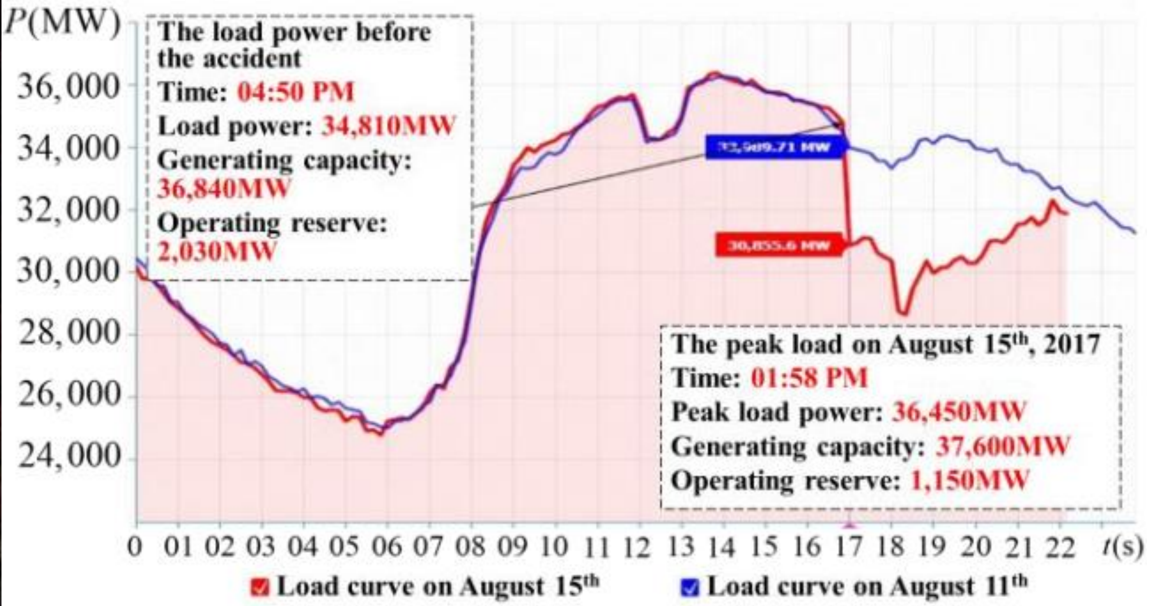
integrated electricity and gas systems (IEGS) is proposed

- Coordinated planning, operation, analysis……

1.2 Reliability issues brought by integration



Over **$3 million** loss



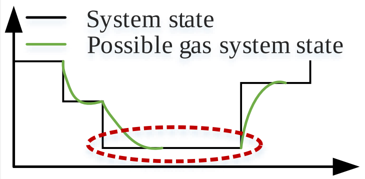
2017 Taiwan Blackout

Contingency management scheme is needed for handling such circumstances.

1.3 Contingency management in ……

Electricity system | Component failures | Min {generation cost + load shedding cost}

Major difference:
Gas flow dynamics



Partial derivative equations
(PDEs)

IEGS

Recent studies
- 1 steady-state based integrated optimal power flow (SIOPF)
- 2 SIOPF + solving the PDEs

Nonlinearity
Large-scale variables
Time-interdependent
……

How to solve?

Contribution of this paper

Contingency management scheme in this paper
- Embed the discretized PDEs of gas flow dynamics into the optimization problem

Better solution

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2.1 Structure of the studied IEGS

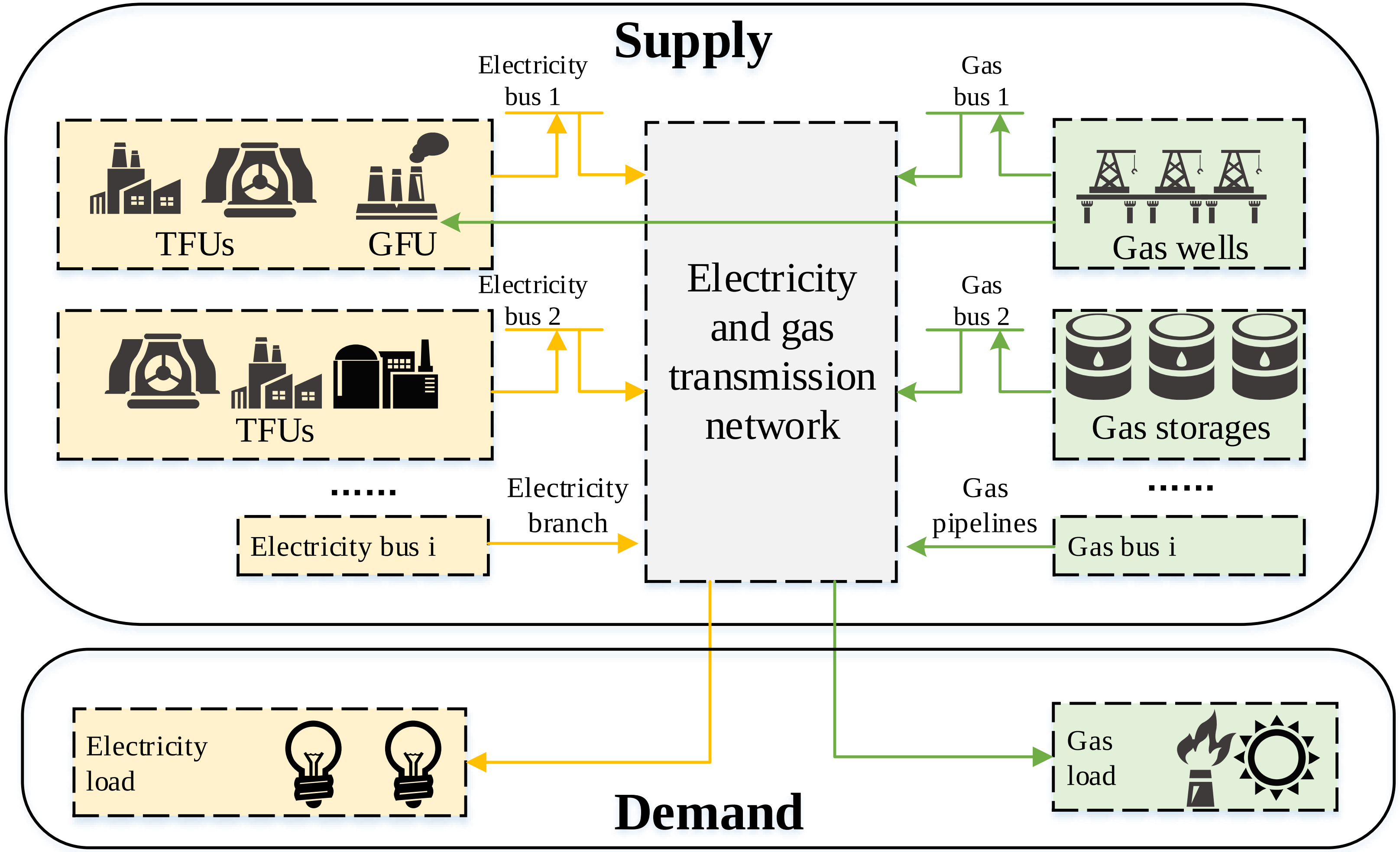


Fig 1 Structure of the studied IEGS.

TWO networks:

- Gas transmission network
- Electricity transmission network

THREE components:

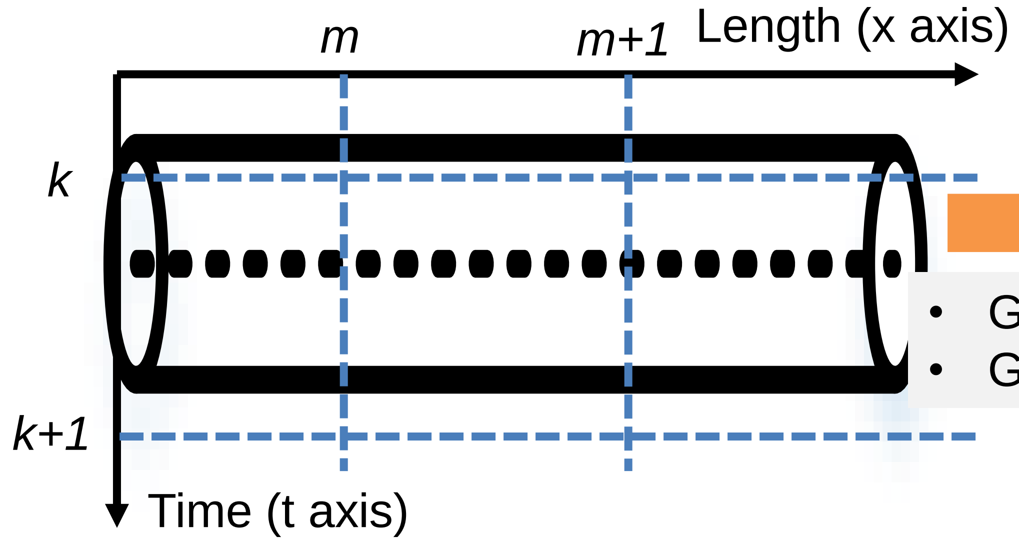
- Gas source (GS)
- Conventional fossil generating unit (CFU)
- Gas fired generating unit (GFU)

TWO loads:

- Electricity load
- Gas load

2 Reformulation of dynamic gas flow equations

2.2 Gas flow dynamics in a single pipeline



- Gas pressure: p(x,t)
- Gas flow: q(x,t)

Continuous domain:

- Continuity equation:

$$f_{co}(x,t)=\frac{B^2}{\rho_0 A}\frac{\partial q}{\partial x}+\frac{\partial p}{\partial t}=0$$

- Motion equation:

$$f_{mo}(x,t)=\frac{\partial p}{\partial x}+\frac{\rho_0}{A}\frac{\partial q}{\partial t}+\frac{2\rho_0^2 B^2}{F^2 D A^2}\frac{q|q|}{p}=0$$

Discretized:

- Continuity equation:

$$\frac{1}{B^2}(p_{m+1,k+1}+p_{m,k+1}-p_{m+1,k}-p_{m,k})+\frac{\Delta t\rho_0}{\Delta x A}(q_{m+1,k+1}-q_{m,k+1}+q_{m+1,k}-q_{m,k})=0$$

Linear

- Motion equation:

$$4((p_{m+1,k+1}+p_{m+1,k})^2-(p_{m.k+1}+p_{m,k})^2)+\frac{\Gamma\rho_0 B^2\Delta x}{F^2 D A^2}(q_{m+1,k+1}+q_{m+1,k}+q_{m,k+1}+q_{m,k})^2=0$$

Non-linear

2.3 Reformulation of the discretized PDEs

- Motion equation (assuming the direction of the gas flow doesn't change):

$$\left\| p_{m.k+1} + p_{m,k}, \sqrt{\frac{\rho_0^2 B^2}{F^2 D A^2} \Delta x (q_{m+1,k+1} + q_{m+1,k} + q_{m,k+1} + q_{m,k})} \right\|_2 \le p_{m+1,k+1} + p_{m+1,k}, \Gamma = 1$$

$$\left\| p_{m+1,k+1} + p_{m+1,k}, \sqrt{\frac{\rho_0^2 B^2}{F^2 D A^2} \Delta x (q_{m+1,k+1} + q_{m+1,k} + q_{m,k+1} + q_{m,k})} \right\|_2 \le p_{m.k+1} + p_{m,k}, \Gamma = -1$$

We can now use commercial solvers(e.g. Gurobi, Cplex, etc.)

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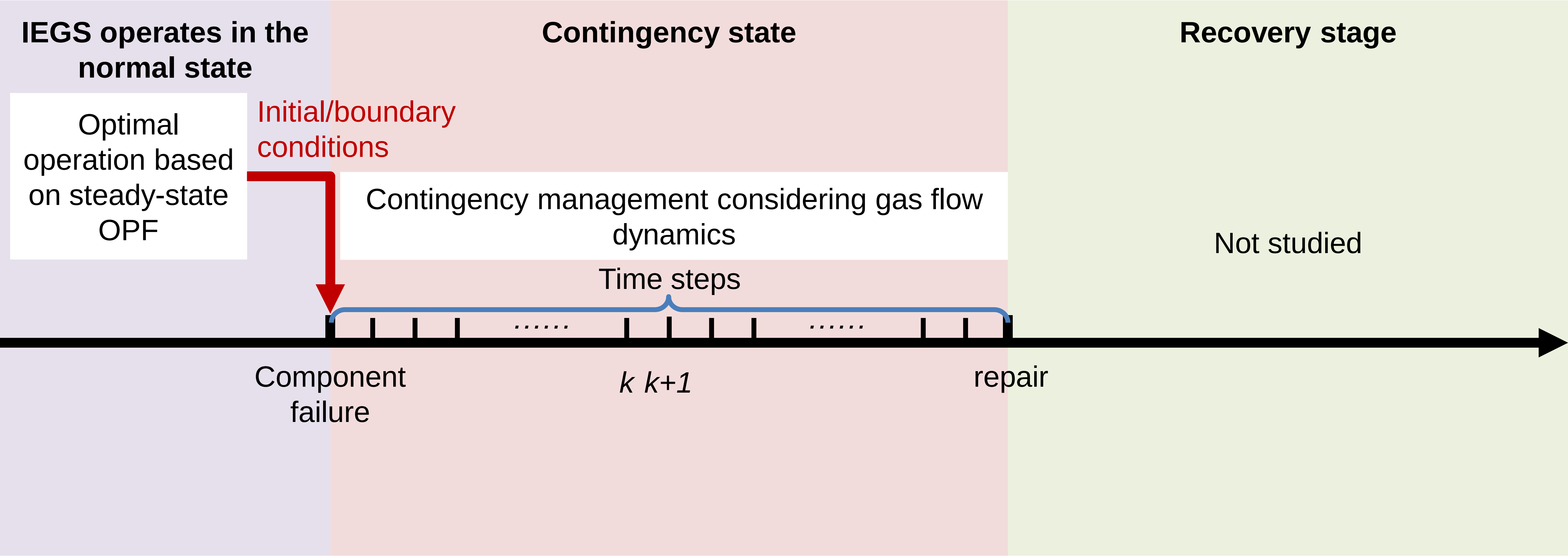
3 Contingency management scheme of the IEGS

3.1 Timeline



3.2 Initial & boundary conditions

Operation in the normal state

$$\underset{sg_i,\, g_{i,j},\, g_{i,j}^{gfu}}{Min} \quad C_{IEGS} = \underbrace{\sum_{i \in GB} gp_i\, sg_i}_{\text{Gas purchasing cost}} + \underbrace{\sum_{i \in EB} \sum_{j \in NG_i} cst_{i,j}(g_{i,j})}_{\text{Electricity generation cost}}$$

s.t.

- Gas flow constraints:

$$q_{ij} = C_{i,j}\,\mathrm{sgn}(p_i - p_j)\sqrt{\left|p_i^2 - p_j^2\right|}$$

$$sg_i - gd_i - \sum_{j \in NG_i^{gfu}} g_{i,j}^{gfu} / \xi_{i,j} - \sum_{j \in \Omega_i^g} q_{ij} = 0$$

- Electric power flow constraints:

$$ef_{i,j} = (\theta_i - \theta_i) / X_{i,j}$$

$$\sum_{j \in NG_i^{gfu}} g_{i,j}^{gfu} + \sum_{j \in NG_i} g_{i,j} - ed_i - \sum_{j \in \Omega_i^e} f_{ij} = 0$$

- Upper/lower boundaries for gas sources, generating units, electricity & gas flows

$$sg_i^- \le sg_i \le sg_i^+ \qquad g_{i,j}^- \le g_{i,j} \le g_{i,j}^+$$

$$g_{i,j}^{gfu,-} \le g_{i,j}^{gfu} \le g_{i,j}^{gfu,+} \qquad \left|q_{ij}\right| \le q_{ij}^+ \qquad \left|f_{ij}\right| \le f_{ij}^+$$

Solution

Initial conditions

- Gas productions from gas source sg_i^*
- Nodal gas pressure p_i^*
- Gas flow in the pipeline q_{ij}^*
- Gas pressure along the pipeline:

$$p_{ij,m,0} = \sqrt{p_i^{*2} - \mathrm{sgn}(p_i^* - p_j^*) q_{ij}^{*2} (C_{ij}^2 L_{ij})^{-1} m\Delta x}$$

3.3 Contingency management formulation

$$\min_{sg_{i,k},g_{i,j,k},ec_{i,k},gc_{i,k}} J=\sum_{k=1}^{NK}\left(\sum_{i\in EB}\left(\underbrace{CDF^{e}ec_{i,k}}_{\text{Electricity load shedding cost}}+\underbrace{\sum_{j\in GEN_i}cst_{i,j}(g_{i,j,k})}_{\text{Electricity generation cost}}\right)+\sum_{i\in GB}\left(\underbrace{sg_{i,k}\rho_i^{g}}_{\text{Gas purchasing cost}}+\underbrace{CDF^{g}\cdot gc_{i,k}}_{\text{Gas load shedding cost}}\right)\right)$$

Control variables

（for each time period k):

- gas production of the gas sources $sg_{i,k}$
- electricity generation of TFUs and GFUs $g_{i,j,k}$ $g_{i,j,k}^{gfu}$
- the quantities of electricity and load shedding $ec_{i,k}$ $gc_{i,k}$

Subject to:

（for each time period k):

- Initial condition constraints
- Gas flow dynamic constraints
- Gas system boundary condition constraints
- Electricity power flow constraints
- Upper and lower boundaries (particularly for gas pressures) $p_{ij}^{-}\le p_{ij,m,k}\le p_{ij}^{+}$

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3.4 Solution procedures

Determine the normal operating condition of IEGS using steady-state based OPF

Receive the contingency information, such as the failure of generating units, duration, etc..

Set the parameters and for discretizing the PDEs of gas flow dynamics

Calculate the initial condition of the contingency state in the gas system

Formulate the contingency management problem

Solve the SOC programming problem using the Gurobi solver

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4.1 Case setup

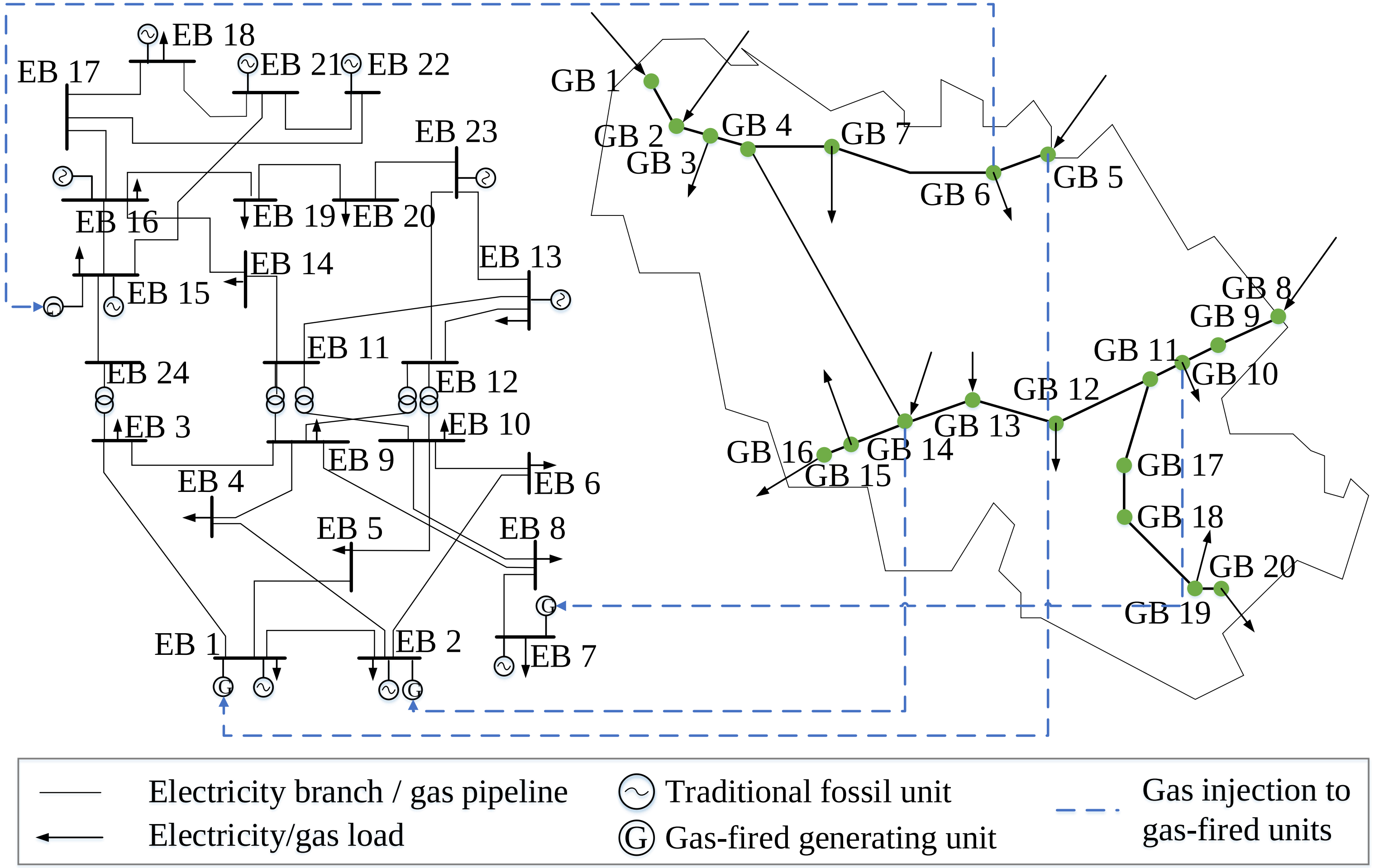

Fig 2 Integrated IEEE RTS and Belgium natural gas transmission system

Strategy A
- steady-state based OPF

Strategy B
- SIOPF + solving the PDEs

Previous studies

Strategy C
- proposed contingency management scheme

4.2 Performance VS computation speed

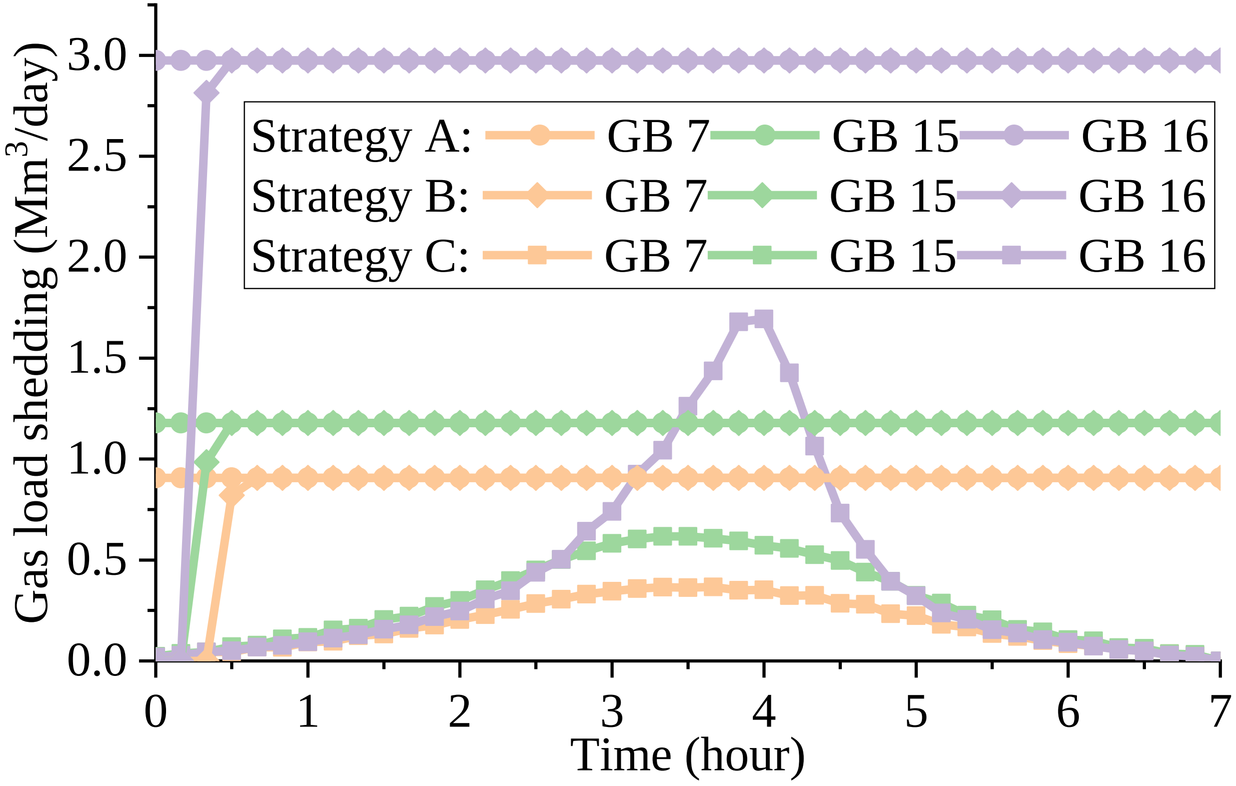

Fig 3 Comparison of gas load shedding in different strategies

- Strategy C demonstrates the most superior performance on the load shedding.

- Strategy A is fastest for its small scale.
- Though Strategy C is much more complex, it is also fast owing to the proposed SOC relaxation technique.

Table 1 Computation times of different strategies

Strategy	Solver	Computation Time (s)
A	Interior point method in Matpower	0.061
B	Interior point method in Matpower + fsolve in Matlab	35.59
C	Interior point method in Matpower + Gurobi	2.61

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4.3 Cost of being superior

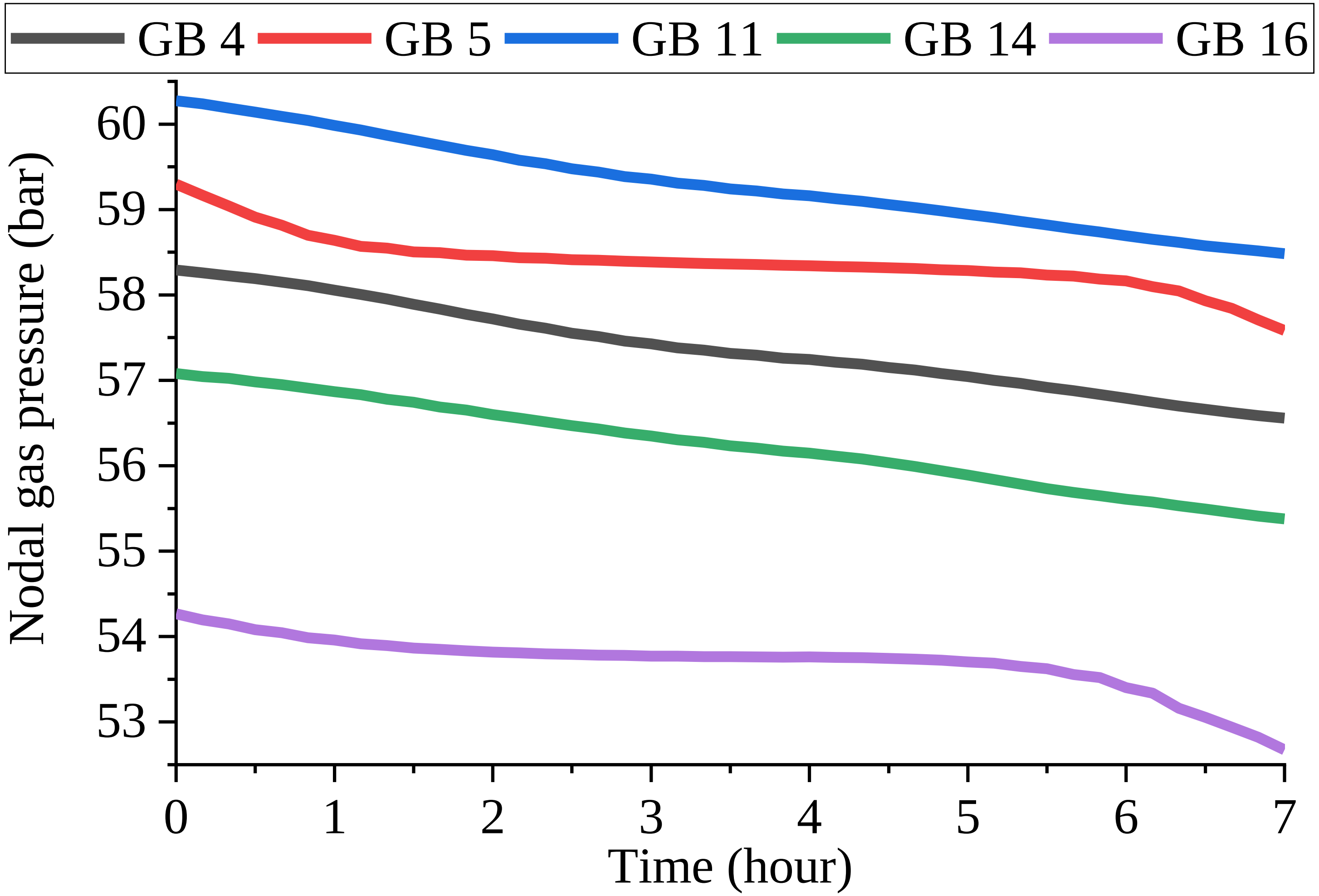

Fig 4 Nodal gas pressures during the contingency state

lower boundaries of gas pressure are set to 0.97 times of their pressures in the normal operating state.

- Though strategy C leads to minimal load shedding, it is delivered by using the linepacks, lowering the gas pressures.

Capability of solving the crises at the moment (component failure, gas shortage)

How to balance?

Capability of withstanding the risk in the future (possible component failures, load volatility…)

4 Case studies

4.4 Further comparisons

- The gas load shedding is higher when the duration of failure increases and lower gas pressure limits are higher.
- from a certain point, the gas source failure can be fully handled with linepacks without any load shedding.

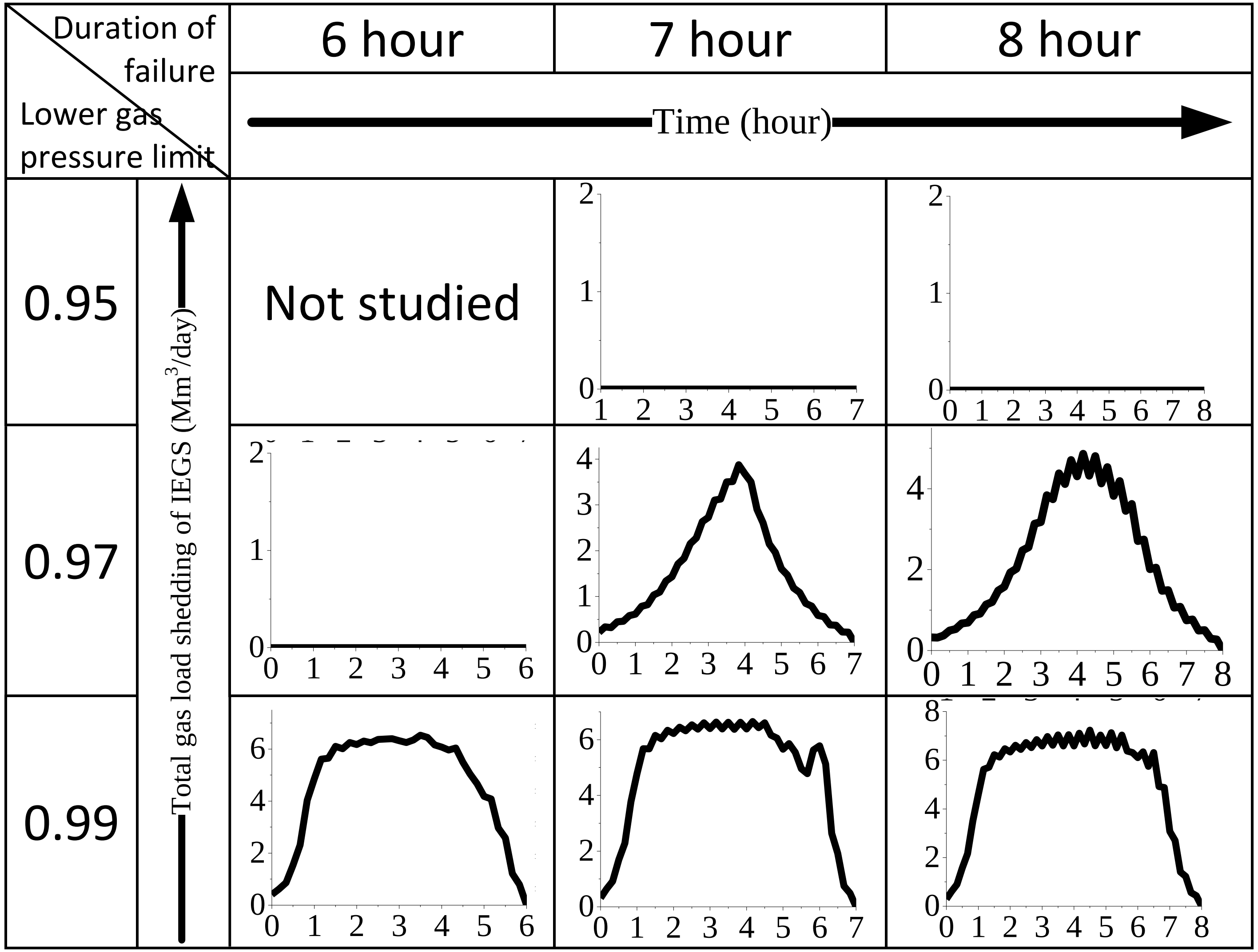

Fig 5 Comparison of total gas load shedding with different durations of failure and different lower gas pressure boundaries

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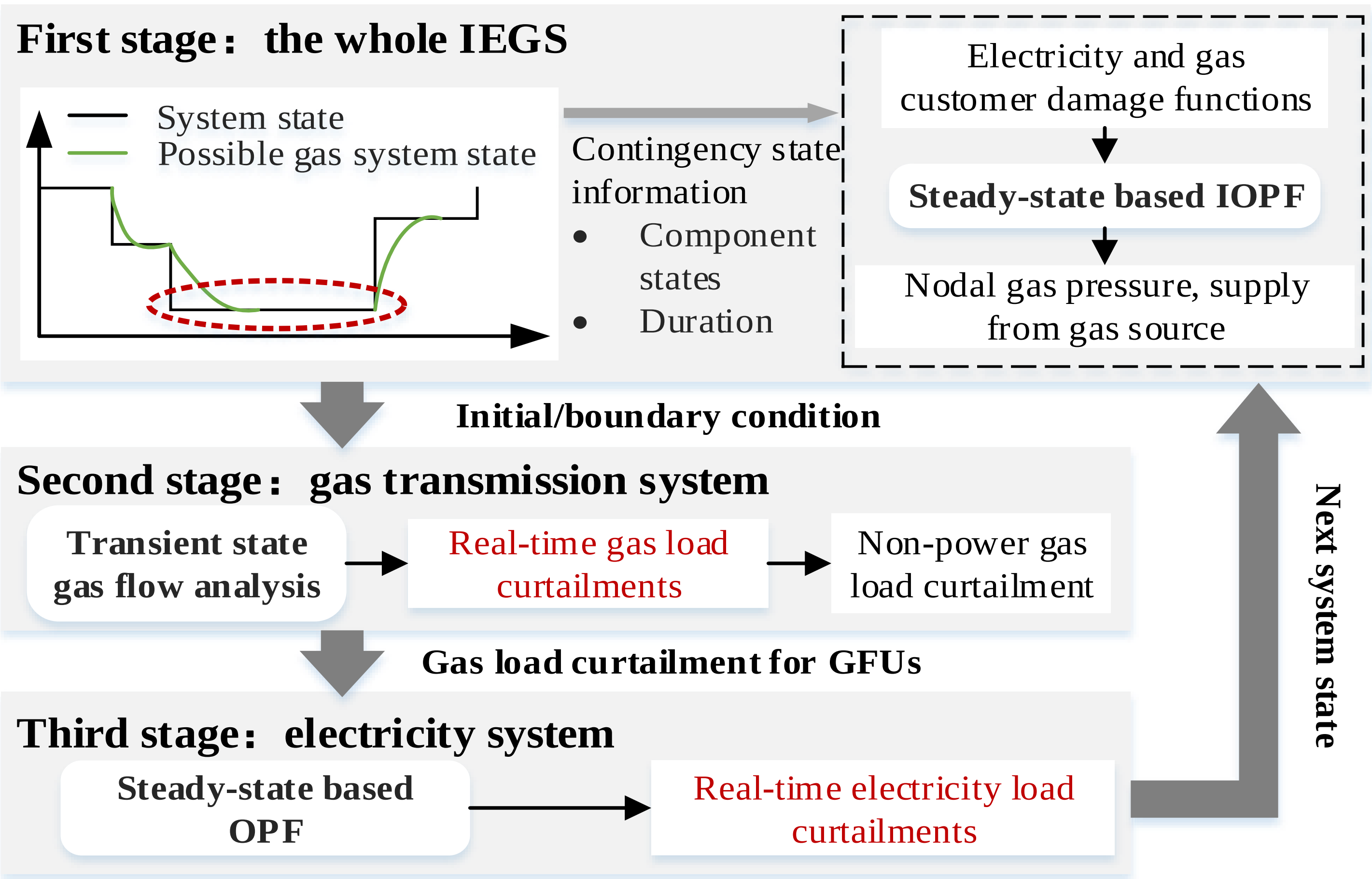
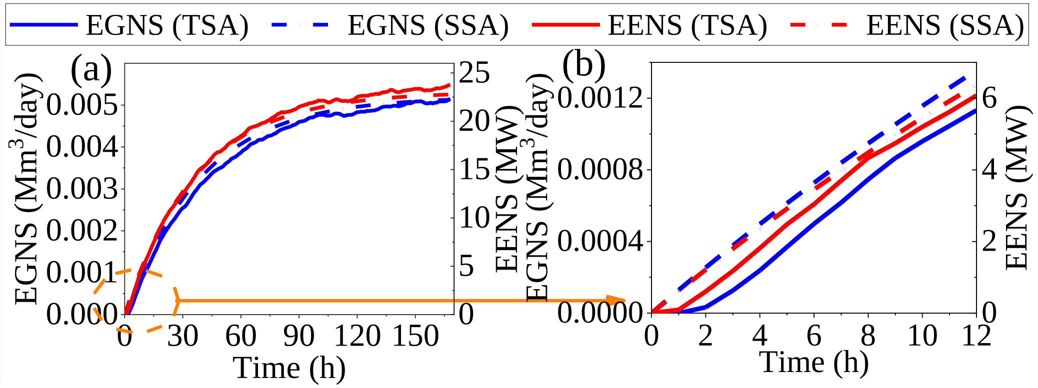
5.1 Operational reliability of IEGS

Focus on the operational phase → Time-varying reliability indices → Assist the ISO in the reliability management, day-ahead unit commitment, load curtailment devising……





- Owing to gas flow dynamics, the operational reliability of IEGS differs significantly from electricity systems, especially in the first several hours.
- The occurrence of gas or electricity shortage is expected to be delayed, and the operational reliabilities of both systems tend to be superior.

5.2 Look-ahead & probabilistic contingency management

Normal operating state

Optimal operation based on steady-state OPF

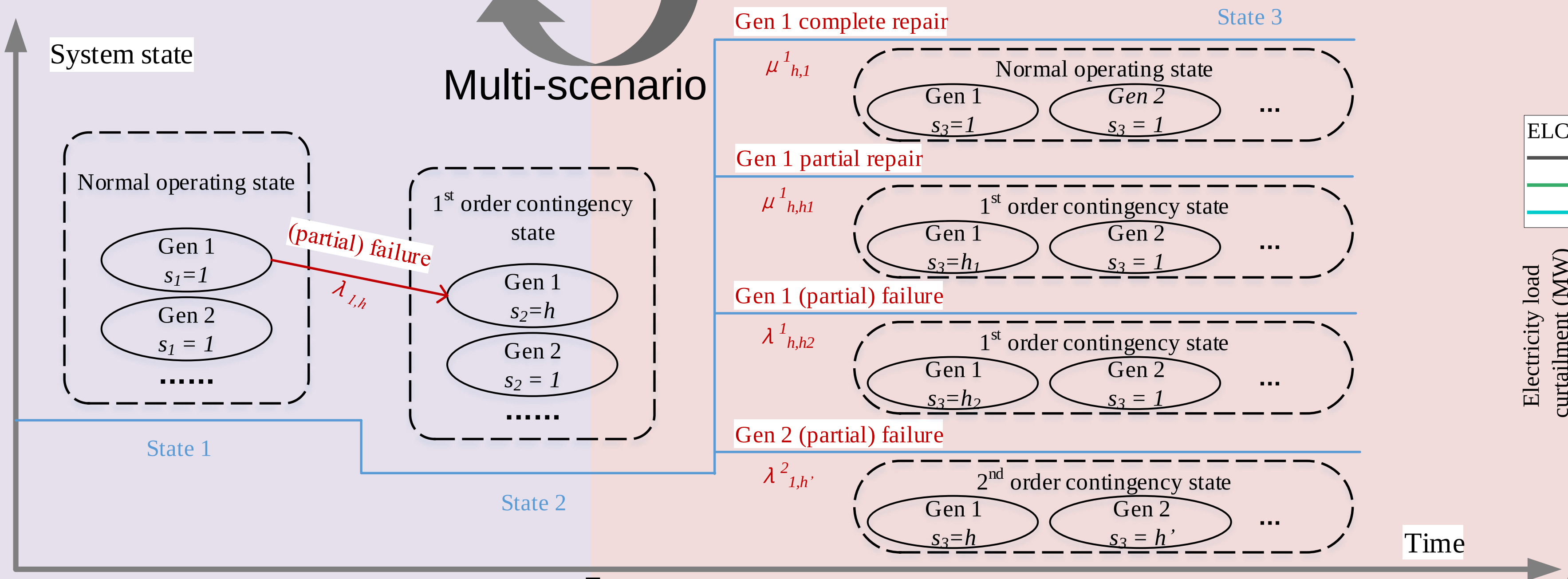
Contingency state

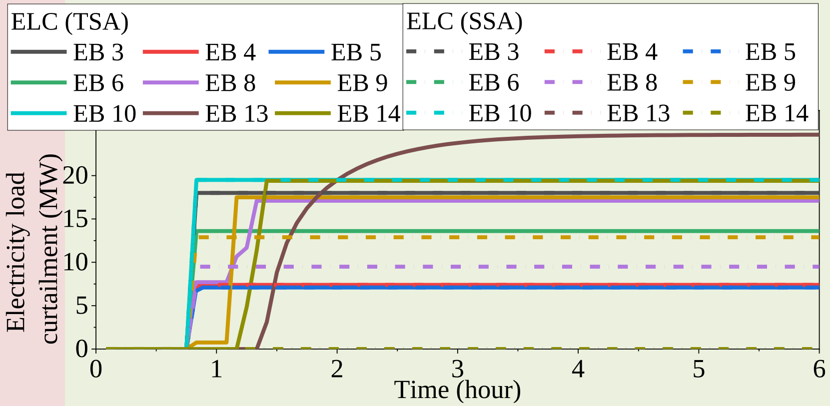
Look-ahead & get prepared
Based on failure/repair state probabilities

Recovery stage

Recover from gas pressure drops

Multi-scenario

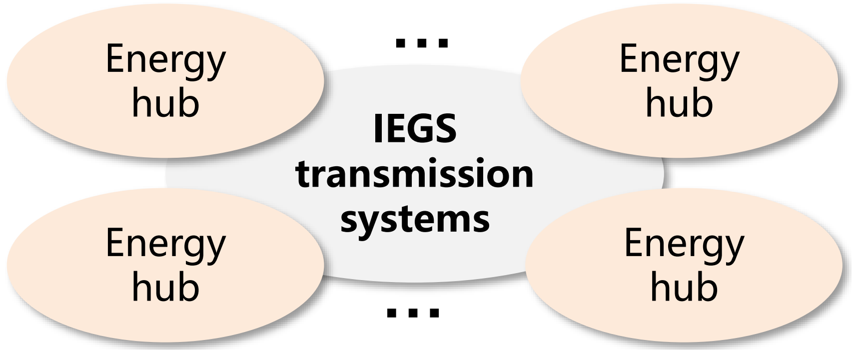




Component failure

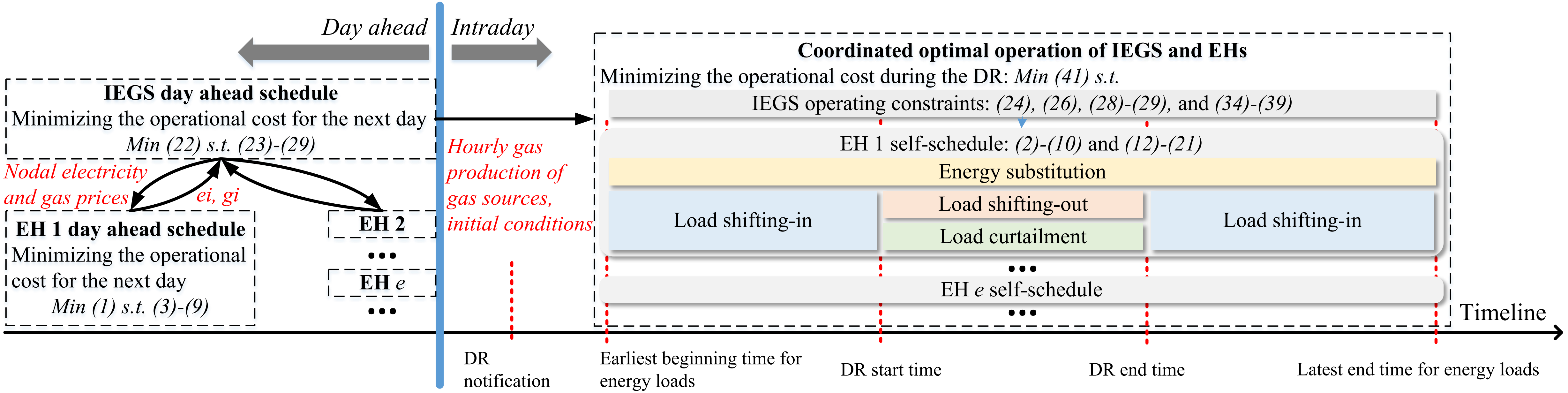
repair

5.3 Multi-energy demand response (DR)



DR signal → reschedule energy hubs to provide DR capacity

→ Substitute part of the electricity consumption with gas consumption → Gas demand spikes → Coordination with IEGS transmission system



Thanks!

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