Cascading Imbalance in Coupled Gas-Electric Energy Systems

Gang Huang¹⁺, Jianhui Wang², Cheng Wang³, Chuangxin Guo⁴

Abstract

There has been growing interest in modeling energy systems as a whole in order to deal with the interdependence within modern energy systems. Previous analyses, however, have been limited in their ability to assess potential adverse impacts associated with the independent dispatch of energy systems, which is typically done today. A fundamental property of coupled systems is that imbalance in one network may lead to imbalance in the interconnected networks, and this may happen recursively which leads to a cascade of imbalance. Herein, a framework is developed to understand the above phenomenon when network damage occurs. The modified Belgian gas-electricity networks are used as an instance, and the modeling of gas-fired generators and electricity-driven compressors is taken into account. Two different operational strategies (i.e., independent dispatch and joint dispatch) are compared and it is demonstrated that the independent dispatch will lead to greater loss not only in total cost but also in individual energy supply. The reason behind this conundrum is researched and the existence of cascading imbalance phenomenon is shown in the coupled energy systems. Moreover, this paper provides evidence for the recommendation of cooperation between different energy industries for the purpose of energy optimization and resilience enhancement.

Keywords: cascading effect, electricity network, emergency response, energy system, gas network, resilience enhancement

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Nomenclature

Sets

\( \mathcal{B}^p \) set of buses in the electricity network
\( \mathcal{L}^p \) set of transmission lines in the electricity network
\( \mathcal{U}_1^p \) set of gas-fired generators in the electricity network
\( \mathcal{U}_2^p \) set of other generators in the electricity network
\( \mathcal{D}_1^p \) set of compressor-related demand in the electricity network
\( \mathcal{D}_2^p \) set of other demand in the electricity network
\( \mathcal{B}^g \) set of nodes in the gas network
\( \mathcal{L}^g \) set of pipelines in the gas network
\( \mathcal{C}^g \) set of compressors in the gas network
\( \mathcal{U}^g \) set of terminals in the gas network
\( \mathcal{D}_1^g \) set of generator-related demand in the gas network
\( \mathcal{D}_2^g \) set of other demand in the gas network

Variables

\( p_u \) output of generator \( u \)
\( p_d^s \) shedding quantity of electricity load \( d \)
\( p_{d1}^s \) shedding quantity of compressor-related electricity load \( d_1 \)
\( p_{d2}^s \) shedding quantity of other electricity load \( d_2 \)
\( p_{ij} \) power flow between bus \( i \) and bus \( j \)
\( \theta_i \) voltage angle of bus \( i \)
\( g_u \) output of terminal \( u \)
\( g_d^s \) shedding quantity of gas load \( d \)
\( g_{d1}^s \) shedding quantity of generator-related gas load \( d_1 \)
\( g_{d2}^s \) shedding quantity other gas load \( d_2 \)
\( g_{ij} \) gas flow between node \( i \) and node \( j \)
\( v_i \) gas pressure of node \( i \)
\( \phi_{ij} \) status of compressor \((i, j)\)

Parameters

\( c_u^p \) generation price of generator \( u \)
\( P_{u_{\text{max}}} \) generation capacity of generator \( u \)
\( c_d^p \) shedding price of electricity load \( d \)
As the backbone of our society, energy systems provide us a variety of energies, including electric power, natural gas, and crude oil [1]. These individual energy systems had little or no dependence on each other originally [2], but driven by political, economic, and technological reasons, modern energy systems have dramatically evolved and have developed into a complex network of coupled systems [3]. An example is provided by the European energy system [4], which aims to enhance sustainability and security by establishing a more coupled energy system. This newly emerging issue has attracted a great deal of attention around the world [5, 6, 7, 8]. Notably, China put forward the concept of Global Energy Interconnection [9], the United States introduced the roadmap of integrated energy systems [10], and the European Union planned to create a pan-European integrated energy system by the year 2050 [11].

Within coupled energy systems, the electricity network is the core because electric energy is extremely versatile and the grid could connect different primary energies and secondary energies. Among these energies, natural gas has played an important role over the past decades, and it is expected to play an even more prominent role in the future mainly due to the revolution in the field.
of shale gas and the rapid development of gas turbines for the electricity industry [12]. In fact, almost all of the constructed power plants in the United States from 2000 to 2005 use natural gas to generate electric power [13], and by 2035, over 50% of the total generation is expected to be supplied by natural gas [14]. Several historical incidents have illustrated the increasing interdependence between the electricity network and gas network [15], and their dependence on each other will further increase as the two networks are becoming more deeply coupled. The roles of electricity network and gas network are so outstanding that they are used as an instance for the coupled energy systems in this paper.

There are a number of works recently done within the field of coupled gas-electric energy systems, mainly for security issues [16, 17, 18, 5, 19, 7, 8], market problems [20, 21, 22, 23], computation algorithms [24, 25, 26, 27], expansion planning [28, 29], and privacy concerns [30, 6]. For example, in the security aspect, [16] proposed a tri-level optimization model to harden the coupled electric power and natural gas systems against malicious attacks, [5] presented a two-stage robust optimization model for the operation of power systems considering the physical and economic interactions with natural gas systems. In the market aspect, [21] studied the equilibrium problem of gas and electricity markets under the background of strategic offering behaviors and [22] studied the day-ahead clearing problem of gas and electricity markets considering wind power uncertainty. For computation issues, [24] studied the distributed algorithm of gas-electricity network operation using the alternative direction method of multipliers and [27] proposed a one-segment linear gas flow model based on deep learning for the fully-linear modeling of gas-electric energy systems. For expansion planning, [28] described a combined gas and electricity network optimization model with the consideration of gas-fired generators and [29] proposed a stochastic decentralized model for gas and electricity networks expansion. For computation issues, [24] studied the distributed algorithm of gas-electricity network operation using the alternative direction method of multipliers and [25] proposed a convex optimization based distributed algorithm for multi-period optimal gas-power flow problem. For privacy concerns, [30] proposed a decentralized optimal energy flow calculation method to protect information privacy and [6] presented a static equivalent model of the natural gas network which could preserve its operating characteristics for power industry.

While existing studies intend to investigate the interdependence between
the gas network and electricity network, the dependence of gas network on the electricity network is often overlooked. It is widely known that electricity generation is increasingly dependent on natural gas supply, but the fact that the gas network also relies on electricity supply in order to function well [31] is not yet fully understood. In particular, electricity-driven compressors require a reliable supply of electricity to compress the natural gas [32], otherwise the natural gas cannot flow as desired. This issue can be found in the 2011 Southwest cold weather event [33], when the gas network and electricity network both got damaged. This problem will become more urgent as old compressors built over half a century ago are widely proposed to be replaced by electricity-driven ones [34, 35]. In fact, electricity-driven compressors have grown to have twice the market share of gas turbine compressors since 2010 [36]. In Table 1, we summarize the reasons why gas-fired generators and electricity-driven compressors are being increasingly used from the perspectives of economic considerations, technical issues, and environmental requirements.

Table 1: Reasons behind the increase of gas-fired generators and electricity-driven compressors [29, 34, 35, 36, 37]

<table>
<thead>
<tr>
<th>Perspective</th>
<th>Gas-fired generators</th>
<th>Electricity-driven compressors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic</td>
<td>Lower cost, higher efficiency, shorter construction period</td>
<td>Higher efficiency, less maintenance, longer lifespan</td>
</tr>
<tr>
<td>Technical</td>
<td>Backup for renewable energies</td>
<td>Limited real estate requirements</td>
</tr>
<tr>
<td>Environmental</td>
<td>Low carbon policies</td>
<td>Methane emission savings</td>
</tr>
</tbody>
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In this paper, the phenomenon of cascading imbalance within coupled energy systems is critically assessed. We compare two different operational strategies, namely the independent response method and the joint response method, corresponding to no global visibility and perfect global visibility, respectively. The mathematical formulation for these two methods are provided in this paper, and mathematical reformulation and a sequential second-order cone programming (SSOCP) algorithm are proposed to obtain the optimal solution. We demonstrate through the modified Belgian networks that the independent response method will lead to greater loss, not only in total cost, but also in individual energy supply. The reason behind this conundrum is the phenomenon we term as “cascading imbalance”, which is an emerging type of cascading effect that is caused by the interdependence
between networks and is a hidden vulnerability for modern energy systems. To better understand the gas-electricity networks, the roles of gas-fired generators and electricity-driven compressors within the coupled energy system are also researched in this paper.

The remainder of this paper is organized as follows. In Section 2, the two operational strategies we will compare are introduced. Section 3 provides the mathematical formulation for these two methods while Section 4 provides the solution methodology. The modified Belgian networks are introduced in Section 5, and Section 6 presents the results and discussion. Finally, Section 7 elaborates the concluding remarks.

2. Operational models

The operation problem considered in this paper minimizes the loss once damage occurs. When either network gets damaged, system operators are assumed to be able to dispatch the part within their span of control.

![Flowchart](image)

Figure 1: Dispatch logic of different response methods for gas-electric energy systems. (a) Independent response. (b) Joint response.

We compare two different operational strategies: an independent response approach where the operator of either network has no information about
the other network and seeks to minimize the loss that is within their own system; and a joint response approach where the operator of either network has perfect information about the counterpart and decides on the countermeasures over the entire system. Figure 1 illustrates the dispatch logic of these two operational strategies when network damage occurs.

These two response strategies are compared because they represent plausible yet distinct paradigms for dispatching coupled energy systems against disasters. Herein, the independent response method prioritizes achieving as little loss as possible solely in the individual networks, while the joint response method minimizes the loss from the perspective of coupled systems. By considering these two plausible yet distinct response strategies, we show the range of impacts that would result from response strategies with different visibility. We note that similar comparison has been made in the cyber-physical systems [38].

3. Mathematical formulation

The mathematical formulation for the independent response method and the joint response method is provided in this section.

3.1. Independent response method

The independent response method for operational management of gas-electric energy systems considers variables defined over 12 sets: $\mathcal{B}^p$, $\mathcal{L}^p$, $\mathcal{U}^p_1$, $\mathcal{U}^p_2$, $\mathcal{D}^p$, $\mathcal{D}^g$, $\mathcal{B}^g$, $\mathcal{L}^g$, $\mathcal{C}^g$, $\mathcal{U}^g$, $\mathcal{D}^g_1$, and $\mathcal{D}^g_2$. The explanation of these sets and full notation for this method are provided in Nomenclature.

The objective of the operational model is to minimize the cost of the dispatchable network when damage occurs. Thus, the objective function can be defined as the total cost of load shed and generation for either network, as given in Eq. (1) for electricity network and Eq. (2) for gas network:

\[ f_s(p) = \sum_d c_d^p p_d^s + \sum_u c_u^p p_u \]  
\[ f_s(g) = \sum_d c_d^g g_d^s + \sum_u c_u^g g_u. \]
3.1.1. Electricity network operational constraints

Based on the common DC power flow model [39, 40, 38], power balance for each bus within the electricity network is described in constraint (3):

$$
\sum_u p_u - \sum_{ij} p_{ij} = \sum_{d_1} (P_{d_1} - p_{s_{d_1}}) + \sum_{d_2} (P_{d_2} - p_{s_{d_2}}), \ i \in B^p,
$$

and constraint (4) describes the power flow of each transmission line:

$$
p_{ij} = -B_{ij} \theta_{ij}, \ ij \in L^p,
$$

where $B_{ij} = -1/X_{ij}$.

The generation capacity of each generator is:

$$
p_u \leq P_{u}^{\text{max}}, \ u \in U_1^p \cup U_2^p.
$$

The transmission capacity of each transmission line is:

$$
-P_{ij}^{\text{max}} \leq p_{ij} \leq P_{ij}^{\text{max}}, \ ij \in L^p.
$$

The voltage angle limit of each bus is:

$$
\Theta_{i}^{\text{min}} \leq \theta_i \leq \Theta_{i}^{\text{max}}, \ i \in B^p.
$$

Constraints (8)–(9) are involved when load shedding is performed:

$$
p_{s_{d_1}} \leq P_{d_1}, \ d_1 \in D_2^p \\
p_{s_{d_2}} \leq P_{d_2}, \ d_2 \in D_2^p.
$$

When the interaction with gas network is taken into account, constraint (10) is involved as electricity-driven compressors might close and consume no electricity:

$$
P_{d_1} - p_{s_{d_1}} \leq \sum_{ij} P_{ij} \phi_{ij}, \ d_1 \in D_1^p.
$$

Constraint (11) should be considered as gas-fired generators might get inadequate gas supply:

$$
p_u \leq \sum_{d_1} (G_{d_1} - g_{d_1}^s), \ u \in U_1^p.
$$

We note that $\phi_{ij}$ and $g_{d_1}^s$ are pre-determined by the operation of gas network. See Nomenclature for further details regarding the notations.
3.1.2. Gas network operational constraints

Based on the steady-state gas flow model [41, 42], gas balance for each node within the gas network is given in constraint (12):

$$\sum_u g_u - \sum_{ij} g_{ij} = \sum_{d_1} (G_{d_1} - g_{d_1}^s) + \sum_{d_2} (G_{d_2} - g_{d_2}^s), i \in B^g,$$  \hspace{1cm} (12)

and constraint (13) describes the gas flow of each gas pipeline:

$$g_{ij} |_{g_{ij}} = C_{ij} (v_i^2 - v_j^2), ij \in L^g. \hspace{1cm} (13)$$

The export capacity of each terminal is:

$$g_u \leq G_{u}^{\text{max}}, u \in U^g. \hspace{1cm} (14)$$

The transmission capacity of each gas pipeline is:

$$-G_{ij}^{\text{max}} \leq g_{ij} \leq G_{ij}^{\text{max}}, ij \in L^g. \hspace{1cm} (15)$$

The gas pressure limit of each node is:

$$V_{i}^{\text{min}} \leq v_i \leq V_{i}^{\text{max}}, i \in B^g. \hspace{1cm} (16)$$

Each gas compressor follows constraints (17)–(18), indicating that a compressor can manipulate the outgoing node pressure by a maximum ratio of $R_{ij}$ when it is on [24]:

$$v_i \leq v_j \leq R_{ij} v_i, ij \in C^g \hspace{1cm} (17)$$

$$v_j \leq v_i + (V_j^{\text{max}} - V_j^{\text{min}}) \phi_{ij}, ij \in C^g. \hspace{1cm} (18)$$

Constraints (19)–(20) are involved when load shedding is performed:

$$g_{d_1}^s \leq G_{d_1}, d_1 \in D_2^g \hspace{1cm} (19)$$

$$g_{d_2}^s \leq G_{d_2}, d_2 \in D_2^g. \hspace{1cm} (20)$$

When gas-fired generators require no gas supply, the gas supplied follows:

$$G_{d_1} - g_{d_1}^s \leq \sum_u p_u, d_1 \in D_1^g. \hspace{1cm} (21)$$

Constraint (22) is involved as electricity-driven compressors might have inadequate electricity supply in emergency state:

$$P_{ij} \phi_{ij} \leq \sum_{d_1} (P_{d_1} - p_{d_1}^s), ij \in C^g. \hspace{1cm} (22)$$

Herein, $p_u$ and $p_{d_1}^s$ are pre-determined by the operation of interconnected electricity network. Further details regarding the notations are provided in Nomenclature.
3.2. Joint response method

Similar to the independent response model, the joint response method considers variables over the same sets. However, the objective differs, as the joint response method minimizes the total cost of the whole system when damage occurs. Thus, the objective function is as follows:

\[ f_s = \sum_d c_d^g g_d^s + \sum_d c_d^p p_d^s + \sum_u c_u^g g_u + \sum_u c_u^p p_u. \] (23)

An important distinction between the joint response method and the independent response method is whether global visibility about the entire system is available. Taking the joint response strategy, operators derive an optimal strategy based on the supply-demand balance of the whole coupled system. All the constraints for independent response work in the joint response method, except for constraints (10)–(11) and constraints (21)–(22). Instead, the following constraints are invoked because the operator could now keep balance the gas supply from the gas network to gas-fired generators and the electricity supply from the electricity network to electricity-driven compressors.

\[ P_{d_1} - p_{d_1}^s = \sum_{ij} P_{ij} \phi_{ij}, d_1 \in D_1^p \] (24)

\[ p_u = \sum_{d_1} (G_{d_1} - g_{d_1}^s), u \in U_1^p \] (25)

\[ G_{d_1} - g_{d_1}^s = \sum_u p_u, d_1 \in D_1^g \] (26)

\[ P_{ij} \phi_{ij} = \sum_{d_1} (P_{d_1} - p_{d_1}^s), ij \in C^g. \] (27)

4. Solution methodology

While the operational model for electricity network is linear, the operational model for gas network is non-linear and in fact non-convex, mainly due to the Weymouth equation (i.e., constraint (13)). To solve the above issue, we here reformulate the problem into a mixed-integer second-order cone programming problem and propose a sequential second-order cone programming (SSOCP) algorithm to obtain the optimal solution.
4.1. Mathematical reformulation

Inspired by [42], we introduce binary variables $g_{ij}^+$ and $g_{ij}^-$ to indicate the flow direction in gas pipelines, use variable $v_i'$ to denote $v_i^2$, and introduce variable $\tau_{ij}$ which equals to $(g_{ij}^+ - g_{ij}^-)(v_i' - v_j')$. Then, constraint (13) can be converted to constraints (28)–(34), which are easier to compute.

$$g_{ij}^2 = C_{ij} \tau_{ij}, \ ij \in L^g$$  
(28)

$$\tau_{ij} \geq v_j' - v_i' + (V_i^{\min 2} - V_j^{\max 2})(g_{ij}^+ - g_{ij}^- + 1), \ ij \in L^g$$  
(29)

$$\tau_{ij} \geq v_i' - v_j' + (V_i^{\max 2} - V_j^{\min 2})(g_{ij}^+ - g_{ij}^- - 1), \ ij \in L^g$$  
(30)

$$\tau_{ij} \leq v_j' - v_i' + (V_i^{\max 2} - V_j^{\min 2})(g_{ij}^+ - g_{ij}^- + 1), \ ij \in L^g$$  
(31)

$$\tau_{ij} \leq v_i' - v_j' + (V_i^{\min 2} - V_j^{\max 2})(g_{ij}^+ - g_{ij}^- - 1), \ ij \in L^g$$  
(32)

$$(V_i^{\min 2} - V_j^{\max 2})(1 - g_{ij}^+) \leq v_i' - v_j' \leq (V_i^{\max 2} - V_j^{\min 2})(1 - g_{ij}^-), \ ij \in L^g$$  
(33)

$$g_{ij}^+ + g_{ij}^- = 1, \ ij \in L^g.$$  
(34)

As a result, constraints (15)–(18) also need to be updated to the following ones:

$$- G_{ij}^{\max}(1 - g_{ij}^+) \leq g_{ij} \leq G_{ij}^{\max}(1 - g_{ij}^-), \ ij \in L^g$$  
(35)

$$V_i^{\min 2} \leq v_i' \leq V_i^{\max 2}, \ i \in B^g$$  
(36)

$$v_i' \leq v_j' \leq R_{ij}^2 v_i', \ ij \in C^g$$  
(37)

$$v_j' \leq v_i' + (V_j^{\max 2} - V_i^{\min 2}) \phi_{ij}, \ ij \in C^g.$$  
(38)

Still, we note that constraint (28) is non-convex in the above formulation, and it can be rewritten in a clearer way as follows:

$$g_{ij}^2 \leq C_{ij} \tau_{ij}, \ ij \in L^g$$  
(39)

$$g_{ij}^2 \geq C_{ij} \tau_{ij}, \ ij \in L^g.$$  
(40)

The reformulated problem is a mixed-integer second-order cone programming problem without considering constraint (40). However, we note that constraint (40) is not intractable, as it is in fact concave. Taking advantage of this property, we propose an SSOCP algorithm in Section 4.2 to solve this non-convex problem.
Algorithm 1 SSOCP algorithm

1: Initialization: set algorithm parameters, including $k_{\text{max}}$, $\lambda^0$, $\lambda^{\text{max}}$, $\mu$, $\epsilon_f$, and $\epsilon_\delta$; set $k \leftarrow 0$.

2: Solve the relaxed SOCP problem:

\[
\begin{align*}
    f^0 & = \min \sum_d c_d g_d^s + \sum_u c_u g_u \\
    \text{s.t.} \quad (12), (14), (20)-(22), (29)-(39),
\end{align*}
\]

then set $g_{ij}^0 \leftarrow g_{ij}^*$.

3: Solve the enhanced SOCP problem:

\[
\begin{align*}
    f^{k+1} & = \min \sum_d c_d^g g_d^s + \sum_u c_u^g g_u + \lambda^k \sum_{ij} \delta_{ij} \\
    \text{s.t.} \quad (12), (14), (20)-(22), (29)-(39) \\
    C_{ij} \tau_{ij} - g_{ij}^{k+1} - 2g_{ij}^k(g_{ij} - g_{ij}^k) \leq \delta_{ij} \\
    \delta_{ij} \geq 0,
\end{align*}
\]

then set $g_{ij}^{k+1} \leftarrow g_{ij}^*$, $\lambda^{k+1} \leftarrow \min(\mu \lambda^k, \lambda^{\text{max}})$, and $\Delta^{k+1} = \sum_{ij} \delta_{ij}$.

4: while neither $|f^{k+1} - f^k| \leq \epsilon_f$ nor $\Delta^{k+1} \leq \epsilon_\delta$ is satisfied do

5: Repeat Step 3.

6: end while

4.2. SSOCP algorithm

The SSOCP algorithm (shown in Algorithm 1) is an extension of the second-order cone programming (SOCP) method proposed in [42]. Different from the traditional SOCP algorithm which cannot guarantee the feasibility of its solution for non-convex problems, the SSOCP algorithm avoids this wildness by iteratively solving an enhanced SOCP problem. Herein, through the relaxation of our problem by ignoring constraint (40), we get a relaxed SOCP problem (see model (41)), which is solved to provide an initial value for our algorithm. Then, the first-order Taylor polynomial is utilized to approximate constraint (40) and it is added to model (41), thus an enhanced SOCP problem can be obtained as shown in model (42). Based on the theory of convex-concave optimization [43, 44], the SSOCP algorithm will converge after a finite number of iterations and the optimal solution of the non-convex
optimization problem we are confronted with will be derived.

In the above SSOCP algorithm, \( k^{\text{max}} \) is the maximum iteration limit, \( \lambda^0 \) is the initial penalty coefficient, \( \lambda^{\text{max}} \) is the maximum penalty coefficient, \( \mu \) is the penalty coefficient step, \( \epsilon_f \) is the tolerance for the objective function, and \( \epsilon_\delta \) is the tolerance for penalty. Note that the relaxed SOCP problem and the enhanced SOCP problem can be directly solved by the state-of-the-art SOCP solvers such as CPLEX.

5. Case study

To show how coupled gas-electric energy systems could respond to network damage, the modified Belgian networks are used as a study example in this paper. Their topologies are depicted in Figure 2, where the lower part represents the modified Belgian 380 kV electricity network and the upper part represents the modified Belgian high-calorific gas network. Note that larger nodes in the networks represent the nodes which have positive demand, while smaller nodes represent the nodes which have no demand and act as interconnections for the system. The data for the 380 kV electricity network are shared by Elia [45], the Belgian grid operator. The data for the high-calorific Belgian gas network could be found in [41, 42].

The gas network consists of six terminals and 21 pipelines, with three compressors maintaining the gas pressure within operating limits. The electricity network includes six generation nodes and 35 transmission lines. Three of the six generation nodes in the electricity network are gas-fired, and compressors between Voeren and Berneau are assumed to be electricity-driven. We assume these components get energy from the (geographically) neighboring nodes in the interconnected network. For the sake of clarity, we consider only one connection between every two nodes.

The demand data used here is based on the historical values provided by [41, 42, 45]. The total value of gas demand we consider here is 11,574 MW and that of electricity demand is 4,993 MW. Note that gas consumption has been converted from the unit of \( m^3 \) to kWh by a conversion factor of 10, following the tradition of Brussels [46]. Furthermore, we consider energy demand on average power with the unit of MW throughout this paper.

6. Results and discussion

In this section, we will first present the results of operational strategy impacts. Then, the cause behind the impacts of operational strategies will
be investigated, which reveals the phenomenon of cascading imbalance. The impacts of gas-fired generators and electricity-driven compressors will also be analyzed in this section.

6.1. Operational strategy impacts

To evaluate the impacts of operational strategies, we run the two operational models for different N-k failures that happen in either network. The failures we consider happen at either transmission lines or gas pipelines as they are highly exposed to potential threats and are often the real-world vulnerabilities [47]. For the sake of clarity, the disaster severity is defined as the number of damaged lines in each network.

We calculate the total cost by the independent response method and the joint response method when disaster severity varies from level-1 (i.e., N-1 failure) to level-10 (i.e., N-10 failure), which means 10 lines in the network fail at the same time. For each disaster severity, 100 scenarios are randomly generated, and we therefore have 1,000 scenarios in total for either operational strategy. The two operational models are run for each scenario,
and Figure 3 gives the simulation results for all these scenarios. To better compare the results, the LOWESS (i.e., locally weighted linear regression) curves for regression analysis are also provided in the figure.

![Figure 3: Total cost by different operational strategies.](image)

As Figure 3 illustrates, total cost of the joint response method is always lower than that of the independent response method. This indicates that the joint response method is preferable to the independent response method in almost all scenarios. In particular, the two operational strategies lead to largely different total costs when the system is less heavily damaged. For example, the average total cost by the independent response method is € 64.44 million when the disaster severity is level-1, while that by the joint response method is € 24.40 million. In other words, over 60% (on average) of the total cost by utilizing the independent response method could be saved if we apply the joint response method instead.

A more detailed analysis of the operational strategy impacts is conducted by researching the loss in each individual network. Both electricity loss and gas loss in the above 1,000 scenarios, which correspond to the cases in Figure 3, are provided in Figure 4. LOWESS curves are given in the figure to see the relationship between different response methods and also the trends.
As shown in Figure 4, electricity loss and gas loss of the joint response method are both always lower than those of the independent response method. Thus, it can be concluded that while the joint response method always sheds less electricity load, it also sheds less gas load for almost all disaster severities. This finding is interesting because it indicates that the independent response method, which we typically apply today, also engenders unnecessary loss in either individual network. As counterintuitive as it may seem, there is no need to sacrifice one network for the other if the paradigm shift from independent response method to joint response method is taken.

6.2. The phenomenon of cascading imbalance

To investigate the cause behind the impacts of operational strategies, we pick one scenario for detailed analysis.

The disaster severity is level-2 (i.e., N-2 failure, which means two lines in the network fail at the same time) and the damaged lines are colored yellow in Figure 5. Consider that we take the independent response method, Figure 5 illustrates the change of energy supply for each network in a sequence of time steps. Here by “time step” we distinguish the dispatch of different networks, and the sequence begins from the dispatch of electricity network because the electricity network has shorter response time. In Figure 5, the first sub-figure represents the initial state of the system, and the remaining sub-figures

Figure 4: Energy loss by different operational strategies. (a) Electricity loss. (b) Gas loss.

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The disaster severity is level-2 (i.e., N-2 failure, which means two lines in the network fail at the same time) and the damaged lines are colored yellow in Figure 5. Consider that we take the independent response method, Figure 5 illustrates the change of energy supply for each network in a sequence of time steps. Here by “time step” we distinguish the dispatch of different networks, and the sequence begins from the dispatch of electricity network because the electricity network has shorter response time. In Figure 5, the first sub-figure represents the initial state of the system, and the remaining sub-figures
indicate the change of energy supply after the independent response method is applied. The damaged lines are colored yellow, and the color red is used to highlight the node with load shed while the color orange indicates the node which will have further shedding in the following steps.

Figure 5: An illustration of the cascading imbalance process. (a) The initial state of the system. (b) The system state after the first-round dispatch of electricity network. (c) The system state after the first-round dispatch of gas network. (d) The system state after the second-round dispatch of electricity network. (e) The system state after the second-round dispatch of gas network. (f) The system state after the third-round dispatch of electricity network (till now, the system is re-balanced).
From the above figure, the phenomenon of cascading imbalance in the coupled energy system can be clearly seen. It is intuitive that cascading failure could happen if humans are weakly involved [39, 8, 48], however, the above results confirm that even though operators apply an optimal dispatch to the system, another cascading effect could occur provided that the independent response method is taken. We term this emerging cascading phenomenon as “cascading imbalance” because it is similar to the traditional notion of cascading failures but exists although humans are strongly involved (by optimal dispatch). During this cascading process, the imbalance propagates from the electricity network to the gas network and then vice versa repeatedly, until both networks reach balance again.

Figure 6 illustrates the cascading imbalance process for each energy demand intuitively. The innermost circle of nodes represents the initial state of each energy demand (with connections shown), and the outermost circle of nodes represents the ultimate state of each energy demand. The remaining circles in between illustrate how the imbalance propagates for each demand. Note that tiny nodes in each circle represent the nodes which have no demand and act as interconnections for the system.

Figure 6: Energy loss during the cascading imbalance process.

Figure 7 summarizes the energy supply in each time step. The dark blue represents the total gas supply in each time step and the light blue represents
the total electricity supply in each time step. Each bar here summarizes a
circle of nodes in Figure 6.

From Figure 6 and Figure 7, we can see again the cascading effect with
the time step increasing. When the coupled system is re-balanced in the end
step, only 7,180 MW energy can be supplied, which indicates that 9,387 MW
energy has to be shed by the independent response method. In contrast, if the
joint response method is implemented, 14,479 MW energy can be supplied
after this disaster scenario. In other words, 7,299 MW energy loss caused
by the independent response method, which accounts for 44% of the total
energy demand, could be saved if we shift to the joint response method.

6.3. Impacts of gas-fired generators and electricity-driven compressors

As previously mentioned, the interdependence of coupled systems might
be overlooked sometimes. To demonstrate the consequences, we run the
independent response method with the modeling of either dependence or both
dependence ignored. Figure 8 demonstrates the energy loss for each demand
in the above three situations. Herein, sub-figures (a)–(c) correspond to no
gas-fired generators modeled, no electricity-driven compressors modeled, and
neither gas-fired generators nor electricity-driven compressors are modeled,
respectively. Similar to Figure 6, the innermost circle of nodes in each sub-
figure here represents the initial state of each demand (with connections) and
the outermost circle of nodes represents the ultimate state of each demand.
The circles in between illustrate the intermediate states, and tiny nodes in
each circle represent the nodes which have no energy demand and act as interconnections for the system.

Figure 8: Energy loss when the modeling is insufficient. (a) No gas-fired generators modeled. (b) No electricity-driven compressors modeled. (c) Neither gas-fired generators nor electricity-driven compressors modeled.

Compared to Figure 6, Figure 8 has fewer circles of nodes in each sub-figure. In fact, it is intuitive that we can see no more than three circles of nodes (in addition to the innermost circle) if the coupled system is not modeled sufficiently, because the imbalance propagates between the networks through gas-fired generators and electricity-driven compressors. However, with the above interdependence within the coupled energy system, imbalance could propagate and therefore leads to an expanding circle effect as shown in Figure 6. This observation emphasizes the importance of proper modeling and indicates that the overlook of infrastructure interdependence will lead to misleading guidance for operating the coupled systems.

In the ultimate state for each sub-figure in Figure 8, 14,015 MW, 14,609 MW, and 15,741 MW energy in total can be supplied, respectively. Note that these are misleading results as the ripple effect of cascading imbalance has been ignored. On the other hand, the observation also inspires us that backup energy supply during disasters could alleviate the loss in the emergency state.

7. Conclusions

Research on cascading effects has traditionally focused on cascading failures that have the potential to exacerbate an initial shock and produce
large-scale blackouts. To avoid possible catastrophic failures, mitigation strategies are often required. However, another cascading effect we term as “cascading imbalance” will occur if the disasters are mitigated with no global visibility. To the best of our knowledge, this is the first attempt to identify and analyze this emerging type of cascading effect. Specifically, a framework is developed in this paper to compare the independent response method and joint response method when disasters happen, and the modified Belgian gas-electricity networks are used as an instance to show the cascading imbalance phenomenon. The results verify that the independent dispatch method will lead to a catastrophic cascade of imbalance and therefore greater loss not only in total cost but also in individual energy supply.

As modern energy systems remain largely separate and independently operated, this work has significant insights for system operators and policy makers. The findings reveal the risk of current energy policy and operation paradigm and recommend cooperation between different energy industries for the purpose of energy optimization and resilience enhancement. These results highlight the importance of transforming current energy management systems to integrated energy management systems, and also have wide implications for other interdependent systems, such as transportation systems, financial systems, and social systems. This paper will enhance our understanding of cascading effects and resilience enhancement, and stimulate wider research throughout interdependent systems.

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