Assessing the criticality of interdependent power and gas systems using complex networks and load flow techniques

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Abstract

Gas and electricity transmission systems are increasingly interconnected, and an attack on certain assets can cause serious energy supply disruptions, as stated in recommendation (EU) 2019/553 on cybersecurity in the energy sector, recently approved by the European Commission. This study aims to assess the vulnerability of coupled natural gas and electricity infrastructures and proposes a method based on graph theory that incorporates the effects of interdependencies between networks. This study is built in a joint framework, where two different attack strategies are applied to the integrated systems: (1) disruptions to facilities with most links and (2) disruptions to the most important facilities in terms of flow. The vulnerability is measured after each network attack by quantifying the unmet load (UL) through a power flow analysis and calculating the topological damage of the systems with the geodesic vulnerability ($\bar{v}$) index. The proposed simulation framework is applied to a case study that consists of the IEEE 118-bus test system and a 25-node high-pressure natural gas network, where both are coupled through seven gas-fired power plants (GFPPs) and three electric compressors (ECs). The methodology is useful for estimating vulnerability in both systems in a coupled manner, studying the propagation of interdependencies in the two networks and showing the applicability of the $\bar{v}$ index as a substitute for the UL index.

Keywords: Cascading failures, complex network theory, coupled power and gas flows, critical infrastructures, vulnerability.

Nomenclature

$e_{(i)}$	amount of gas demanded by the generator coupled at node *i*
$K_{0(i)}, K_{1(i)}, K_{2(i)}$	gas consumption coefficients of the generator coupled at node *i*.
$P_{G(i)}$	active power of the generator coupled at node *i*.
HP	compressor power.
n_{st}	compression steps.
n_p	polytropic coefficient.
$q_{G(i,j)}$	flow in the pipeline located between nodes *i* and *j*.
$T_{(i)}$	gas temperature at node *i*.
Z_{av}	gas compressibility factor.
η	compressor efficiency.
$\frac{p_{(j)}}{p_{(i)}}$	compression ratio.
$UL_{electrical\ network}$	unmet load on the electrical network.
P_{Di}^{LC}	active power demand in node *i* in the largest electricity network connected after each node removal.
Q_{Di}^{LC}	reactive power demand in node *i* in the largest electricity network connected after each node removal
P_{Di}^{BC}	active power demand in node *i* in the base case
Q_{Di}^{BC}	reactive power demand in node *i* in the base case.

$UL_{gas\ network}$	unmet load on the gas network.
D_i^{LC}	gas demand in node i in the largest gas network connected after each node removal.
D_i^{BC}	gas demand in node i in the base case.
$\bar{v}$	geodesic vulnerability.
d_{ij}^{LC}	geodesic distance between the node pair i, j of the coupled graph after removing a node.
d_{ij}^{BC}	geodesic distance between the node pair i, j of the coupled graph for the base case.

1. Introduction

On April 3, 2019, the European Commission published Recommendation (EU) 2019/553 on cybersecurity in the energy sector, which lists the main problems of energy infrastructures [1]. The recommendation indicated that natural gas and power systems are highly interconnected, which consequently a malicious act could cause catastrophic consequences, such as cascading failures that would result in a total or partial outage of the power supply [2]. Therefore, the Commission made an urgent exhortation to develop new methodologies that evaluate the joint performance of both integrated networks and provide analysis tools for transmission system operators (TSOs).

Gas and power networks are highly interdependent because of the high consumption of natural gas for electricity generation and for the electricity demand of the different facilities of the gas infrastructure. As an example, in Spain alone, approximately 25% of electricity generation depends on GFPPs, and 14 of the 19 ECs require a safe and reliable electricity supply [3], [4]. These numerous interactions could increase the potential risk of disturbances and make the systems very vulnerable since a disruption could spread among the common assets.

On the other hand, many countries are experiencing a major shift towards a low-carbon economy, making natural gas, in the short and medium-term, the best solution for replacing coal as a fuel for power plants and a necessary complement to renewable energy to guarantee the reliability of the power system. In addition, the gas can be produced as bio-methane, hydrogen or synthetic gas from various renewable sources. Also, the gas can be produced as bio-methane, hydrogen, or synthetic gas from various renewable sources. The International Energy Agency (IEA) forecasts that natural gas for electricity generation will increase until 2040 by incorporating existing and announced energy policies within a broad international perspective. In this regard, gas-fired power generation is growing, supported by the expansion of LNG markets [5].

Therefore, the joint operation of gas and power systems requires the development of robust models that increase the reliability of both infrastructures against various types of contingencies and operating conditions. Some of the papers consulted have addressed the above problem by modeling n-1 contingencies and considering the flow changes during failure events [6]–[9]. Other articles have instead proposed to evaluate the resilience conditions to decrease the load loss caused by deliberate attacks and reduce operating costs in both integrated systems [10], [11].

Similarly, the problem of planning the expansion of both networks is another issue that has been addressed in recent years [12]–[15]. Some of the prerequisites include a modeling approach that analyzes joint coordination, considers demand uncertainties, achieves an integrated operation between each facility, and promotes economical and reliable solutions. Additionally, the quantification of the impacts of malicious events, natural disasters, as well as the identification and protection of critical components, have been other hot topics of study [16]–[18]. In both cases, one of the main conclusions is that the natural gas system must be a priority because of its vulnerable radial topology [19].

The joint operation of power and gas networks is based mainly on electrical and hydraulic models that interact according to the external conditions; for that reason, other studies have focused on evaluating the adequacy and safety of gas and power flows in both infrastructure systems [20]–[22]. Contingencies, robustness, and cascading failures are some of the areas addressed in previous studies [23]–[25]. There is also a source that provides a more comprehensive review of other research on the integrated operation of gas and electricity infrastructures [26].

On the other hand, certain works apply the graph theory approach to evaluate the overall performance of critical natural gas and electricity infrastructure systems against different types of attacks and failures. These networks can be modeled as a set of nodes and links to study the inherent structural characteristics of these infrastructures [27]. Documents based on these representations generally use indices that consider the topologies and technical parameters of the systems, such as clustering, geodesic distances, degree of connectivity and network efficiencies [28]–[30]. Some other articles consider generator capabilities, loads on nodes, and flows on lines [31], [32].

In the same way, scholars combine graph theory with risk assessment methodologies, stochastic models and optimization methods to assess structural vulnerability and analyze the impact of topology on the propagation of cascading failures [33]–[37]. Similarly, researchers incorporate load flow studies and Monte Carlo simulation techniques with the different graph measures described above [38]. These methods are useful for quantifying the degree of impact on infrastructure and for carrying out resilience studies against natural disasters and terrorist attacks [39].

The graph approach is also accurate for measuring the impact associated with disruptions in gas supply and determining the degree of robustness of transmission systems [40]. In this sense, some network-based studies use the technical capabilities of systems to assess reliability indices, identify critical nodes and links, analyze bottlenecks and evaluate the implementation of new infrastructure [41], [42].

To respond to the initial intent of recommendation (EU) 2019/553, this study concerns the vulnerability of coupled gas and electricity networks by developing and proposing a common framework based on cascading failures. Vulnerability is defined as the performance drop of the integrated system as a result of disturbances or disruptions. The simulation framework uses coupled load flows and a novel graphs approach to demonstrate the effectiveness of the latter [43]. Cascading events originate from two different actions: (1) deliberate attacks on facilities with numerous links and (2) deliberate attacks on the most important facilities in terms of flow. The above events could represent terrorist attacks, cyber-attacks, and malfunctions of protective devices, among others. In addition, the algorithm takes into account the propagation of interdependencies caused by the outage of four assets during the network decomposition process: (a) GFPPs that are highly dependent on the fuel delivered from the gas network, (b) ECs that depend on the power supplied by the electrical grid, (c) connecting pipelines between GFPPs and gas nodes and (d) the electric transmission lines between ECs and substations.

The methodology also incorporates the electrical and hydraulic models along with new topological representations of both systems constructed based on graph theory. The network technical models are used to determine gas and power flows in the infrastructures. The linear-analog transformation approach is used to find the solution to coupled flows using the AC power flows combined with the linear-analog concept, as shown in the literature [44]. The latter yields a more accurate study of the possible behavior of both integrated systems when subjected to disruptive events. Performance drops of the separate and joint networks during the decomposition iterations are quantified using UL and $\bar{v}$ measures, which have already demonstrated their application in electrical networks [45], [46]. These indices are used to compare the results and demonstrate that the $\bar{v}$ index is useful for determining the unmet load (UL) during cascading events, using only the connectivity of the infrastructures. The simulation is run in a flexible environment, easy to implement in other infrastructures.

The rest of this paper is organized as follows. In Section 2, the electrical and hydraulic network models and the topological representation proposals based on graph theory are described. In Section 3, the integrated simulation framework proposal to study the performance of the gas and power networks against n-x contingencies is described in detail. In Section 4, the case study based on the IEEE 118 bus test network coupled to a 25-node natural gas network and three compressors is described, and the results are discussed. Finally, the conclusions are presented in Section 5.

2. Natural gas and power networks representation

In this section, the power and hydraulic models related to the gas and power systems and the topological representations constructed using complex networks theory are described. The two networks are modeled as an interconnected graph composed of a set of vertices or nodes denoted by $\mathscr{M} = \{1, \dots M\}$ and a set of links or edges denoted by $\mathscr{B} = \{\beta_1, \beta_2, \dots, \beta_n\}$. Each link $\beta_n \in \mathscr{B}$ is associated with a pair of nodes (i_n, j_n), such that $i_n, j_n \in \mathscr{M}$, where $i_n \neq j_n$.

2.1 Electrical and topological models of power networks

The power system is the critical infrastructure for the transmission of power produced at the generation points to the final consumers or users through the transmission networks. The transmission system consists of buses that represent generation and load points, and links that represent transmission lines and transformers. The electrical model is used in the load flow studies to determine power flows and losses in the transmission elements, active and reactive power injected by generators and loads, and bus voltages and angles, under certain input parameters. Some traditional load flow analysis techniques can be found in the literature [47]. The above results help the TSO evaluate the operating conditions or stress of the power network and determine the actions necessary to achieve safe and reliable operating conditions.

On the other hand, the topological model proposed in this paper is designed to provide a realistic representation of the electrical infrastructure and its assets, unlike other graphs used in the scientific literature that omit many network components [25],

[28]. The proposal of using a more thorough topological graph facilitates vulnerability studies because all assets are incorporated into the network topology mapping. In Fig. 1, the traditional electrical model compared to the proposed topological graph constructed using graph theory is shown. The illustration corresponds to the well-known IEEE 39-bus test system is illustrated, which represents the 10-machine New-England Power System [48].

It should be noted that all assets of the electrical model are included in the proposed graph; each one represented by a node. In this representation, power lines, loads and generators are also drawn as nodes. Thus far, the graphs used have been straightforward because only the buses and lines are considered, and the remaining network elements are disregarded.

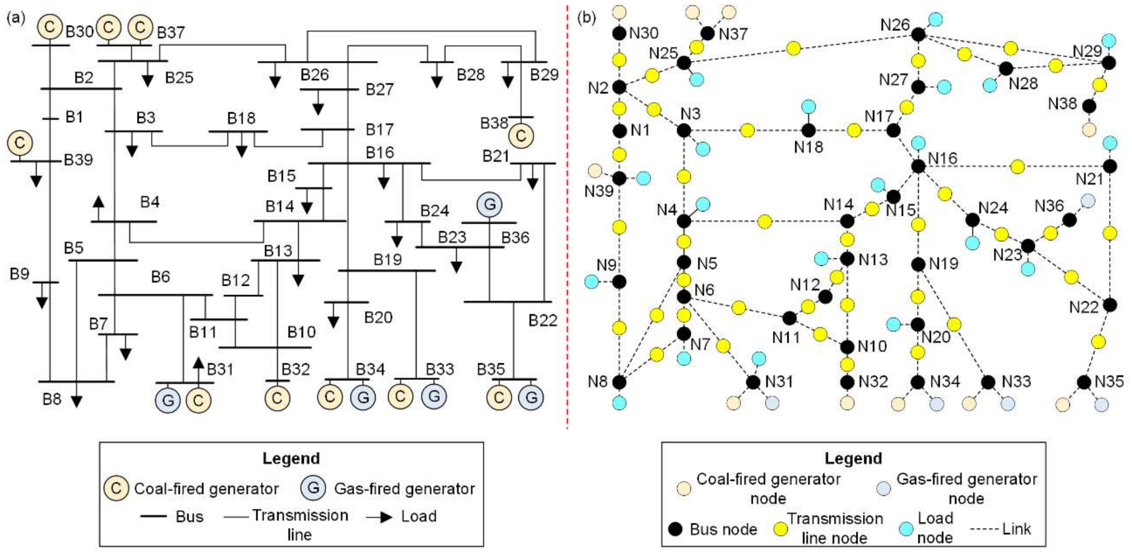

Fig. 1. (a) Traditional electrical model and (b) proposed topological graph. All assets of the electrical model are incorporated as nodes in the proposed graph.

2.2 Hydraulic and topological models of gas networks

The gas infrastructure is the network that transports natural gas fuel for industrial and commercial use, as well as for electricity generation in combined-cycle power plants. The hydraulic model is primarily composed of nodes, which represent the points of gas injection (supply) and demands, and links which represent pipelines and compressors. The gas flow problem is modeled with mathematical equations that describe the physical characteristics of the pipe, fluid compositions, physical characteristics of compressor stations, etc.; these enable the determination of pipeline flows and pressures at different points of the network [49], [50]. The techniques most commonly used for solving the above equations can be found in the literature [51]. Therefore, the operator of these networks always runs a model to determine the optimum operating conditions in the infrastructure.

In Fig. 2, the traditional model of a gas infrastructure compared to the proposed topological graph representation is shown [52]. Similar to the electrical infrastructure graph, the proposed network takes into account each of the assets of the gas infrastructure. Gas supplies, loads, compressors, pipelines, etc., are represented as nodes, unlike traditional representations that do not take these into account [25].

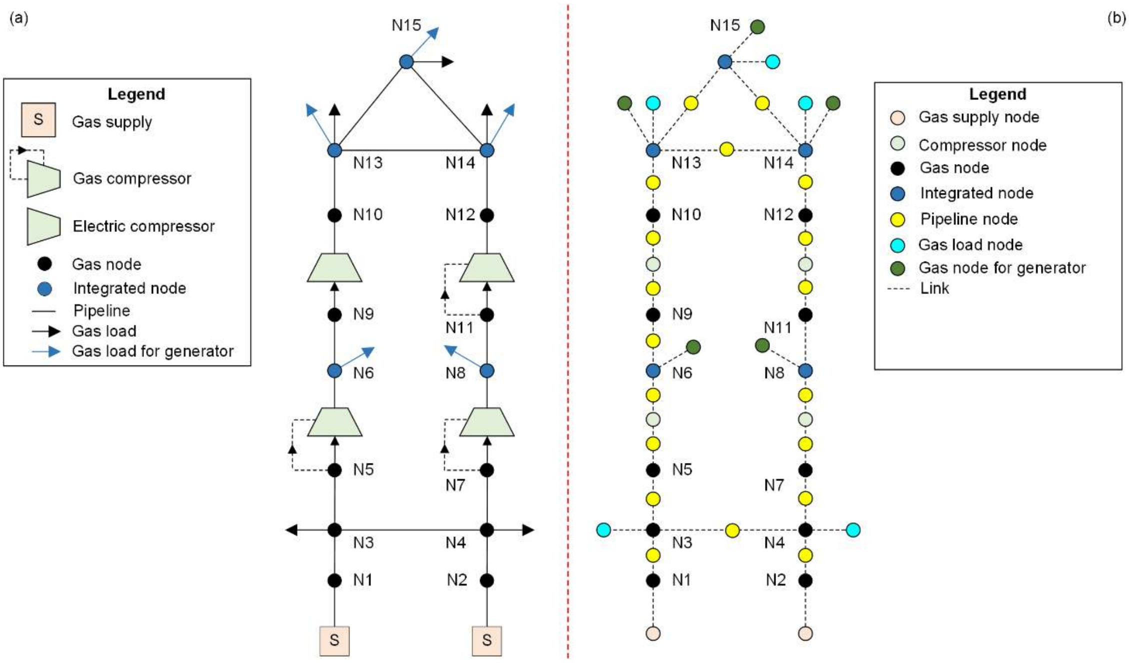

Fig. 2. a) Traditional gas model and b) proposed topological graph. All traditional model assets are incorporated as nodes in the proposed graph.

2.3 Coupled gas and electricity network modeling

In daily operation, these infrastructures interact through specific facilities or assets that require a constant exchange of information on the operating conditions. In the case of the gas system, compressor stations are needed at points of the network to compensate for pressure drops caused by the frictional effect of the inner walls of the pipes. The compressor stations can operate with either an external power supply or a gas-fired electricity supply.

Simultaneously, certain generators of the power system require sufficient natural gas fuel to achieve the electricity production quota generation. These interactions are modeled with equations that describe the power consumption of the compressors and the gas consumption of the generators [22], [44]. In this study, it is assumed, for simulation purposes, that coupling occurs primarily in the two facilities mentioned above. A more detailed description could be included in future models.

In this way, the coupling between the two infrastructures is obtained by combining the established flow models and considering the links between both systems through gas-fired power plants connected to gas pipelines and compressors fed by electricity. On the one hand, the coupling of gas generators is mathematically formulated using eq. (1). This expression, called heat rate curve, represents the conversion efficiency of the energy contained in natural gas into electrical energy. The natural gas consumption of the generators is related to the active power and natural gas available at the integrated node of the gas infrastructure [44].

$$e_{(i)} = K_{2(i)} P_{G(i)}^{2} + K_{1(i)} P_{G(i)} + K_{0(i)} \quad (1)$$

On the other hand, the power consumption of compressors to increase gas pressure is related to compression steps, compressor efficiency, and natural gas properties. This relationship is mathematically expressed in eq. (2) [44].

$$HP = 0.0857 \frac{n_{st} \cdot n_p}{n_p - 1} q_{G(i,j)} T_{(i)} Z_{av} \left(\frac{1}{\eta}\right) \left[\left(\frac{p_{(j)}}{p_{(i)}}\right)^{n_p - 1/n_{st} \cdot n_p} - 1 \right] \tag{2}$$

This paper uses the linear-analog transformation approach to solve the set of nonlinear equations that represent the state variables of the two networks [44]. The above procedure simultaneously applies the Newton-Raphson method and the linear-analog concept. The first one determines the solution of the power system equations to calculate the magnitudes and phase angles of the voltages in each bus, as well as the active and reactive powers flowing in each transmission line. Meanwhile, the second one provides the solution of the gas system equations to determine the pressures in the nodes and the flow rates in the pipelines. All the above is executed within an iterative framework to accurately assess the joint operation of the coupled infrastructure against cascading failures. A more detailed analysis of the approach can be consulted in reference [44].

The proposed coupled graph incorporates the topological networks of Figs. 1 (b) and 2 (b), linking them with couplings at the compressor stations and gas-fired power plants. The resulting model is shown in detail in Fig. 3. It should be noted that, unlike in the literature [25], the topological representation developed and proposed in this study is more accurate because the detailed graphs of both networks are included and the interconnections are represented. This representation is very useful for vulnerability studies, as shown in other sections.

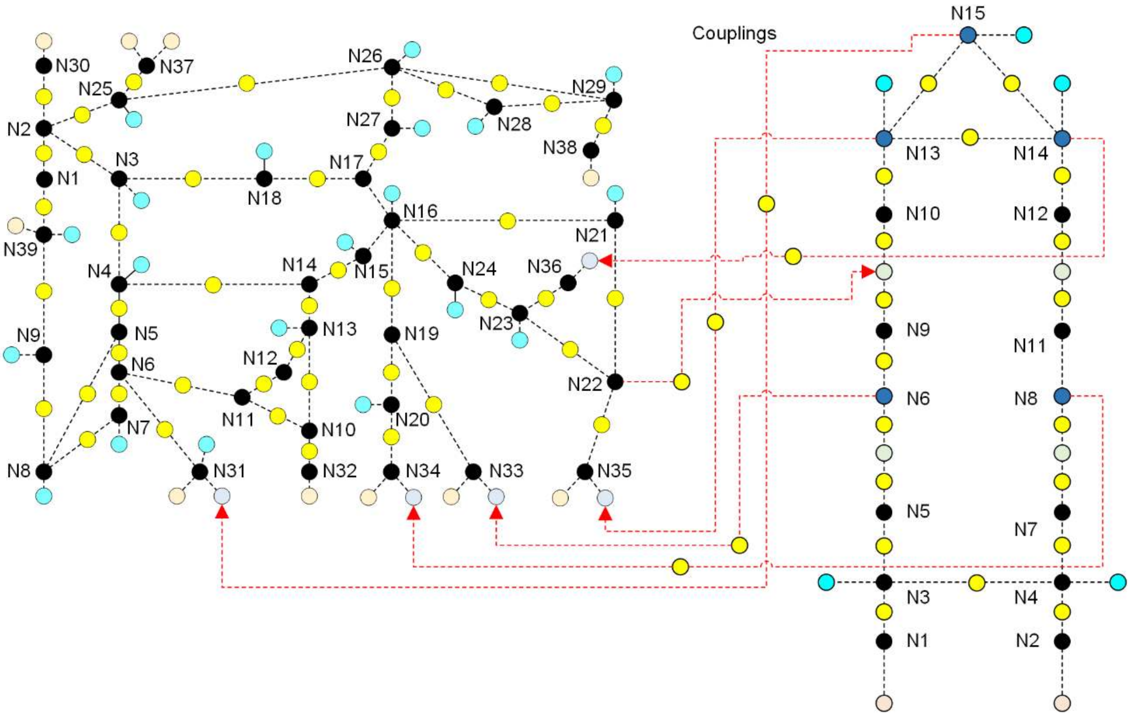

Fig. 3. Proposed coupled topological graph. The interconnection links are represented as nodes.

3. Proposed integrated simulation framework

Power system security is the ability of the electrical network to withstand sudden disturbances or contingencies. This definition considers several categories along with their corresponding indicators such as adequacy, quality of supply, stability, reliability, tension, collapse, among others.

On the one hand, reliability indices are traditionally used to evaluate n-1 or n-2 contingencies, analyzing the continuity of power grid operations in case of failure or disruption of an asset by means of metrics such as the frequency and duration of power outages, loss of load expectation, loss load of probability, expected energy not supplied, etc. On the other hand, vulnerability indices are used to study and quantify the weakness of the power grid against n-*x* contingencies (i.e., cascading failures), generally using load flow studies [43], [53].

Graph theory is a widely accepted method for modeling cascading failures in power and gas systems. This technique represents infrastructures as a coupled graph to analyze the relationships between assets and cascading events through centrality measures [43]. Some indices show a strong correlation with the unmet load during cascading failures and others characterize the structural vulnerability of the topologies [45].

In this section, the proposed simulation procedure to assess the vulnerability of coupled gas and power networks to cascading events is described. The simulation framework uses the electrical and hydraulic models as well as the topological representations of both systems combined. In summary, the algorithm models both infrastructures as an interconnected graph of nodes and links, calculates electricity and gas flows in a coupled manner according to the technical models, uses two different attack strategies for the networks, simulates cascading failures and interdependence propagation, and quantifies the performance drop of the joint system through the unmet load (UL) and geodesic vulnerability ($\bar{v}$) indices. The results obtained with both indices are compared at the end of the study. The simulation framework was built in the MATLAB® programming environment.

3.1 Architecture of the simulation algorithm

The proposed algorithm provides a flexible simulation tool to estimate cascading failure propagation in both systems combined. The architecture is built with five modules that interact sequentially throughout the simulation process, shown in detail in Fig. 4.

Module one constructs the coupled graph using the interconnection topologies of the gas and electricity networks according to the description given in Section 2; module two estimates the interdependent power and gas flows in a stationary state based on the input data and the load profiles of both systems; module three determines the nodes that should be disrupted based on two different attack strategies; module four simulates cascading failure propagation and interdependencies; and finally, module five quantifies network damages during the cascading disintegration stages.

In summary, the algorithm evaluates the criticality of the integrated power and gas networks through the evolution of the unmet load (UL) and geodesic vulnerability ($\bar{v}$)

indices, measured as a function of the fraction of removed nodes (*f*). For illustration purposes, the algorithm uses natural gas and power test systems, which are coupled with interdependent links that represent the relationships between the two infrastructures. It is assumed that the power network has *m* gas generators fed from *n* nodes of the gas system and that the gas network has *p* compressors fed from *q* buses of the power system. The algorithm uses the electrical and hydraulic models of both systems to build the scale-free graphs according to the representations proposed in Section 2 and to solve the coupled load flows problem using the linear-analog transformation approach [44].

Cascading failure simulation is carried out using two different removal strategies such as the disruptions to assets with most links and the disruptions to the most important assets in terms of flow. Cascading effects are modeled by removing the nodes one by one from a coupled network that continually changes its structure with the removal of each asset. Simultaneously, the algorithm builds scale-free graphs and runs the coupled flows to measure all system state variables and quantify the UL and $\bar{v}$ indices in separate and integrated networks during each disintegration step, i.e., each time a node is removed. The $\bar{v}$ measure is calculated using Bellman-Ford's shorter path algorithm [54].

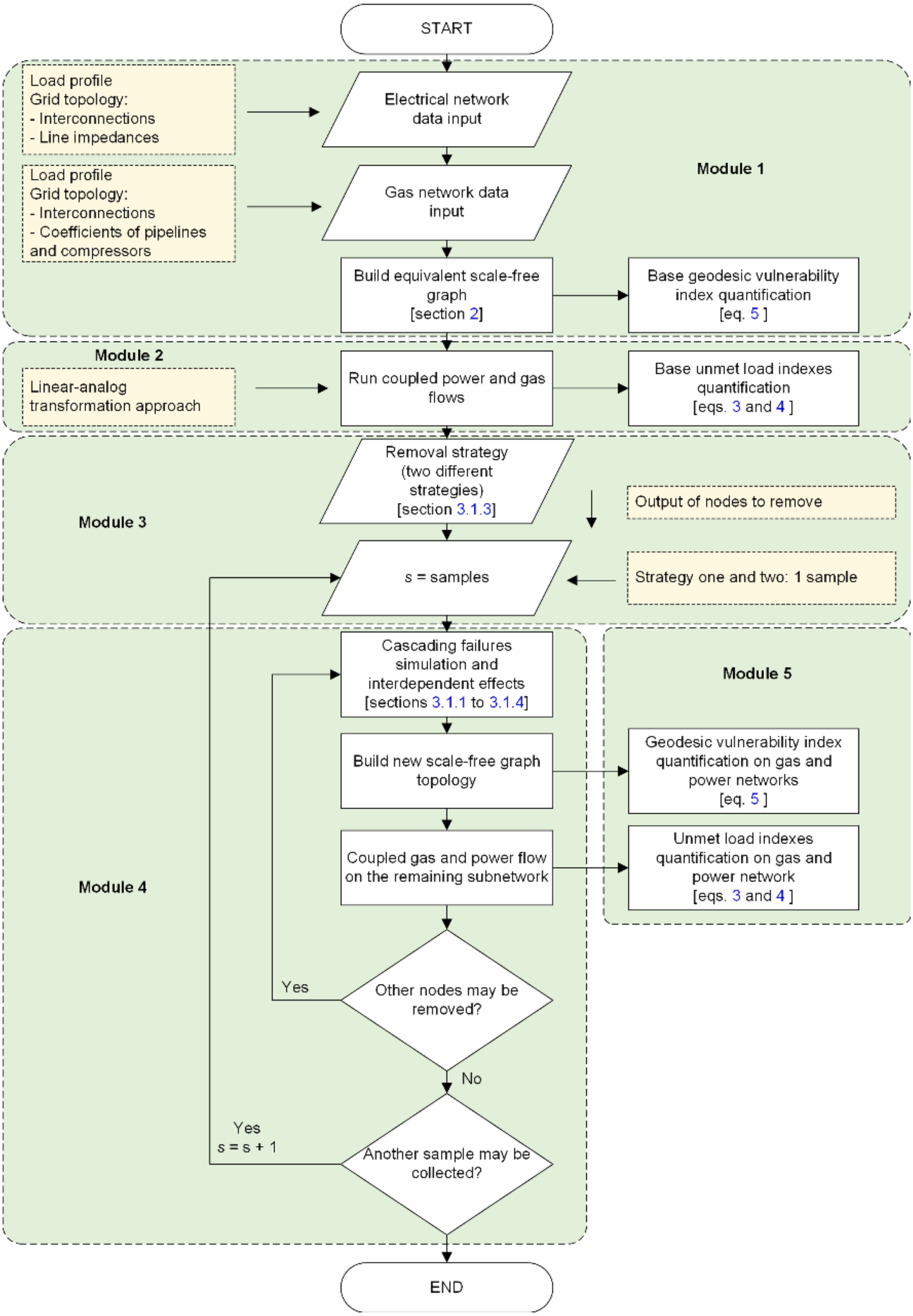

Fig. 4. Architecture of the simulation algorithm to quantify cascading failures in joint gas and power systems.

3.1.1 Module one. Interdependent gas and electricity networks

This module builds the proposed coupled graphs using the connectivity data collected from the networks. The output of this module is a topological representation with nodes and links that shows in detail each asset within the studied infrastructure according to the specifications in Section 2.

3.1.2 Module two. Coupled gas and power flows

The simulation framework uses the electrical and hydraulic systems information as input data to solve the integrated gas and electricity flows. This study uses the novel linear-analog transformation approach to process the data and solve the various equations that govern both systems [44]. This approach uses the Newton-Raphson method to study the power flows, combined with the linear-analog concept for the gas flows problem.

The inputs used in this method are the electrical loads at the nodes, the bus types (PQ, PV and Slack), the natural gas consumption data of the GFPPs, the impedance parameters of the power lines and the interconnections between each network component. It also uses data on the fluid composition, the gas demands, the gas node types (load, pressure-defined, compressors, supply, and gas-electricity coupled), the technical features and the connectivity of the compressors and the pipelines. The model also takes into account the coupled GFPPs and ECs to determine the fuel consumption of the generators and electricity for the compressors.

3.1.3 Module three. Node disruption

Gas and electricity networks may face dangers and threats such as cyber-attacks and terrorism, which could cause the loss of essential elements and compromise the combined operation of the two systems. To respond to the initial recommendation (EU) 2019/553, in this study, two node disruption strategies are incorporated to simulate a network decomposition process and quantify the destructive effects the combined infrastructures could experience. The strategies are as follows:

1. *Disruption of assets with most links*: remove, in descending order, the nodes with the most connections, namely, the nodes with many adjacent lines are removed first.
2. *Disruption of the most important assets in terms of flow:* eliminate the assets according to their degree of interlinking. A node with too many interlinks is one that has great control over the network because large amounts of flow go through it. To determine the degree of interlinking, the node betweenness index is used, as shown in the literature [55].

These two strategies are proposed because they are easy to calculate since network connectivity is all that is required. Regarding this, it is well-known that in many countries around the world, and particularly in the European Union, the topological data of their infrastructures are public; therefore, a malicious person could rapidly use that data for harmful purposes [56]. In this paper, two strategies are proposed to attack the assets of the gas and electricity infrastructure. In the first one, assets are removed according to the number of connections with other assets; namely, the assets with the most links are removed first and then the others follow in order. In the second strategy, the assets are deleted depending on the amount of electricity or gas passing through them, attacking first those with the most energy flows.

The output of this module consists of a vector the assets of the coupled system that must be removed during network disintegration.

3.1.4 Module four. Simulation of cascading outages and interdependent effects

Cascading events are simulated by removing each of the nodes contained in the output vectors of module three. The continuous removal of these assets might disintegrate the entire network on islands; therefore, this module incorporates a graph transversal algorithm based on the depth-first search (DFS) procedure to check the topology of the net in each iteration [57]. Each time a node is removed, the DFS algorithm identifies all subgraphs that are formed.

The islands may or may not have gas generation and supply, which would not allow the processing of coupled load flows. To avoid this condition, it is assumed that the nodes that represent the generator, the slack bus, the reference gas supply node and the node that represents the coupling link between the slack generator and the gas network cannot be removed. These nodes are shown in red in Figs. 5 - 7. This approach enables the creation of a single graph, where the joint gas and power flows can be executed together.

On the other hand, the operation state of a network could be affected by events that occur in the other coupled infrastructure from their interdependent operation; it is, therefore, necessary to reflect these interactions on the integrated graph. The proposed simulation framework assumes that four assets could generate interdependencies towards one or the other network as follows:

1. *Gas-electricity nodes*: the disruption of assets that supply fuel to the GFPPs produce interdependent effects on the electrical grid, namely, the loss of the coupled electrical generator. Fig. 5 reflects the propagation in the electrical infrastructure caused by the gas node outage, where the links of the gas, pipeline and generator nodes are eliminated.

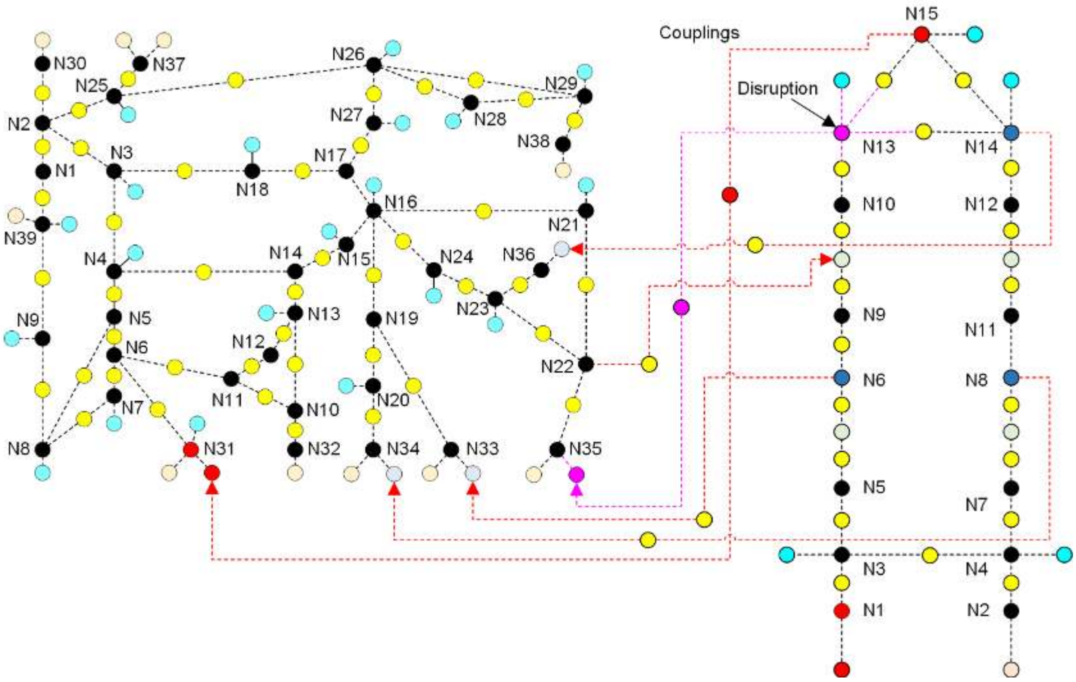

Fig. 5. Representations of the interdependent effects on the integrated gas and power systems. Interdependence towards the electricity network is from disrupting gas node N13. The removed links are identified with pink dotted lines.

2. *Substation-compressor nodes*: disruption of the electrical substations that supply electricity to the ECs causes interdependent effects on the gas network, namely, the loss of the coupled electric compressors. Propagation within the joint graph results in the removal of the substation, the power line and the coupled compressor node, as shown in Fig. 6.

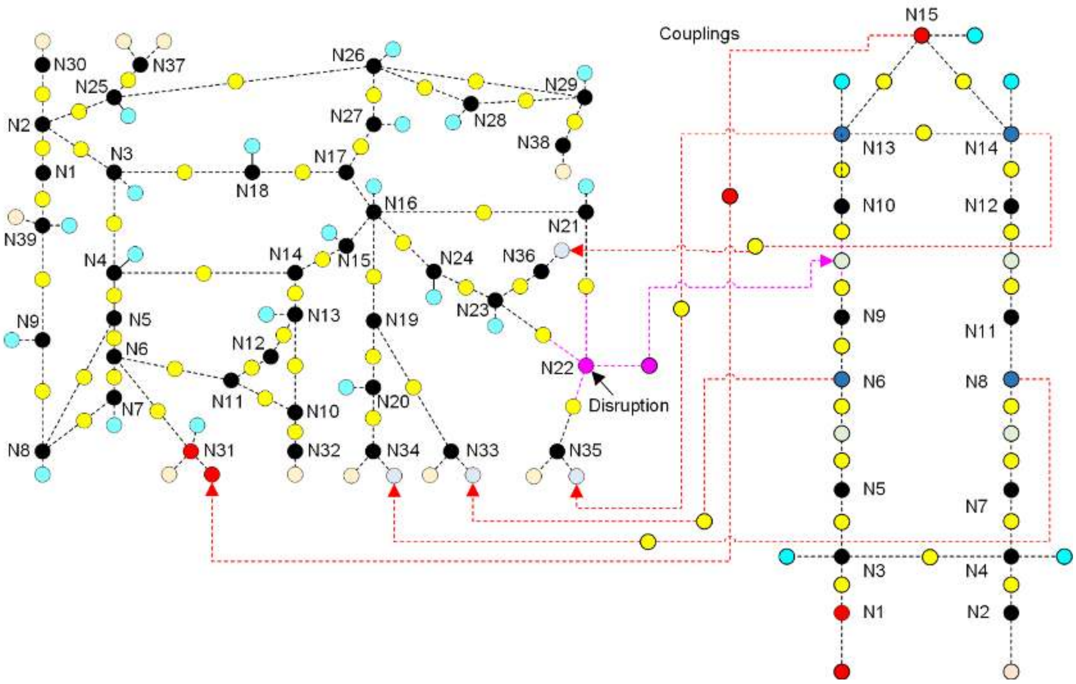

Fig. 6. Representations of the interdependent effects on the integrated gas and power systems. Interdependence towards the gas network is from the disruption of electrical substation N22. The removed links are identified with pink dotted lines.

3. *Coupled pipeline nodes*: the pipelines outage that transport natural gas to the coupled generators could affect the operation of the electricity network. In Fig. 7, this effect is represented by the elimination of the links of the attacked and coupled generator node (disruption (a)).
4. *Coupled transmission line nodes:* Same as the above, the removal of the lines that supply electricity to the coupled compressors could affect the operation of the gas network. In Fig. 7, this effect is represented by the elimination of the links of the node representing the transmission lines, as well as the coupled compressor (disruption (b)).

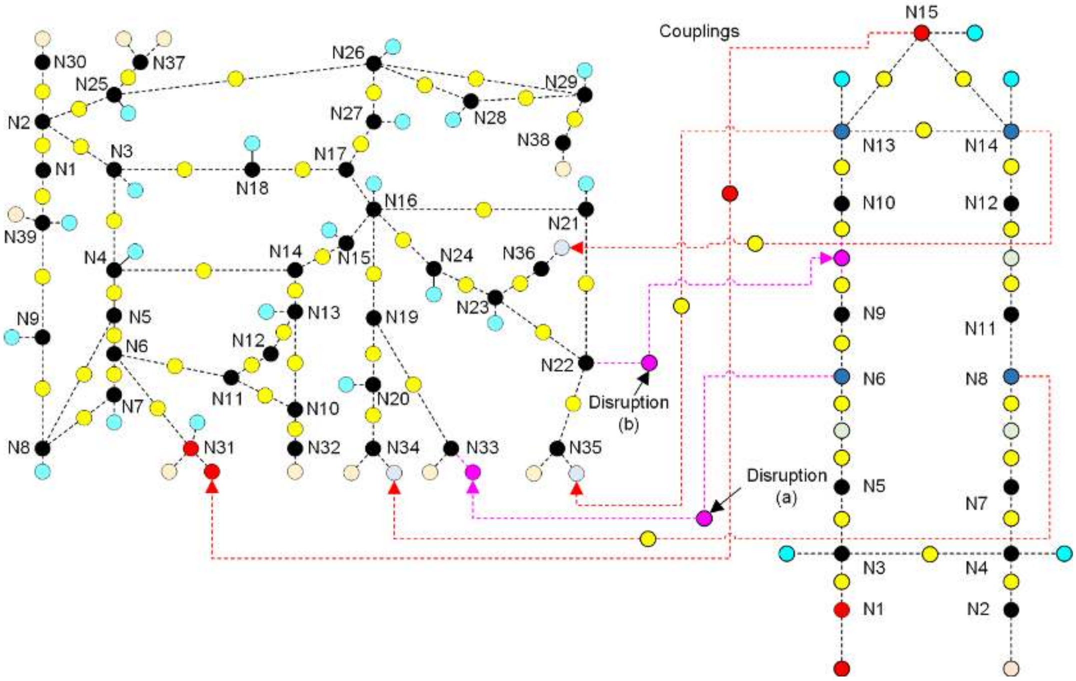

Fig. 7. Representations of the interdependent effects on the integrated gas and power systems. (a) Interdependence towards the electricity network from gas line loss and (b) interdependence towards the gas network from transmission line loss. The removed links are identified with pink dotted lines.

The output of this module is a sorted topological graph that takes into account the parameters and connectivity of the networks, but without the elements that were attacked and removed by the interdependent effects.

3.1.5 Module five. Vulnerability assessment of the coupled system

One of the main concerns, when a coupled infrastructure is damaged, is determining the amount of unmet load and quantifying the topological damage caused by such events. This paper uses the UL and $\bar{v}$ measures as the primary indicators to measure damage.

On the one hand, given the different measuring units between electrical loads and gas demand, it is assumed that gas demands must be homogenized with its electrical equivalent, which is determined according to the heating power, pressure and operating temperature of each network node [58]. In this study, 1 m^3= 11.63 kWh in all gas network loads. This measure is calculated as follows:

For the electricity subnetwork,

$$UL_{electrical\,network} = 1 - \frac{\sum_i \sqrt{\left(P_{Di}^{LC}\right)^2 + \left(Q_{Di}^{LC}\right)^2}}{\sum_i \sqrt{\left(P_{Di}^{BC}\right)^2 + \left(Q_{Di}^{BC}\right)^2}} \tag{3}$$

For the gas subnetwork,

$$UL_{gas\,network} = 1 - \frac{\sum_i D_i^{LC}}{\sum_i D_i^{BC}} \tag{4}$$

On the other hand, the $\bar{v}$ index is used to balance the network decomposition process. This index is calculated as follows:

$$\bar{v} = 1 - \frac{\sum_{i \neq j} \left(\frac{1}{d_{ij}^{CG}}\right)}{\sum_{i \neq j} \left(\frac{1}{d_{ij}^{BC}}\right)} \tag{5}$$

The geodesic distance is the shortest distance between two nodes, calculated by counting the minimum number of nodes that must be crossed to join them [59]. This measure is calculated using Bellman-Ford's shortest path algorithm [54].

These measures are well-documented in other studies [45], [46].

4. Vulnerability assessment of the integrated gas and electricity networks

This section assesses the vulnerability of the coupled gas and power systems using the proposed study framework based on cascading failures and propagation of interdependencies. The coupled network is subjected to two different attack profiles: a) attacks on highly connected assets and b) attacks on assets crucial to flow transmission. The vulnerability is measured for each strategy, quantifying the *UL* (eqs. 3 and 4) and $\bar{v}$ (eq. 5) at every disintegration step. These indices vary between 0 and 1, where 0 represents the case where the entire load is met and the network topology is connected and 1 represents the case where all loads are disconnected and the topological structure is disintegrated, representing total operational failure of the systems. In reality, the elimination of all elements is unlikely; however, this behavior generalizes researchers' attempts to study vulnerability.

The proposed simulation framework is run under platform MATLAB 2018b, using a personal computer with an Intel Core ™ i7 processor, 3.40-GHz CPU and 32 GB of RAM.

4.1 Case study description

Numerical experiments are conducted on a coupled infrastructure consisting of the IEEE 118-bus test system, and a 25-node natural gas network and three compressors. The power system is a simple approximation of the American Electric Power System in the U.S. Midwest, and the natural gas system is similar to the high-pressure network in Belgium [51], [60], [61]. In Fig. 8, the case study is shown in detail.

The integrated system contains 35 synchronous condensers, 177 transmission lines, nine transformers, 91 loads, and 19 generators, of which 7 are gas-fired plants, and 12 are coal-fired generators. It also contains 35 pipelines, three compressors, 18 nonelectric loads, and one gas supply. The technical data for these networks are collected from the literature [51], [60]. Table 1 shows other technical parameters considered in the case study.

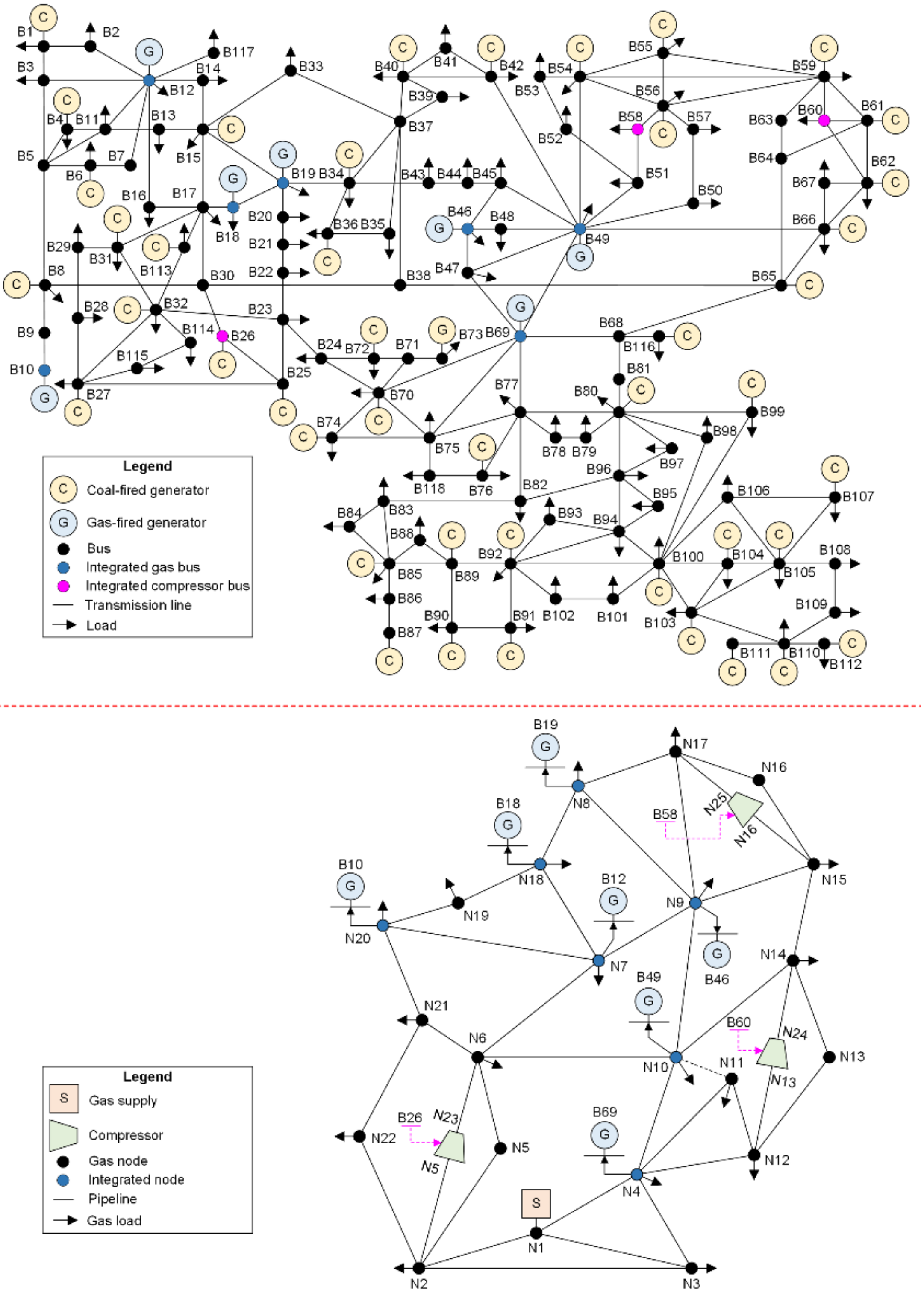

Fig. 8. Topologies of the gas and electricity networks under study.

Table 1. Technical parameters of the case study.

Gas network	
Gas flow equation	Weymouth
Node one	Supply
Average gas temperature	520 °R
Average compressibility factor	0.90
Specific gravity	0.69
Pipeline position	Horizontal
Pipeline efficiency	1.0

Compressors	
Consumption factor	199.92 SCFD/HP
Suction temperature	535 °R
Average compressibility	0.90
Polytropic coefficient	1.4
Steps	1
Compression ratio	1.8
Efficiency	0.90
Generators	
Gas consumption coefficient	$K_{0(i)}$ = 0 $K_{1(i)}$ = 0.00516 $K_{2(i)}$ = 0

4.2 Results and discussion

In Fig. 9, the different plots that represent the performance drops of the integrated gas and power networks once the cascading failures occur are shown. These graphs contain vulnerability curves that are measures of electrical and hydraulic damage (unmet load) and topological damage (loss of nodes and links) against different attack strategies, measured based on the fraction of assets removed (*f*). In Figs. 9 (a) and (c), the results obtained with the UL measure, while the results obtained with the $\bar{v}$ measure are shown in Figs. 9 (b) and (d). The behavior of the gas and electricity networks in a separate manner is also shown.

The results show that the coupled and separate systems are very vulnerable to deliberate events such as attacks on strongly connected facilities, since the elimination of 8% of the nodes is sufficient to produce a quick blackout, as evidenced with strategy 1 in Fig. 9 (a). Similarly, attacks on the critical assets in terms of flows, as in strategy 2, is also harmful to the integrated and separate infrastructures since the elimination of 9% of the nodes is detrimental to the supply of gas and electricity, as shown in Fig. 9 (b). However, a comparison of the two attack profiles shows that strategy 1 is more efficient that strategy 2 to lead to a widespread blackout more quickly. Therefore, it is essential to protect those facilities that are highly connected to ensure correct operation in contingency conditions.

The plotted results also show that the electrical system is vulnerable to the propagation effect of interdependencies and disruptions, which reduce network performance once cascading failures begin. Contrarily, gas transmission dynamics result in a less vulnerable gas infrastructure, which suggests that, if the fault is stopped on time, the operation of the natural gas network could remain intact.

On the other hand, we propose the $\bar{v}$ measure to estimate the damages in the separate and joint networks, using only the connectivity of the infrastructures. This index has already been used and validated in other documents to quantify the structural vulnerability of power systems against cascading failures [45]. Due to the above, we extend this indicator to the interdependent gas and power networks and verify if there is a correlation between the UL and $\bar{v}$ results.

Using the results shown in Figs. 9 (a) and (b) as an example, the normalized values of geodesic vulnerability for the three curves are graphically very similar to those obtained with the load flow process (UL index). Likewise, the trend shown in Figs. 9 (c) and (d) does not change, although in these cases the behavior of the $\bar{v}$ index is slightly higher than the UL index. However, the results are satisfactory and intuitive because $\bar{v}$ determines the degree of network vulnerability, but without using the technical parameters of the infrastructure studied.

More evidence that shows that $\bar{v}$ measure is similar to the UL measure is the Pearson correlation coefficient calculation [62]. This calculation is used to measure the degree of relation between two variables; it's range is [-1,1], where -1 indicates a perfect negative correlation, 0 indicates no correlation and 1 indicates a perfect positive correlation.

Table 2 lists the Pearson correlation coefficient results between each pair of curves in Figs. 9 (a) and (b), and each pair in Figs. 9 (c) and (d). The coefficients are greater than 0.9 in all cases, which implies a positive linear relationship between the results of the UL and $\bar{v}$ curves. This means that $\bar{v}$ is useful to calculate the unmet load in a cascading failure process.

Therefore, the analysis of the results produces the conclusions already obtained graphically, where the comparison between the UL and the $\bar{v}$ indices for Figs. 9 (a) and (b) shows that the results are very close to each other, while for Figs. 9 (c) and (d), the results vary slightly; however, the variations are very acceptable because only network connectivity is taken into account. This confirms again the suitability of graph theory and, in particular, of the proposed $\bar{v}$ index as a good substitute of the UL measure obtained with coupled gas and electricity flows.

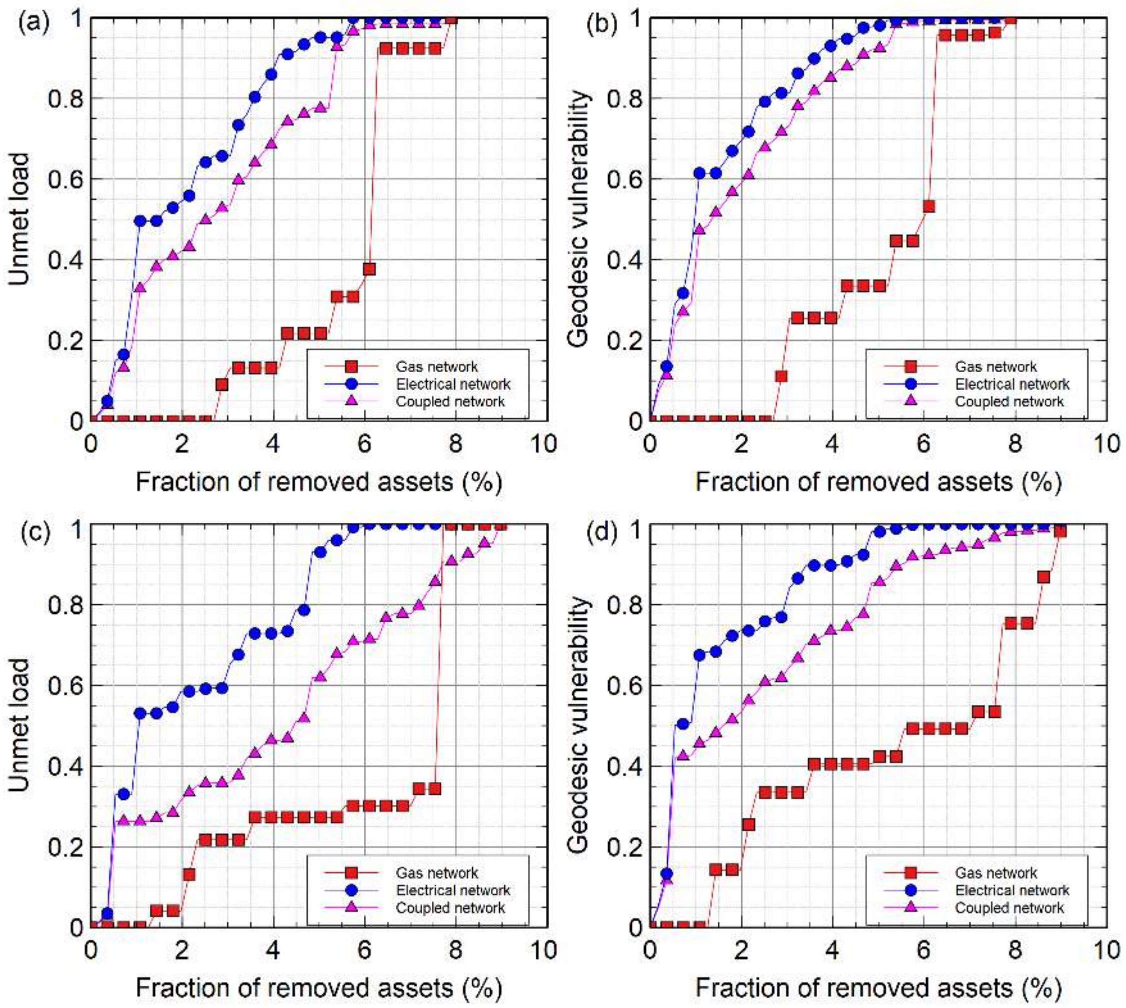

Fig. 9. Cascading failures simulation results in the integrated gas and power network under study. (a) - (b) Strategy 1. Disruptions of the facilities with the most links; (c)-(d) Strategy 2. Disruptions of the most important facilities in terms of flows.

Table 2. Pearson correlations between UL and $\bar{v}$.

Attack strategy	Networks	Pearson correlations (UL and $\bar{v}$)
Strategy 1	Power system	0.983
(Figs. 9 (a)-(b))	Gas system	0.987
	Coupled system	0.975
Strategy 2	Power system	0.964
Figs. 9 (c)-(d)	Gas system	0.915
	Coupled system	0.952

5. Conclusions

This article has proposed a simulation framework for assessing the vulnerability of integrated power and gas systems, where cascading failures and interdependencies have also been taken into account. The case study has consisted of a combined test system composed of the IEEE 118-bus system and a 25-node gas network with three compressors. The developed procedure has incorporated the technical parameters of the networks, as well as new topological representations based on graph theory. Two strategies have been used to remove nodes such as (1) disruptions to facilities with most links and (2) disruptions to the most important facilities in terms of flow. The algorithm has also quantified the geodesic vulnerability ($\bar{v}$) index to benchmark against the results obtained with the traditional flow index, finding that the trends in the results of the graph measure are very similar to the unmet load (UL) index. These findings have been validated both graphically and numerically. Thus, the topological $\bar{v}$ index might be used to quantify the criticality level of interdependent power and gas systems.

Simulation results have shown that the case study is highly vulnerable to strategy one, as the removal of 8% of the nodes has been sufficient to achieve a widespread blackout. However, the findings have demonstrated that strategy two can also have a damaging effect because the removal of 9% of the nodes causes a severe impact on the integrated infrastructure. Similarly, the results have exposed that the propagation of cascading events and interdependencies increase the vulnerability of electrical infrastructure, while the gas system is slightly less vulnerable. This is because the gas flows move at low speed, which favors the spread of disturbances to be relatively low compared to the response behavior shown by the power grid.

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