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Jesús Beyza Bravo

Nuevas técnicas para modelizar y analizar la vulnerabilidad de infraestructuras críticas de energía interdependientes

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Tesis Doctoral

NUEVAS TÉCNICAS PARA MODELIZAR Y ANALIZAR LA VULNERABILIDAD DE INFRAESTRUCTURAS CRÍTICAS DE ENERGÍA INTERDEPENDIENTES

Autor

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2. J. Beyza, E. Garcia-Paricio, and J. Yusta, "**Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures**," Energies, vol. 12, no. 3, p. 421, 2019.
3. J. Beyza and J. M. Yusta, "**Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures**," *IET Gener. Transm. Distrib.*, vol. 12, no. 21, pp. 5753–5760, Nov. 2018.

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Informe favorable del director de tesis

El director de la tesis, el Dr. D. José María Yusta Loyo, ingeniero industrial y profesor titular del Departamento de Ingeniería Eléctrica de la Universidad de Zaragoza, hace constar:

Que D. Jesús Beyza Bravo, ingeniero electromecánico por el Instituto Tecnológico de la Costa Grande y maestro en ciencias por el Instituto Tecnológico de Morelia, ha realizado bajo su dirección y supervisión la presente tesis doctoral, que lleva por título:

«*Nuevas técnicas para modelizar y analizar la vulnerabilidad de infraestructuras críticas interdependientes*»

y autoriza su presentación en la modalidad de compendio de publicaciones. Y para que así conste a los efectos oportunos, se firma la presente autorización.

Zaragoza, España, a febrero de 2019

Fdo. Dr. D. José María Yusta Loyo

Dedicada a mis padres y hermanos con todo mi amor

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Jesús Beyza Bravo – marzo 2019

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1. Introducción

LAS REDES de electricidad y gas natural son esenciales para el funcionamiento cotidiano de las infraestructuras críticas de cualquier país. La pérdida de funcionalidad de cualquiera de estos dos sistemas tendría consecuencias devastadoras para la economía y la calidad de vida de la población. En los últimos años el creciente desarrollo de infraestructuras de transmisión y distribución de gas natural, tanto para el suministro doméstico e industrial como para la generación de electricidad en centrales de ciclo combinado, ha aumentado la interacción entre las redes de transmisión de electricidad y gas natural y también la probabilidad de que un problema en una de las infraestructuras afecte seriamente a la otra.

Generalmente, la infraestructura de gas natural está compuesta por estaciones de compresión, tuberías, instalaciones subterráneas de almacenamiento de gas, plataformas de perforación, etc. Algunas de estas instalaciones dependen para su operación de un suministro seguro y fiable de electricidad.

Por otro lado, en los países desarrollados la infraestructura eléctrica muestra una elevada dependencia de las redes de gas natural ya que una cuota importante de la producción de electricidad se obtiene de centrales eléctricas de ciclo combinado de gas natural. Así, para satisfacer el funcionamiento óptimo del sistema eléctrico en términos de seguridad y fiabilidad, las redes de gas natural deben disponer de la capacidad suficiente para facilitar el suministro a las centrales de ciclo combinado [1], [2]. Se evidencia, entonces, la creciente dependencia mutua entre ambas infraestructuras.

La estrecha relación entre las redes de electricidad y gas natural está aumentando el riesgo potencial de eventos catastróficos [3], [4]. Un ejemplo que ilustra esta dependencia ocurrió en febrero de 2011 en el suroeste de EE. UU, cuando las temperaturas extremas ocasionaron problemas en la extracción de gas natural por la congelación de las instalaciones de los pozos de almacenamiento, lo que junto al aumento de la demanda de gas natural para calefacción, produjo caídas de presión significativas en la red de tuberías y redujo drásticamente la disponibilidad de gas para las centrales de generación eléctrica de ciclo combinado, provocando la interrupción del suministro de electricidad a 4.4 millones de clientes. La falta de energía eléctrica afectó simultáneamente a las estaciones de compresión de gas que funcionaban con electricidad, causando un agravamiento de la situación [5]. En [6], [7] se presentan otros eventos similares que evidencian los efectos de la interdependencia entre estas redes.

En los últimos años, los investigadores se han interesado en analizar las interdependencias en las infraestructuras críticas, estableciendo una nueva área de estudio mediante la aplicación de distintas técnicas de análisis para redes acopladas [8]–[13]. Los sistemas de transmisión de electricidad y gas pueden fallar no solo por la complejidad de su propia operación técnica, sino también por las relaciones interdependientes que los unen. Las interdependencias pueden contribuir a la pérdida de operatividad conjunta de los sistemas acoplados y también amplificar el impacto de pequeñas perturbaciones de un sistema en el otro. Para modelar el comportamiento complejo de los sistemas de electricidad y gas se han desarrollado distintas estrategias de representación de los activos de ambos sistemas, tanto con perspectiva económica como técnica [14].

Los modelos económicos analizan cómo se propagan las perturbaciones y cómo implementar medidas preventivas efectivas. Estos modelos miden las interdependencias por las relaciones económicas y son útiles para el análisis macroeconómico a consecuencia de peligros naturales, ataques maliciosos o eventos accidentales. Algunos ejemplos de este modelo se han enfocado en los mercados energéticos debido a la competencia en la generación y comercialización de energía eléctrica [15]–[19] y el impacto de las centrales de ciclo combinado y de la red eléctrica sobre la infraestructura de gas [2], [20]. Otros trabajos consideran las incertidumbres asociadas a los precios de la electricidad y el consumo de gas natural [21]–[23].

Por otro lado, los modelos técnicos analizan la interacción utilizando flujos de carga donde se estudian eventos específicos sobre las redes acopladas, requiriendo utilizar ecuaciones y parámetros físicos que describan el comportamiento conjunto de ambos sistemas. En estos trabajos se representan los sistemas de electricidad y gas con una red simple compuesta de nodos y enlaces que asocian algunos activos de las infraestructuras [24]–[26]. Otras propuestas representan el efecto de los compresores, los tipos y limitaciones de los combustibles, la capacidad de generación y las características de arranque de las centrales de ciclo combinado [27] y el efecto de la temperatura del gas en la operación de la red de gas [28]. Modelos restantes de optimización de flujos de carga para redes de electricidad y gas natural se pueden encontrar en [29]–[33]. La mayoría de las referencias mencionadas utilizan modelos de simulación y optimización, ya que estudian el comportamiento de las redes acopladas bajo una condición dada, involucrando el cálculo de las presiones nodales y los caudales en las tuberías mediante complejos métodos de solución.

Algunos modelos más recientes proponen la utilización de la teoría de grafos para la representación de las infraestructuras mediante nodos y enlaces. Esta técnica demuestra ser adecuada para modelar las propiedades topológicas de los grandes sistemas complejos, pero hasta el momento ha sido muy poco utilizada para estudiar el caso de las infraestructuras de electricidad y gas. El auge de esta técnica se debe principalmente al uso reducido de parámetros técnicos en los modelos. Sin embargo, la representación de las redes eléctricas y de gas mediante grafos se realiza en la mayoría de los casos de manera muy simple, ya que excluye componentes importantes en la operación de ambos sistemas [34], [35]. Los modelos deberían tener un mayor nivel de detalle de los activos de las redes y permitir su escalabilidad a sistemas energéticos reales.

Por otro lado, algunos trabajos de investigación previos consideran únicamente la interacción de la infraestructura de gas sobre la red eléctrica, y se requiere mayor investigación en la dependencia bidireccional entre estos dos sistemas, ya que una interrupción en el sistema de gas combinada con las restricciones operacionales de la red eléctrica puede afectar la capacidad de suministro de electricidad a todos los usuarios [4], [27], [28]. Las redes eléctricas más robustas permitirán minimizar el efecto de las posibles interrupciones que ocurran en la red de gas.

Una perturbación simultánea en las redes de transmisión de gas y electricidad puede no resultar crítica si se evalúan las infraestructuras como sistemas separados, pero dado que las redes están acopladas en la realidad, el análisis debe efectuarse conjuntamente ya que el impacto resultante puede multiplicar el efecto individual de ambas perturbaciones.

No obstante, para realizar los estudios anteriores se requiere de mucha información técnica, además de elevados tiempos computacionales y requerimientos de software especiales. Por ello, en esta tesis doctoral se defiende que las representaciones topológicas mediante el uso de la teoría de grafos pueden ser una herramienta muy útil ya que permiten el análisis y visualización de los comportamientos físicos de estos dos sistemas, con una cantidad mínima de información, bajo tiempo computacional y sin programas informáticos especiales, facilitando la realización de análisis en múltiples escenarios con una gran flexibilidad según los intereses de los analistas. Así, el trabajo doctoral aquí presentado intenta dar soluciones a parte de las problemáticas planteadas a lo largo de estos párrafos.

A continuación, se presentan algunas definiciones importantes para este documento:

- **Vulnerabilidad**: es una medida de la debilidad del sistema de energía con respecto a una secuencia de eventos en cascada que pueden incluir cortes en los activos, mal funcionamiento u operaciones indeseables de los dispositivos de protección, fallos en el sistema de información o comunicación y errores humanos [36].
- **Robustez:** es la capacidad intrínseca de una infraestructura de energía para mantener los niveles de disturbio asignados cuando cambian las condiciones externas [37].
- **Resiliencia:** es la capacidad de la red para prepararse y adaptarse a las condiciones cambiantes, así como para resistir y recuperarse rápidamente de las perturbaciones [38].

Las principales contribuciones de los artículos científicos expuestos en esta tesis por compendio son como siguen:

1. J. Beyza, J. A. Dominguez-Navarro, and J. M. Yusta, "**Linear-analog transformation approach for coupled gas and power flow analysis**," *Electr. Power Syst. Res.*, vol. 168, pp. 239–249, Mar. 2019.
   - Este artículo desarrolla una metodología original y novedosa para analizar la operación integrada de las redes de electricidad y gas natural acopladas en estado estable. Aquí, la mayoría de las publicaciones revisadas durante la revisión bibliográfica demostraron la necesidad creciente de obtener una solución más flexible de los flujos de carga acoplados. Así, la metodología propuesta aquí ha resultado útil y precisa en los diferentes estudios llevados a cabo durante el desarrollo de esta tesis doctoral, convirtiéndose en una gran aportación para este campo de estudio.

2. J. Beyza, E. Garcia-Paricio, and J. Yusta, "**Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures**," *Energies*, vol. 12, no. 3, p. 421, 2019.
   - Este artículo evalúa el uso de medidas estadísticas de la teoría de grafos como una posible alternativa a las técnicas de flujo de potencia para el análisis de fallos en cascada en sistemas de transmisión de energía eléctrica y gas natural acoplados. Como resultado, se propone

una metodología con índices de grafos que es capaz de obtener los mismos resultados que la bien conocida técnica de flujos de carga, pero sin la necesidad de emplear los parámetros eléctricos e hidráulicos de las redes. La propuesta aquí desarrollada solo necesita la conectividad de los sistemas.

3. J. Beyza and J. M. Yusta, "**Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures**," *IET Gener. Transm. Distrib.*, vol. 12, no. 21, pp. 5753–5760, Nov. 2018.
   - Este artículo propone una nueva metodología basada en la teoría de grafos para evaluar la robustez estructural de los diferentes planes de expansión de las redes reales de transporte de gas natural y electricidad acopladas en España, teniendo en cuenta sus interdependencias. El estudio llevado aquí ha demostrado la aplicabilidad y usabilidad de la metodología desarrollada en el artículo dos sobre infraestructuras energéticas reales. Este documento ha corroborado la hipótesis que el uso de la teoría de grafos puede ser correctamente empleado por los operadores de los sistemas de transmisión.

4. J. Beyza, G. J. Correa-Henao, and J. M. Yusta, "**Cascading Failures in Coupled Gas and Electricity Transmission Systems**," in *2018 IEEE ANDESCON*, 2018, pp. 1–6. Disponible en IEEEXplore.
   - Este artículo analiza la vulnerabilidad estructural de los sistemas de electricidad y gas natural de España, contrastando el desempeño de las redes separadas, así como de las redes acopladas. Este estudio ha demostrado que los sistemas de energía acoplados son mucho más vulnerables que cuando están separados. Por tal motivo, se ha demostrado la importancia de las interdependencias entre ambas infraestructuras críticas.

1.1 Presentación de los trabajos publicados

Los trabajos publicados que conforman esta tesis son:

1. J. Beyza, J. A. Dominguez-Navarro, and J. M. Yusta, "**Linear-analog transformation approach for coupled gas and power flow analysis**," *Electr. Power Syst. Res.*, vol. 168, pp. 239–249, Mar. 2019.
2. J. Beyza, E. Garcia-Paricio, and J. Yusta, "**Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures**," *Energies*, vol. 12, no. 3, p. 421, 2019.
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1.1.1 Linear-analog transformation approach for coupled gas and power flow analysis

La creciente adopción de las energías renovables como una alternativa a los combustibles convencionales para la generación de energía eléctrica ha sido acompañada por un incremento en el desarrollo de instalaciones de gas natural debido a su capacidad para hacer frente a las variaciones inesperadas de fuentes intermitentes como la generación eólica y solar fotovoltaica [39]. La interdependencia entre ambos sistemas se basa principalmente en el hecho de que los generadores que funcionan con gas natural representan más del 40% de la producción de electricidad en algunos países. Por lo tanto, estas redes no pueden ser consideradas como sistemas separados porque la operación de uno puede tener un impacto en el otro. Por todo lo anterior, los investigadores y académicos están sumamente interesados en desarrollar métodos y estrategias para obtener la solución en estado estacionario de los flujos de carga de electricidad y gas natural acoplados.

En términos generales, hay tres métodos de uso extendido en la literatura científica para resolver la problemática de arriba [40].

- *Método Newton-nodal*: utiliza un conjunto de ecuaciones nodales que son representaciones matemáticas de la primera ley de Kirchhoff que establece que el flujo de entrada y salida en cada nodo debe ser igual. Aquí, se lleva a cabo una aproximación inicial de las presiones nodales y, después, se corrigen hasta alcanzar la solución final. Este método tiene características de convergencia muy pobres porque es muy sensible a las condiciones iniciales.
- *Método de Newton-lazo*: parte de la segunda ley de Kirchhoff que establece que la suma de las caídas de presión alrededor de cualquier lazo debe ser cero. Este método necesita identificar cada uno de los diferentes lazos en la red, por lo que requiere un cálculo adicional para producir y optimizar este último.
- *Método Newton-lazo-nodal*: es un enfoque híbrido que combina los dos métodos anteriores. Las ecuaciones de lazo se transforman en un conjunto equivalente de ecuaciones nodales que luego se resuelven para calcular las presiones en los nodos y determinar las correcciones en los flujos. Este método tiene baja eficiencia computacional pese a tener buenas características de convergencia.

Los métodos descritos arriba, como se puede inferir, presentan una serie de desventajas a la hora de ser aplicados en los sistemas de energía; por tal motivo, más recientemente, en [41], [42] se ha propuesto el concepto análogo-lineal con el fin de reducir la complejidad de las ecuaciones algebraicas usadas para evaluar el desempeño de las redes de gas natural.

Por lo tanto, el artículo uno que lleva como nombre «*Linear-analog transformation approach for coupled gas and power flow analysis*» recoge parte de la formulación de [41], [42] y propone por primera vez un novedoso marco conjunto denominado *enfoque híbrido análogo-lineal* para obtener la solución en estado estable de los flujos de carga de electricidad y gas natural acoplados. El método desarrollado aquí presenta grandes ventajas sobre los enfoques descritos anteriormente, entre los que se pueden mencionar:

1. No necesita identificar ecuaciones de lazo, calcular derivadas parciales, formular Jacobianos, utilizar ecuaciones algebraicas no lineales y suponer presiones iniciales.
2. Conserva todas las ventajas de los tres enfoques de arriba.
3. Solo requiere ecuaciones algebraicas lineales.
4. No tiene problemas de convergencia.

El enfoque propuesto puede aplicarse a cualquier infraestructura de energía acoplada y puede utilizar cualquier formulación de estudios de flujos de carga para la red eléctrica. El conjunto de ecuaciones algebraicas lineales que representan al sistema de gas natural se resuelve mediante cualquier método de solución estándar de ecuaciones lineales, lo que origina que el coste computacional para obtener la solución sea muy bajo.

En suma, la aportación de este artículo en esta área de trabajo es muy amplia ya que ha abierto la oportunidad de que la propuesta sea aplicada en una variedad de estudios y trabajos.

1.1.2 Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures

El funcionamiento de las sociedades modernas depende de sistemas cada vez más complejos e interdependientes, como las redes de electricidad y gas, entre otros. Estos sistemas pueden estar sujetos a amenazas y riesgos de diferentes tipos, ocasionando que el ataque origine un fallo en un componente o activo y este, a su vez, cause que otros activos adyacentes también se vean afectados. A este efecto de propagación se le denomina fallos en cascada [43]. Las amenazas y los peligros pueden ser desastres naturales, condiciones meteorológicas adversas, fallos técnicos, factores humanos, conflictos laborales, ciberataques, terrorismo, actos de guerra, etc.

En años anteriores, los trabajos de investigación estudiaban estas redes de manera aislada; sin embargo, en la actualidad es bien sabido que estas infraestructuras no se pueden considerar aisladas y una amenaza en una de ellas puede tener impacto significativo en la otra. Por lo tanto, hay que abordar el problema conjunto de la interdependencia entre infraestructuras críticas [9].

El artículo dos que lleva como nombre «*Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures*» defiende la idea que el uso de la teoría de grafos pueden ser una técnica muy útil para analizar y visualizar los comportamientos físicos de estos dos sistemas. Este manuscrito investiga la efectividad de las medidas estadísticas de teoría de grafos como una metodología novedosa para evaluar la vulnerabilidad estructural de las redes de electricidad y gas natural acopladas. La investigación se lleva a cabo a través de la comparación de los resultados obtenidos mediante índices clásicos de flujos de carga versus índices estadísticos de teoría de grafos, incluyendo evaluaciones ante errores aleatorios y ataques deliberados. La comparación tiene como objetivo conducir a validaciones del uso del enfoque de grafos como un método de análisis más rápido y eficiente que las rutinas tradicionales de flujo de carga.

Las principales contribuciones de este artículo pueden resumirse como sigue:

1. Se propone una nueva metodología con teoría de grafos para evaluar la vulnerabilidad estructural de las infraestructuras eléctricas y de gas natural interdependientes.
2. Se valida la efectividad de los índices estadísticos de grafos frente a la técnica tradicional de flujos de gas natural y electricidad acoplados.
3. Se emplean nuevas representaciones topológicas originales de los sistemas de gas natural y electricidad.

1.1.3 Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures

Las redes de electricidad y gas natural son sistemas fundamentales para el funcionamiento cotidiano de cualquier país del mundo. Estos sistemas complejos e interdependientes están propensos a fallos y amenazas que pueden ocasionar graves interrupciones en los servicios que prestan a la sociedad. La Directiva 2009/72/CE del parlamento europeo resalta la importancia de contar con un suministro seguro y fiable de electricidad [44].

La seguridad del suministro de energía implica evaluar la robustez de las redes ante diversas contingencias para abordar sus deficiencias; sin embargo, el alto grado de complejidad de los sistemas de energía plantea grandes desafíos [9]. Esto se evidencia en el caso de España, donde la gran integración de las redes de electricidad y gas ha creado numerosos retos de análisis [45]. Como tal, ha llegado a ser un tema de estudio reciente de académicos e investigadores.

El artículo tres que lleva como nombre «*Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures*» propone una metodología novedosa con índices de grafos para evaluar la robustez estructural de la red acoplada de electricidad de 400 kV y la red de gas natural de alta presión de 80 bar de España. La red conjunta se somete a fallos en cascada eliminando nodos aleatoriamente y se determina el impacto sobre la robustez estructural de los planes de expansión propuestos por ambos gestores de la red. En total se tienen en cuenta 22 casos de estudio con distintas topologías.

Las principales contribuciones de este manuscrito pueden resumirse como sigue:

1. Se propone una representación de las infraestructuras de electricidad y gas natural acopladas en España con un alto nivel de detalle.
2. Se desarrolla un procedimiento novedoso basado en teoría de grafos para evaluar la robustez de los planes de expansión de los sistemas acoplados de electricidad y gas natural.

1.1.4 Cascading failures in coupled gas and electricity transmission systems

Las redes de electricidad y gas natural son parte de la prosperidad económica del mundo moderno. Estos sistemas son propensos a fallos en cascada debido a peligros naturales, terrorismo, deterioro de componentes, etc. Una evaluación adecuada es importante para evitar la ocurrencia de estos fenómenos indeseables; no obstante, minimizar estas amenazas plantea grandes retos de análisis.

En la actualidad, la mayoría de los estudiosos analizan ambas redes de manera aislada. Sin embargo, estos sistemas no se encuentran aislados, ya que un evento en una infraestructura puede tener consecuencias en la otra [35]. Por ejemplo, las centrales eléctricas de ciclo combinado requieren de un suministro fiable de gas natural. Por otro lado, los compresores de la red de gas demandan energía eléctrica para su operación. Por tanto, se tiene que abordar el problema de la interdependencia entre infraestructuras [9].

En la literatura científica se ha encontrado que los manuscritos no comparan los resultados de desempeño de las redes separadas frente a fallos en cascada en comparación con aquellos obtenidos en la red conjunta.

El artículo cuatro que lleva como nombre «*Cascading failures in coupled gas and electricity transmission systems*» propone una metodología novedosa para analizar fallos en cascada en redes acopladas de electricidad y gas natural reales. Primero, se estudia la vulnerabilidad de las redes separadas y, después, se evalúa la vulnerabilidad de la red conjunta. Al final, se comparan los resultados obtenidos entre ambas simulaciones. El caso de estudio ha correspondido a la red de electricidad de 400 kV y la red de gas natural de 80 bar de España.

1.2 Justificación de la unidad temática

Las infraestructuras energéticas críticas, incluidos los sistemas de electricidad y gas natural, proporcionan un combustible esencial para el funcionamiento continuo y fiable de la seguridad nacional o regional, las operaciones económicas y la salud pública. La interrupción o pérdida de la funcionalidad de estas infraestructuras tendría un impacto debilitante en la defensa, la seguridad económica y la calidad de vida de la población. Los sistemas de infraestructura energética crítica no están aislados sino cada vez más interconectados y son interdependientes con el desarrollo de la tecnología moderna. Por ejemplo, el suministro fiable de electricidad es una necesidad en todo el sistema de gas natural para mantener la operación normal, mientras que el suministro de gas natural es un requisito para generar electricidad en las centrales eléctricas de gas. Las interdependencias más altas entre estos sistemas hacen que toda la red de energía sea más vulnerable que nunca, ya que una interrupción que ocurre en un sistema (por ejemplo, un fallo inesperado) tiene consecuencias en los otros sistemas dependientes y posiblemente incluso en el sistema donde se ha originado la interrupción. Estas relaciones estrechas están aumentando el riesgo potencial de eventos catastróficos, desencadenados por los efectos en cascada de los tipos de interrupciones intencionales y no intencionales.

Por todo lo anterior, se hace totalmente evidente la gran importancia de estudiar las redes de electricidad y gas natural de una manera conjunta. Por esta razón, se han detectado las siguientes áreas por desarrollar:

- Desarrollo de enfoques más flexibles para analizar la operación integrada de las redes de gas y electricidad en estado estable.
- Desarrollo de metodologías más originales para evaluar la vulnerabilidad estructural de los sistemas de gas natural y electricidad sin necesidad de recurrir a los parámetros eléctricos e hidráulicos de las dos infraestructuras.
- Estudios que demuestren cómo las perturbaciones en una red pueden podrían ocasionar la caída de desempeño de todo el sistema conjunto.
- Desarrollo de estudios que evalúen la robustez de los planes de expansión de las redes de gas y electricidad propuestos por los operadores de ambas infraestructuras.

Así, los cuatro artículos presentados en esta tesis doctoral dan solución a cada uno de los problemas citados anteriormente. La Fig. 1 esquematiza el orden y aportaciones de cada manuscrito.

Artículos	
Linear-analog transformation approach for coupled gas and power flow analysis	Desarrollo de un marco conjunto para analizar la operación integrada de las redes de gas y electricidad en estado estacionario.
Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures	Desarrollo de una metodología para evaluar la vulnerabilidad estructural de los sistemas de potencia y gas natural acoplados frente a fallos en cascada, mediante la propuesta de un índice estadístico de la teoría de grafos que usa solamente la conectividad de los sistemas bajo estudio.
Cascading Failures in Coupled Gas and Electricity Transmission Systems	Propuesta de una metodología para estudiar la vulnerabilidad de las redes de electricidad y gas natural de manera separada y conjunta, determinado la influencia de cada una de las infraestructuras en el desempeño global.
Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures	Propuesta de una metodología novedosa basada en teoría de grafos para evaluar la robustez estructural de los planes de expansión de las redes de transmisión de electricidad y gas natural acopladas en España.

Fig. 1 Esquematización de las aportaciones de los artículos.

2. Trabajos publicados

Los trabajos publicados que conforman esta tesis son:

J. Beyza, J. A. Dominguez-Navarro, and J. M. Yusta, "**Linear-analog transformation approach for coupled gas and power flow analysis**," *Electr. Power Syst. Res.*, vol. 168, pp. 239–249, Mar. 2019.

J. Beyza, E. Garcia-Paricio, and J. Yusta, "**Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures**," Energies, vol. 12, no. 3, p. 421, 2019.

J. Beyza and J. M. Yusta, "**Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures**," *IET Gener. Transm. Distrib.*, vol. 12, no. 21, pp. 5753–5760, Nov. 2018.

J. Beyza, G. J. Correa-Henao, and J. M. Yusta, "**Cascading Failures in Coupled Gas and Electricity Transmission Systems**," in *2018 IEEE ANDESCON*, 2018, pp. 1–6.

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Linear-analog transformation approach for coupled gas and power flow analysis

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ABSTRACT

In this paper, we present a methodology to analyze the integrated operation of coupled natural gas and electricity networks in steady-state. The interaction of the gas network with the electrical grid is modeled through mathematical equations that represent the energy exchange between the two infrastructures. The joint natural gas and power flow is solved using the linear-analog transformation (LAT) and the Newton-Raphson (NR) algorithm, respectively. Here, a unified solution framework of the two systems is presented using the previous proposed methods. The applicability of the methodology is illustrated using two case studies: IEEE-14 bus test system combined with a 16-node natural gas network and the IEEE-30 bus test system integrated with a 15-node natural gas network with 4 compressors. The proposed methodology proves to be useful for the assessment of coupled natural gas and electricity critical infrastructures.

1. Introduction

The growing adoption of renewable energies as an alternative to conventional fuels for power generation has been accompanied by an increasing deployment of natural gas installations due to its capacity to deal with the unexpected variations of intermittent sources such as wind and solar photovoltaic generation [1]. The interdependence between both systems lies mainly in the fact that natural gas-fired generators accounted for more than 40% of the operating electricity generating capacity in some countries. Thus, these networks cannot be considered as separated systems because operation of one can have an impact on the other.

This situation has established a very close relationship between power and gas systems from both financial and operational perspectives [2]. In this sense, the interaction between these systems for the study of their respective deregulated markets has gained relevance [3,4], as well as for reliability studies [5], optimal control and scheduling [6–8], and critical infrastructures analysis [9,10].

The focus of this work relies on the analysis of the integrated power and natural gas systems, which is a crucial process for most of the studies previously mentioned. On the one hand, power system simulation is performed including transmission lines, active and reactive power consumption, reactive power control, among other assets [11,12]. On the other hand, natural gas networks have been traditionally represented by pipelines and compressors, avoiding the effects of other elements such as valves and regulators [3,13].

The computational simulation of both systems requires the solution of algebraic non-linear equations due to their complex behavior. In this regard, most of the methodologies available in the literature are based on Newton-Raphson method [14]. In the case of power system analysis, voltages across the transmission or distribution systems are generally close to their nominal values, so that in many cases convergence of Newton method is observed [15]. However, in the case of natural gas networks, the solution of non-linear equations strongly depends on the initial approximation. These phenomena were extensively studied by Li et al. [16], who discussed the problem formulation in two different ways, taking into account the nodes (Newton-nodal method) and the loops (Newton-loop method) of the corresponding topology. The Newton-nodal formulation is based on the sum of flows at each node, while Newton-loop method uses the sum of the pressure drops around each loop. As loop formulation is almost quadratic due to the quadratic behavior of flow rates, Newton-loop method offers good convergence when compared to its counterpart. However, the loop to be analyzed has to be adequately selected, thus the formulation of the problem using loops becomes difficult. Otherwise, the use of numerical methods for the calculation of Jacobian matrix can ease the computational implementation of both methods by avoiding the required mathematical derivation in analytical form.

In other proposals that consider technical aspects in the operation of the coupled gas and electricity network, Martínez-Mares and Fuerte-

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List of symbols

i	index for the upstream node
j	index for the downstream node
$q_{G(i,j)}$	flow between pipeline i and j
$C_{(i,j)}$	conductivity of the pipeline between i and j
$s_{(i,j)}$	coefficient of the pipeline elevation
e	pipeline roughness
$p_{(i)}$	network pressure at point i
$L_{(i,j)}$	pipeline conductivity of the linear-analog
$T_{(i,j)}$	conductivity transform between the points i and j
$r_{(i,j)}$	pressure ratio between the points i and j
HP	horsepower of compression station
n_{st}	compression steps
n_p	polytropic coefficient
Z_{av}	compressibility factor of the gas
η	efficiency of the compressor station
$T_{(i)}$	conductivity transform of the well i
k_c	compressor coefficient
$r_{c(i,j)}$	compression ratio of the station between i and j
$C_{c(i,j)}$	constant of the compressor station between i and j
g_k	natural gas taken from the network by the compressor station
k	index for each iteration of LAT method
Cf	natural gas consumption factor
S	gas supplying at the corresponding node
D	natural gas demand for domestic use and industrial
D_g	natural gas demand for power generation
$\Delta P_{(i)}$	active power mismatch of node i
$P_{\text{gen}}^{(i)}$	active power of generation at node i
$P_{\text{load}}^{(i)}$	active power of load at node i
$P_{\text{cal}}^{(i)}$	calculated value of active power injection at node i
ΔP	vector of active power mismatch
$\Delta Q_{(i)}$	reactive power mismatch of node i
$Q_{\text{gen}}^{(i)}$	reactive power of generation at node i
$Q_{\text{load}}^{(i)}$	reactive power of load at node i
$Q_{\text{cal}}^{(i)}$	calculated value of reactive power injection at node i
ΔQ	vector of reactive power mismatch
$V_{(i)}$	voltage magnitude at node i
ΔV	vector of changes on the voltage magnitudes
$G_{(i,j)}$	conductance of the branch between i and j
$B_{(i,j)}$	susceptance of the branch between i and j
$\gamma_{(i)}$	angle of the voltage at node i
$\Delta\delta$	vector of changes on the angle magnitudes
$e_{(i)}$	amount of gas required by the generator of node i
$K_{0(i)}$, $K_{1(i)}$, $K_{2(i)}$	coefficient of gas consumption of generator i
$P_{G(i)}$	active power generation at node i
K	characteristic matrix of gas network
P	vector of gas network pressures
S	vector of gas supply and consumption
$O_{(i)}$	summation of the off-diagonal entries of matrix K
s	elevation coefficient
SG_G	specific gravity of the gas
ΔH	pipelines elevation
T_{av}	average temperature
L_e	pipeline equivalent length
L	horizontal pipeline equivalent length
J	Jacobian matrix
σ_G	parameter of generalized gas model
T_{sc}	absolute temperature at standard conditions
p_{sc}	pressure at standard conditions
f_F	friction factor
d	internal diameter of the pipeline
ε	error on the estimation of gas network pressure
$P_{G,min}$	minimum power of the generator
$P_{G,max}$	maximum power of the generator

Esquivel [11] incorporated the influence of the changes on natural gas temperature over the pipeline, which is an aspect that is not frequently considered to maintain the simplicity of the model. Erdener et al. [17] implemented a technique based on Newton-loop-node formulation combined with the Breadth First Search (BFS) algorithm. As the equation set under study is highly non-linear, BFS algorithm was used to find an initial solution to the algebraic problem. With the high interest on natural gas resources, specifically in urban areas, Shabanpour-Haghighi and Seifi [12] developed a model to incorporate a district heating network to the integrated power and gas system, taking into account the hydraulic as well as the thermal circuits on the balance equation. Wang et al. [18] developed the decoupled implicit method for efficient network simulation (DIMENS), which uses divide-and-conquer technique to increase the computational speed. DIMENS divides the gas network into sub-systems that are later fully analyzed. Dyachenko et al. [13] proposed the operator splitting technique based on the solution of a non-linear hyperbolic partial differential equation set to describe the hydrodynamic behavior of the gas system. As the most important characteristic, the technique is stable and accurate, as well as computationally efficient.

Recently, Ayala and Leong [19,20] proposed the linear-analog concept in order to reduce the complexity of the algebraic equations used to evaluate the performance of natural gas networks. This method is based on applying linear-analog transformation (LAT) approach to the model of each asset of the gas network. Contrary to other proposals, in the LAT approach initial assumptions of pressures and flow rates are not necessary and only a set of algebraic equations that can be solved by standard numerical methods are required.

It can be noted that the works discussed above show that electricity and natural gas networks are well studied separately, however, a scope for improvement is observed in the development of techniques for analyzing the integrated operation of both critical infrastructure systems. This paper presents a methodology that allows to obtain the steady-state solution of coupled electricity and natural gas flows using the novel linear-analog method to solve the gas-flow problem. In the latter, the advantages of Newton's traditional approach using only nodal equations are preserved, but the formulation is simplified, the calculation of derivatives is eliminated and the computational cost is reduced [19,20].

The rest of this paper is organized as follows: Section 2 describes in detail the mathematical models of the generalized gas-flow equation, pipes and compressors of the natural gas infrastructure using the linear-analog approach. Then, Section 3 presents the steady-state power system modeling with Newton-Raphson method. The simulation of the joint system is formulated and performed in Section 4, to be later implemented in two case studies presented in Section 5. Finally, the sum of the main conclusions of this work are discussed in Section 6.

2. Modeling of the natural gas network

Fig. 1 presents a natural gas network with the components considered for the simulation, including supply and demand nodes, as well as the suction and discharge nodes of the compressor station.

The reasoning behind LAT approach consists on substituting the non-linear formulation of system dynamics by an alternative model, simplifying according to some specific assumptions related to the behavior of the gas under laminar conditions. Therefore, this method has proved to be an ideal approach to solve the gas-load flow problem for natural gas infrastructures composed of pipes, compressors, supplies, among others. To find the solution of the gas system, the LAT method

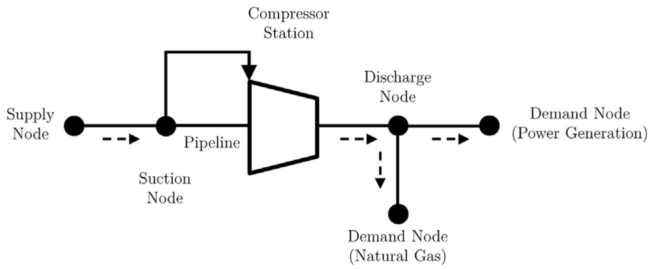

Fig. 1. A simple natural gas network.

only uses nodal equations simplifying the computational calculation [19,20].

2.1. Linear-analog of the pipeline system

Analyzing the behavior of natural gas network starts by establishing the expression that estimate the flow rate $q_{G(i,j)}$ through a pipeline (i, j). A general form of such expression is presented in Eq. (1),

$$q_{G(i,j)} = C_{(i,j)}\sqrt{p_{(i)}^2 - e^{s(i,j)}p_{(j)}^2} \tag{1}$$

It can be noted the non-linear characteristic of Eq. (1), which increases the difficulty to accurately determine the pressure and flow across the system. In order to avoid this problem, LAT method uses a similar expression that is presented in Eq. (2).

$$q_{G_{(i,j)}} = L_{i,j}(p_{(i)} - e^{s(i,j)/2}p_{(j)}) \tag{2}$$

where the inclination of the pipelines are considered by means of the elevation coefficient $s_{(i,j)}$, while the pressure conductivity is included by using $L_{(i,j)} = T_{(i,j)}C_{(i,j)}$, which depends on the conductivity transform $T_{(i,j)} = \sqrt{1 + \frac{2}{r_{(i,j)} - 1}}$, obtained from the generalized gas flow model, and on the conductivity of the pipeline $C_{(i,j)}$.

Now, equating Eqs. (1) and (2) as shown in Eq. (3) [19,20],

$$L_{i,j}(p_{(i)} - e^{s(i,j)/2}p_{(j)}) = C_{(i,j)}\sqrt{p_{(i)}^2 - e^{s(i,j)}p_{(j)}^2} \tag{3}$$

and introducing the pressure ratio defined as $r_{(i,j)} = \frac{p_{(i)}}{e^{s(i,j)/2}p_{(j)}}$, the linear representation of the quadratic expression shown in Eq. (3) is obtained in Eq. (4) [19,20]:

$$L_{(i,j)}^2(r_{(i,j)} - 1) = C_{(i,j)}^2(r_{(i,j)} + 1) \tag{4}$$

Then, the corresponding linear equation system can be solved by means of standard techniques available in the literature. Here, $(T_{(i,j)}) > 1$ due to the pressure ratio $r_{(i,j)} = \frac{p_{(i)}}{e^{s(i,j)/2}p_{(j)}}$, which leads to the pipeline conductivity $L_{(i,j)} > C_{(i,j)}$. Therefore, the calculation of gas flow through the network is an iterative process, starting with the assumption that $L_{(i,j)} = C_{(i,j)}$ or $2C_{(i,j)}$, in order to obtain a first solution. Once the pressures have been initially estimated, the value of pressure ratio is then calculated, as well as the updated value of the pipeline conductivity of the respective linear-analog (the value of $L_{(i,j)}$ for the next iteration).

2.2. The linear-analog of the compressor station

Compression stations are conveniently installed to move the gas through the network and compensate the effects of friction of the pipelines, among other factors. Some compressor stations take gas from the network according to the amount of horsepower required, while others take power from an electrical system to boost the pressure.

The relationship between the power demanded by the station to increase the gas pressure, the compression stages, compressor efficiency and natural gas properties is presented in Eq. (5),

$$\mathrm{HP} = 0.0857\frac{n_{\mathrm{st}}\cdot n_p}{n_p - 1}q_{G_{(i,j)}}T_{(i)}Z_{\mathrm{av}}\left(\frac{1}{\eta}\right)\left[\left(\frac{p_{(j)}}{p_{(i)}}\right)^{n_p - 1/n_{\mathrm{st}}\cdot n_p} - 1\right] \tag{5}$$

This expression can be simplified by introducing the compressor coefficient shown in Eq. (6),

$$k_c = 0.0857\left(\frac{n_{\mathrm{st}}\cdot n_p}{n_p - 1}\right)T_{(i)}(Z_{\mathrm{av}})\left(\frac{1}{\eta}\right) \tag{6}$$

Thus, gas flow through the compressor station can be obtained by re-ordering Eqs. (5) and (6), which results in Eq. (7),

$$q_{G(i,j)} = \frac{\mathrm{HP}}{k_c[(r_{c_{(i,j)}})^{n_p - 1/n_{\mathrm{st}}\cdot n_p} - 1]} \tag{7}$$

The compression ratio of the compressor station located between the nodes i and j is defined according to Eq. (8),

$$r_{c_{(i,j)}} = \frac{p_{(j)}}{p_{(i)}} \tag{8}$$

Once the compression ratio has been defined, gas flow can be simplified and overwritten as presented in Eq. (9) [19,20],

$$q_{G_{(i,j)}} = C_{c_{(i,j)}}\mathrm{HP} \tag{9}$$

where the variable $(C_{c_{(i,j)}})$ is defined according to Eq. (10),

$$C_{c_{(i,j)}} = \frac{1}{k_c[(r_{c_{(i,j)}})^{n_p - 1/n_{\mathrm{st}}\cdot n_p} - 1]} \tag{10}$$

Regarding compressor stations based on gas absorption, the amount of gas drawn from the network $(g_{(k)})$ can be estimated using Eq. (11),

$$g_{(k)} = (Cf)\mathrm{HP}_{(k)} \tag{11}$$

The factor (Cf) is strongly related to the natural gas calorific value. Regarding compressor stations powered by electricity, the corresponding amount of gas drawn is neglected.

2.3. Balance of the natural gas system

The balance of natural gas on each node of the system is shown in Eq. (12), which establishes that the total sum of gas entering and leaving the node must be equal to zero.

$$\sum_{\substack{j\neq i\\ j\in i}}(L_{ij}\cdot(p_i - p_j)) + S_i - D_i - D_{g_i} - g_{(k)} = 0 \tag{12}$$

where $(L_{ij}\cdot(p_i - p_j))$ is the flow rate of the pipelines adjacent to the node i, S_i represents the natural gas inputs, D_i are the domestic and industrial loads, D_{g_i} are the natural gas demands for power generation and $g_{(k)}$ is the natural gas consumption by compressors. The latter is used only in the balance equation of the compressor input node.

3. Modeling of the transmission power system

As in the case of natural gas networks, power system behavior is modeled by using a set of non-linear equations represented in Eqs. (13)–(16) that are frequently solved using Newton-Raphson approach [11]. Power balance of the system is determined through Eqs. (13) and (14) considering the respective value of voltage and angle at each node, as well as the power flows through the transmission lines.

$$\Delta P_{(i)} = P_{\mathrm{gen}}^{(i)} - P_{\mathrm{load}}^{(i)} - P_{\mathrm{cal}}^{(i)} = 0 \tag{13}$$

$$\Delta Q_{(i)} = Q_{\mathrm{gen}}^{(i)} - Q_{\mathrm{load}}^{(i)} - Q_{\mathrm{cal}}^{(i)} = 0 \tag{14}$$

$$P_{\mathrm{cal}}^{(i)} = \sum_{j\in i}\{V_{(i)}^2G_{(i,i)} + V_{(i)}V_{(j)}[G_{(i,j)}\cos(\theta_{(i)} - \theta_{(j)}) + B_{(i,j)}\sin(\theta_{(i)} - \theta_{(j)})]\} \tag{15}$$

$$Q_{\mathrm{cal}}^{(i)} = \sum_{j \in i} \{-V_{(i)}^2 B_{(i,i)} + V_{(i)} V_{(j)} [G_{(i,j)} \sin(\theta_{(i)} - \theta_{(j)}) - B_{(i,j)} \cos(\theta_{(i)} - \theta_{(j)})]\} \tag{16}$$

Next, the slack generator is chosen and the voltages and angles are calculated in order to solve the power flow problem. Finally, the nonlinear equation system is solved by using Newton-Raphson approach.

4. Modeling of the coupled gas and power grid

Once the mathematical model of natural gas and power systems has been described, the interdependency model to study the interaction between them can be created. In this sense, the connection points of both infrastructures are on the gas fired power plants (GFPPs) and on the compressor units.

4.1. Gas fired power plants (GFPPs)

Energy conversion process of GFPP can be briefly described using Eq. (17) [21].

$$e_{(i)} = K_{2_{(i)}} P_{G_{(i)}}^2 + K_{1_{(i)}} P_{G_{(i)}} + K_{0_{(i)}} \tag{17}$$

This expression defines the amount of gas demanded by the generation system to satisfy corresponding amount of power generation P_G. In other words, the gas consumption of each GFPP is related to the real power generation using Eq. (17).

4.2. Compressor units

Power consumption of compressor units is defined in Eq. (5), while those compressor units based on natural gas are modeled according to Eq. (11).

4.3. Unified solution of natural gas and power flows

The unified solution of the coupled electricity and natural gas flow is obtained when the electric and hydraulic models of both infrastructure systems are combined as described in the previous sections. The two networks are coupled with interdependent links that represent the flow exchange between the two systems. The power grid has gas fired power plants connected to their buses that are fed from determined nodes of the gas network. Similarly, the gas network has compressors that operate with external power supplied from certain buses of the electrical grid.

Fig. 2 presents the algorithm proposed to obtain the steady-state solution of coupled natural gas and electricity flow. In the first step of the algorithm of Fig. 2, the information required to simulate the power and natural gas infrastructures is collected assuming the bidirectional links described above. The study starts by solving the load flow problem in the electrical network using the NR method in order to calculate the voltages magnitudes and phase angles at all the buses in the infrastructure according to the defined power generations and loads. Next, active and reactive power flows through transmission lines are obtained. Since the power transmission losses in the electrical grid cannot be determined without first knowing the power flow, a slack generator with its defined voltage magnitude and phase angle is assigned to supply the power generation mismatch. In some instances, the slack generator could be coupled with the gas infrastructure. The power produced by the GFPPs are used to estimate the amount of natural gas required through Eq. (17). Then, the demand for natural gas is incorporated as a load on the gas network. Next, the gas-load flow study is carried out using the LAT method incorporating the linear-analog equation of the compression stations. Here, consider that the amount of gas required for the power generation and the behavior of the mechanical and electrical compression stations are used to estimate the corresponding values of gas supplies and power demands, respectively. Finally, the process ends once the error become lower than a predefined tolerance.

All of the above is executed within an iterative framework to evaluate the joint operation of both coupled infrastructures. That is to

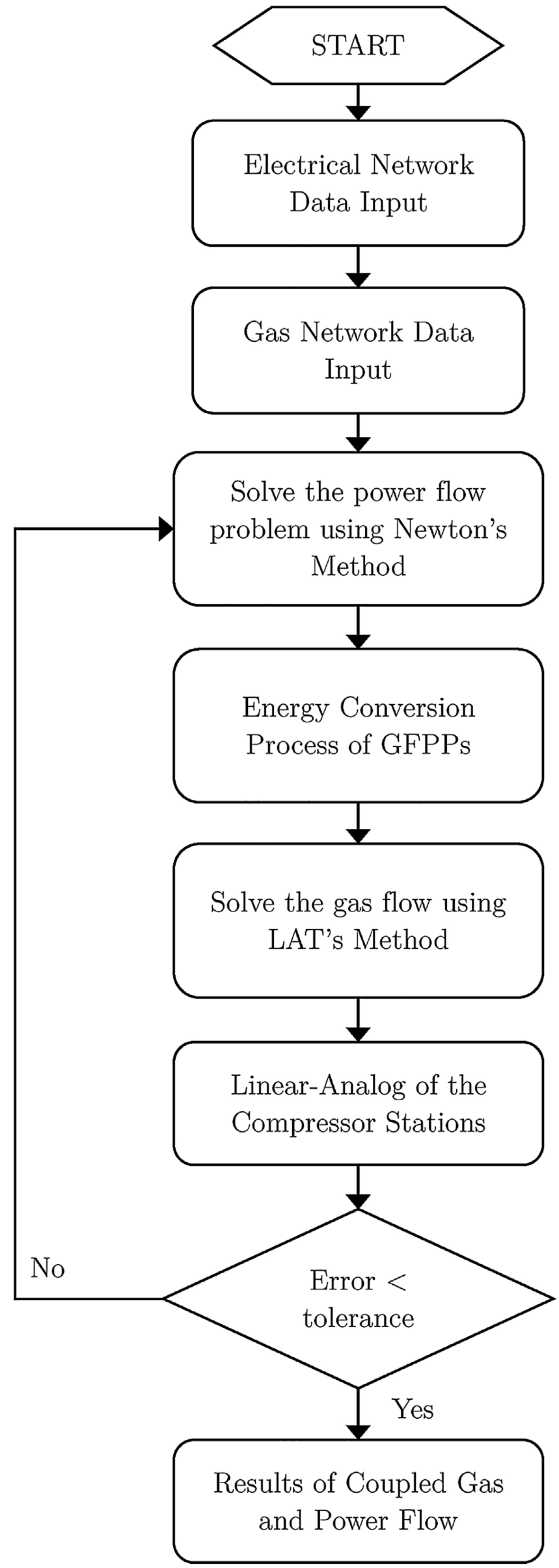

Fig. 2. Flowchart of the proposed LAT-NR method.

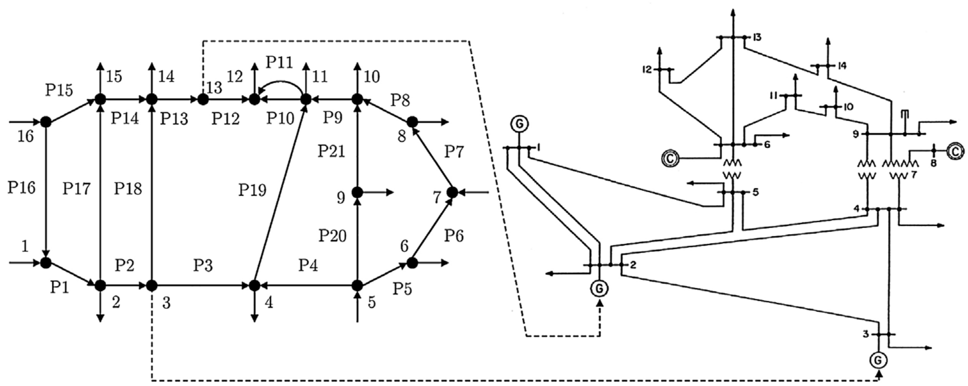

Fig. 3. Natural gas network of 16 nodes coupled to power system of 14 buses.

Table 1
Results of supplies, gas demands and power generation for Case 1.

Electricity supply and demand					Natural gas supply and demand		
Bus	Generation		Load		Node	Supply	Demand
	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)		(MMSCFD)	(MMSCFD)
1	85.63	17.72	0.00	0.00	1	121.00	0.00
2	95.00	8.91	21.70	12.70	2	0.00	4.70
3	83.00	−5.24	94.20	19.00	3	0.00	15.10 (GFPP)
4	0.00	0.00	47.80	−3.90	4	0.00	8.90
5	0.00	0.00	7.60	1.60	5	151.80	0.00
6	0.00	12.67	11.20	7.50	6	0.00	20.10
7	0.00	0.00	0.00	0.00	7	192.60	0.00
8	0.00	17.41	0.00	0.00	8	0.00	83.60
9	0.00	0.00	29.50	16.60	9	0.00	11.20
10	0.00	0.00	9.00	5.80	10	0.00	57.80
11	0.00	0.00	3.50	1.80	11	0.00	60.80
12	0.00	0.00	6.10	1.60	12	0.00	80.80
13	0.00	0.00	13.50	5.80	13	0.00	18.60 (GFPP)
14	0.00	0.00	14.90	5.00	14	0.00	64.20
					15	0.00	50.70
					16	11.10	0.00
Total	263.30	51.47	259.00	73.50		476.50	476.50

Table 2
Power flow and gas flow rate for Case 1.

Power flow							Gas flow rate					
Line	From Bus	To Bus	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	Pipe	From Node	To Node	Gas flow NR (MMSCFD)	Gas flow LAT-NR (MMSCFD)	Error
L1	1	2	42.23	10.46	−41.89	−15.27	P1	1	2	112.91	112.31	0.60
L2	1	5	43.40	7.26	−42.45	−8.65	P2	2	3	83.57	82.40	1.17
L3	2	3	27.12	10.19	−26.74	−13.20	P3	3	4	−25.33	−25.92	0.59
L4	2	4	47.69	0.37	−46.47	−0.30	P4	5	4	142.71	142.12	0.59
L5	2	5	40.38	0.92	−39.52	−2.01	P5	5	6	−75.83	−75.32	0.51
L6	3	4	15.54	−11.04	−15.31	10.31	P6	7	6	95.93	95.42	0.51
L7	4	5	−32.08	4.10	32.22	−3.67	P7	7	8	96.66	97.17	0.51
L8	4	7	29.29	−9.71	−29.29	11.55	P8	8	10	13.06	13.57	0.51
L9	4	9	16.78	−0.49	−16.78	1.91	P9	10	11	28.98	29.57	0.29
L10	5	6	42.15	12.72	−42.15	−8.65	P10	11	12	17.51	17.93	0.42
L11	6	11	6.17	3.88	−6.13	−3.79	P11	11	12	59.15	58.13	1.02
L12	6	12	7.64	2.57	−7.57	−2.42	P12	13	12	4.13	4.72	0.59
L13	6	13	17.14	7.37	−16.94	−6.97	P13	14	13	22.73	23.34	0.61
L14	7	8	0.00	−16.96	0.00	17.41	P14	15	14	−6.87	−5.66	1.21
L15	7	9	29.29	5.41	−29.29	−4.54	P15	16	15	19.18	19.82	0.64
L16	9	10	6.40	3.87	−6.38	−3.83	P16	1	16	8.08	8.72	0.64
L17	9	14	10.17	3.38	−10.04	−3.10	P17	2	15	24.64	25.21	0.57
L18	10	11	−2.62	−1.97	2.63	1.99	P18	3	14	93.80	93.21	0.59
L19	12	13	1.47	0.82	−1.47	−0.82	P19	4	11	108.48	107.29	1.19
L20	13	14	4.91	1.99	−4.86	−1.90	P20	5	9	84.92	84.99	0.07
							P21	9	10	73.72	73.79	0.07

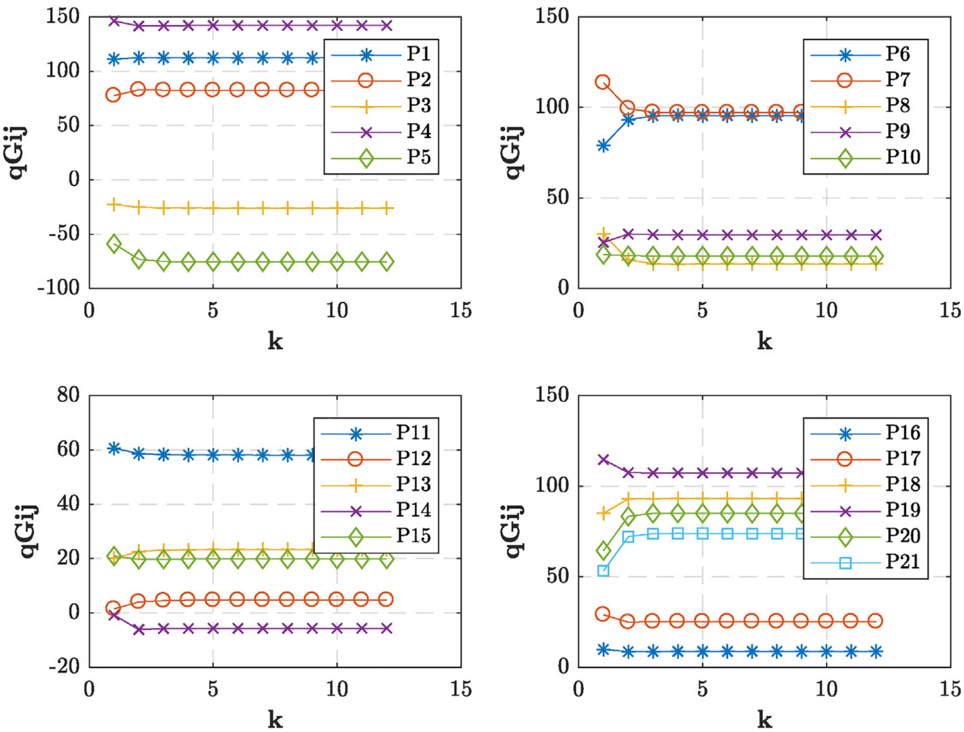

Fig. 4. Convergence of flow rate *qGij* for Case 1.

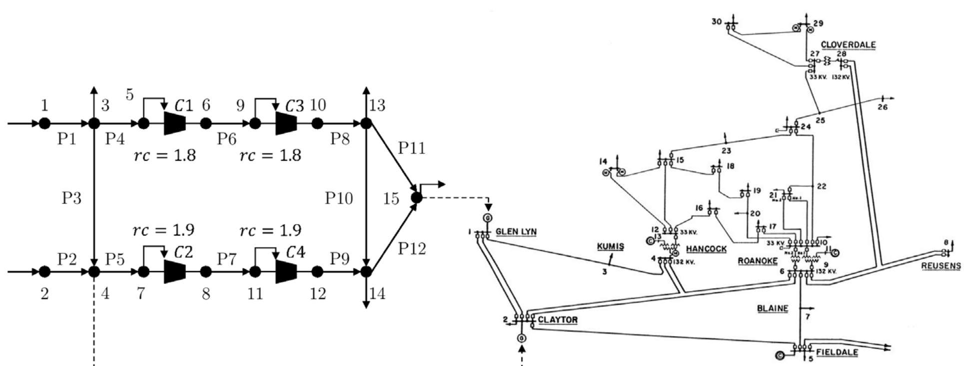

Fig. 5. Natural gas network of 15 nodes coupled to power system of 30 buses.

say, in each step the mismatch of power generation of the slack bus is determined according to the gas supply and the electrical energy demanded by the coupled compressors. In this way, a more realistic and accurate simulation of the two interdependent infrastructures is obtained.

Power flow study is carried out by following the steps presented as follow:

1. Create the Jacobian matrix of the system.
2. Determine the changes on the voltage magnitudes ($V_{(i)}$) and angles ($\theta_{(i)}$), and update the corresponding values using Eq. (18),

$$(18)\left[\frac{\Delta\theta}{\Delta V}\right] = [J]^{-1}\cdot\left[\frac{\Delta P}{\Delta Q}\right]$$

1. Using the updated values of voltages, calculate the values of current ($I_{(i)}$), active ($P_{(i)}$) and reactive power ($Q_{(i)}$). Then, calculate the corresponding active and reactive power mismatch.
2. Repeat the steps previously explained until the active and reactive power mismatches becomes lower than a tolerance.
3. At this step, natural gas required to supply the power generation can be calculated using Eq. (17).

Natural gas flow study can be carried out by following the steps presented as follow [19,20]:

1. Using the information related to the structure of the gas system, the coefficients of the pipeline elevation (s) are calculated using Eq. (19),

$$(19)s = 0.0375\left(\frac{SG_G\cdot\Delta H}{Z_{av}\cdot T_{av}}\right)$$ While the equivalent length (L_e) is calculated using Eq. (20),

$$L_e = \left(\frac{e^s - 1}{s}\right)L \tag{20}$$

Note that $L_e = L$ for horizontal pipelines.

1. The friction factor (f_F) estimated according to a determined model (Weymouth, Panhandle, etc.) is used to calculate the conductivity ($C_{(i,j)}$) as shown in Eq. (21),

$$(21)C_{(i,j)} = \frac{\sigma_G}{\sqrt{SG_G T_{av} Z_{av}}}\left(\frac{T_{sc}}{p_{sc}}\right)\sqrt{\frac{1}{f_F}}\left(\frac{d^{2.5}}{L_e^{0.5}}\right)$$

Table 3
Results of supplies, gas demands and power generation for Case 2.

Electricity supply and load					Natural gas supply and demand		
Bus	Generation		Load		Node	Supply	Demand
	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)		(MMSCFD)	(MMSCFD)
1	25.97	−1.00	0.00	0.00	1	174.29	0.00
2	60.97	32.00	21.70	12.70	2	164.80	0.00
3	0.00	0.00	2.40	1.20	3	0.00	92.11
4	0.00	0.00	7.60	1.60	4	0.00	11.11 (GFPP)
7	0.00	0.00	22.80	10.90	5	0.00	0.00
8	0.00	0.00	30.00	30.00	6	0.00	0.00
10	0.00	0.00	5.80	2.00	7	0.00	0.00
12	0.00	0.00	11.20	7.50	8	0.00	0.00
13	37.00	11.35	0.00	0.00	9	0.00	0.00
14	0.00	0.00	6.20	1.60	10	0.00	0.00
15	0.00	0.00	8.20	2.50	11	0.00	0.00
16	0.00	0.00	3.50	1.80	12	0.00	0.00
17	0.00	0.00	9.00	5.80	13	0.00	102.31
18	0.00	0.00	3.20	0.90	14	0.00	102.57
19	0.00	0.00	9.50	3.40	15	0.00	22.89 + 5.09 (GFPP)
20	0.00	0.00	2.20	0.70			
21	0.00	0.00	17.50	11.20			
22	21.59	39.57	0.00	0.00			
23	19.20	7.95	3.20	1.60			
24	0.00	0.00	8.70	6.70			
26	0.00	0.00	3.50	2.30			
27	26.91	10.54	0.00	0.00			
29	0.00	0.00	2.40	0.90			
30	0.00	0.00	10.60	1.90			
Total	191.64	100.41	189.20	107.20		339.09	336.09

1. The compressor coefficients (k_c and $C_{c_{(i,j)}}$) are calculated using Eqs. (6) and (10), while the conductivity of the linear-analog is estimated by means of $L_{(i,j)} = T_{(i,j)}C_{(i,j)}$.
2. The characteristic matrix (K) is built in order to create the algebraic system of Eq. (22), using the vector of gas supply and demand (S).

$$(22)\underbrace{\begin{bmatrix} -O_{(1)} & e^{s(1,j)/2L(i,j)} & \cdots \\ L_{(2,j)} & -O_{(2)} & e^{s(2,j)/2L(2,j)} \\ L_{(i,n)} & \cdots & -O_{(n)} \end{bmatrix}}_{K} \underbrace{\begin{bmatrix} p_{(1)} \\ \vdots \\ p_{(n)} \end{bmatrix}}_{P} = \underbrace{\begin{bmatrix} s_{(1)} \\ \vdots \\ s_{(n)} \end{bmatrix}}_{S}$$

1. The pressure and compressor ratios ($r_{(i,j)}$ and $r_{c_{(i,j)}}$) are calculated in order to later obtain the values of the conductivity transforms using Eq. (23),

$$(23)T_{(i,j)} = \sqrt{1 + \frac{2}{r_{(i,j)} - 1}}$$

1. This process is repeated until the error on the calculation of all the pressures around the network become lower than a predefined value (ε). The amount of electrical power required by the compressor stations estimated as a result of the gas network analysis is used during the study of transmission power system, which is carried out according to [22].

To enhance the comprehension of the proposed method, two different systems are analyzed in the next section.

5. Case studies

To show the performance of the proposed model in the solution of coupled electricity and gas flow problem, in this paper two case studies are applied as described below:

1) a combined system consisting of the IEEE-14 bus network and a 16-node gas network.
2) a combined system consisting of the IEEE-30 bus network and a 15-node gas network with 4 compressors.

Note that the case study 1) corresponds to a natural gas network that includes only pipes, while case study 2) corresponds to a natural gas network that considers pipes and compressors. The results are compared to the traditional Newton-Raphson approach.

5.1. Case study 1

The LAT-NR methodology is applied to analyze the coupled natural gas and electricity system consisting of a 16-node gas network and the IEEE-14 bus test system [23], shown in Fig. 3. The natural gas infrastructure is composed of 9 gas demands, 4 supplies and 21 pipes as shown in Tables 1 and 2 . The diameters and lengths of pipes can be consulted in Table A.1. Node 1 of the gas network is selected as a slack node with a pressure equal to 547 PSIA. In the simulation an average gas temperature of 495 °R is considered and the Weymouth generalized gas-flow equation with a compressibility factor of 0.9 and a specific gravity of 0.69 is used.

On the other hand, the electrical network has the power generations and demands presented in Table 1, where two GFPPs are considered operating on buses 2 and 3 fed from nodes 3 and 13 of the natural gas infrastructure, respectively. Similar to the gas network, Table 2 presents the connections of the transmission lines. The operation characteristics of the GFPPs with their gas consumption coefficients are presented in Table A.2. Additionally, the mismatch tolerances are 1^{-3} in the gas infrastructure and 1^{-8} in the electrical infrastructure.

The results in Table 1 indicate that the GFPPs located on buses 2 and 3 of the power system require a total gas flow of 33.7 MMSCFD to generate 178 MW. The reference node of the natural gas network provides 121 MMSCFD to satisfy the total demand of the system. Table 2 reports the flow rates in the pipes and power flows in the transmission lines obtained with the proposed methodology. Here, in order to validate the results achieved with the LAT-NR methodology, Table 2 shows the results of flow rates in the pipes obtained by the Newton-Raphson

Table 4
Power flow and gas flow rate for Case 2.

Power flow							Gas flow rate					
Line	From Bus	To Bus	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	Pipe	From Node	To Node	Gas flow NR (MMSCFD)	Gas flow LAT-NR (MMSCFD)	Error
L1	1	2	10.89	−5.09	−10.86	2.17	P1	1	3	174.29	174.29	0.00
L2	1	3	15.08	4.09	−14.96	−5.57	P2	2	4	164.80	164.80	0.00
L3	2	4	16.07	5.21	−15.89	−6.66	P3	3	4	−42.14	−41.78	0.36
L4	3	4	12.56	4.37	−12.54	−4.30	P4	3	5	124.33	123.96	0.37
L5	2	5	13.79	4.51	−13.68	−6.03	P5	4	7	111.55	111.91	0.36
L6	2	6	20.28	7.42	−19.99	−8.50	P6	6	9	123.56	123.20	0.36
L7	4	6	22.50	11.38	−22.43	−11.12	P7	8	11	110.80	111.16	0.36
L8	5	7	13.68	6.21	−13.56	−6.88	P8	10	13	122.80	122.44	0.36
L9	6	7	9.27	3.17	−9.24	−4.02	P9	12	14	110.06	110.42	0.36
L10	6	8	24.82	24.43	−24.69	−23.92	P10	13	14	5.41	5.11	0.30
L11	6	9	5.79	−3.36	−5.79	3.46	P11	13	15	15.08	15.02	0.06
L12	6	10	3.31	−1.92	−3.31	2.00	P12	14	15	12.90	12.95	0.05
L13	9	11	0.00	0.00	0.00	0.00						
L14	9	10	5.79	−3.36	−5.79	3.51						
L15	4	12	−1.67	−2.02	1.67	2.04						
L16	12	13	−37.00	−9.26	37.00	11.35						
L17	12	14	5.39	0.88	−5.35	−0.80						
L18	12	15	9.48	−1.06	−9.41	1.19						
L19	12	16	9.26	−0.10	−9.18	0.28						
L20	14	15	−0.85	−0.80	0.85	0.80						
L21	16	17	5.68	−2.08	−5.65	2.15						
L22	15	18	9.16	0.76	−9.07	−0.57						
L23	18	19	5.87	−0.33	−5.85	0.38						
L24	19	20	−3.65	−3.78	3.66	3.80						
L25	10	20	5.92	4.62	−5.86	−4.50						
L26	10	17	3.37	8.01	−3.35	−7.95						
L27	10	21	−2.23	−11.67	2.28	11.77						
L28	10	22	−3.75	−8.48	3.82	8.62						
L29	21	22	−19.78	−22.97	19.87	23.16						
L30	15	23	−8.81	−5.25	8.91	5.47						
L31	22	24	−2.10	7.80	2.18	−7.68						
L32	23	24	7.09	0.88	−7.02	−0.75						
L33	24	25	−3.86	1.77	3.89	−1.71						
L34	25	26	3.55	2.37	−3.50	−2.30						
L35	25	27	−7.44	−0.66	7.50	0.78						
L36	28	27	−6.11	−6.08	6.11	6.40						
L37	27	29	6.17	1.68	−6.08	−1.51						
L38	27	30	7.12	1.67	−6.95	−1.35						
L39	29	30	3.68	0.61	−3.65	−0.55						
L40	8	28	−5.31	−6.08	5.34	4.33						
L41	6	28	−0.77	−2.70	0.77	1.75						

Table 5
Consumption of compressor stations for Case 2.

Compressor stations	HP NR	HP LAT-NR	Error	Gas consumption NR (MMSCFD)	Gas consumption LAT-NR (MMSCFD)	Error
C1	3821.61	3810.41	11.20	0.7640	0.7617	0.0023
C2	3727.24	3739.19	11.95	0.7451	0.7475	0.0024
C3	3798.13	3787.00	11.13	0.7593	0.7570	0.0023
C4	3702.35	3714.21	11.86	0.7401	0.7425	0.0024
Total				3.0086	3.0089	

method. Likewise, the last column of Table 2 indicates the differences between the NR traditional method and the LAT-NR approach. In this case study, the total mean absolute deviation is 0.61, which confirms the viability of the results achieved.

Fig. 4 shows the convergence of the method during the calculation of the flow rates through the pipes for Case 1. The iterative process was initialized under the assumption that $L_{(i,j)} = C_{(i,j)}$, which results in an overestimation of the gas flow during the first iterations of the iterative process (k). However, it can be observed how the error decreases as the number of iterations increases.

5.2. Case study 2

The case study corresponds to a 15-node natural gas network with four compressors and the IEEE-30 bus test network [23]. The coupling between both infrastructures occurs through two GFPPs located on buses 1 and 2 as shown in Fig. 5. The gas consumption coefficients of the GFPPs are presented in Table B.1. On the other hand, the natural gas network consists of 15 nodes, 12 pipes, 3 demands, 2 supplies and 4 compressors. The diameters and lengths of the pipes are reported in Table B.2. In the gas system the Weymouth equation is considered with an average gas temperature of 520 °R with a compressibility factor of

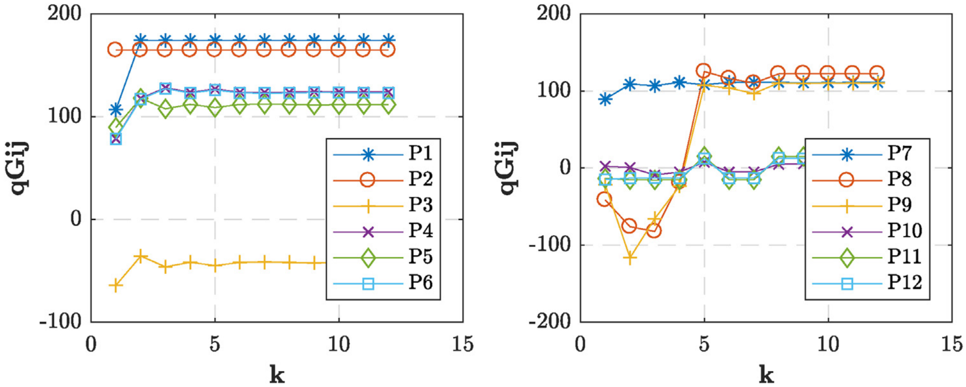

Fig. 6. Convergence of flow rate *qGij* for Case 2.

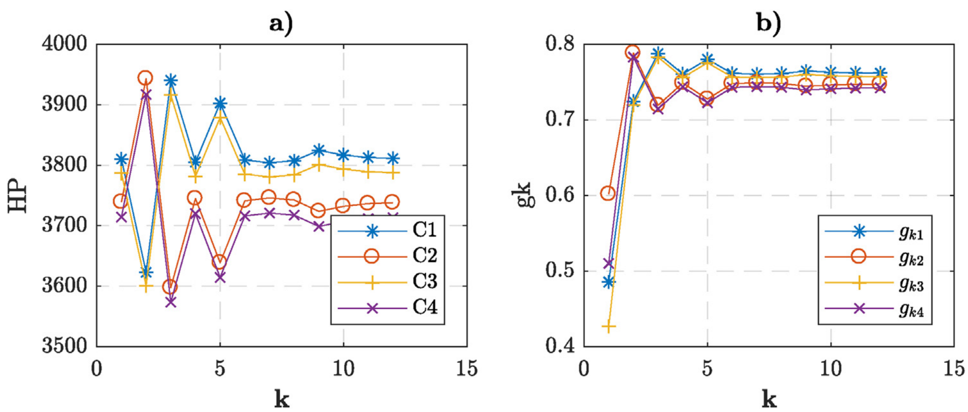

Fig. 7. Convergence of HP and $g_{(k)}$ for Case 2.

Table A.1
Diameters and lengths of pipes for Case 1.

Pipe	Length (miles)	Internal diameter (in)	Pipe	Length (miles)	Internal diameter (in)	Pipe	Length (miles)	Internal diameter (in)
P1	37.49	30.95	P8	13.32	15.5	P15	17.76	12.25
P2	13.88	33.35	P9	15.43	15.5	P16	46.36	12.25
P3	31.26	33.35	P10	10.31	14.18	P17	34.84	15.44
P4	9.13	31.65	P11	19.28	25.17	P18	30.59	25.47
P5	15.99	19.5	P12	21.47	12.25	P19	41.90	25.37
P6	35.52	19.5	P13	11.05	12.25	P20	16.55	23.44
P7	30.18	17.5	P14	5.70	12.25	P21	22.75	23.44

Table A.2
Operation characteristics of GFPPs for Case 1.

Generator	Coefficient of gas consumption (MM^3/MW)			$P_{G_{min}}$ (MW)	$P_{G_{max}}$ (MW)
	K_0	K_1	K_2		
2	0	0.00555	0	0	100
3	0	0.00516	0	0	100

Table B.1
Operation characteristics of GFPPs for Case 2.

Generator	Coefficient of gas consumption (MM^3/MW)			$P_{G_{min}}$ (MW)	$P_{G_{max}}$ (MW)
	K_0	K_1	K_2		
1	0	0.00555	0	0	100
2	0	0.00516	0	0	100

Table B.2
Diameters and lengths of pipes for Case 2.

Pipe	Length (miles)	Internal diameter (in)	Pipe	Length (miles)	Internal diameter (in)	Pipe	Length (miles)	Internal diameter (in)
P1	80.5	19.56	P5	87.9	19.62	P9	97.9	16.69
P2	80.3	19.56	P6	93.5	19.62	P10	86.6	16.69
P3	55.9	19.56	P7	99.7	16.69	P11	79.7	16.69
P4	81.1	19.62	P8	93.5	16.69	P12	83.5	16.69

0.9. Unlike the case study 1, the efficiency of pipes 9 and 12 is assumed to be 0.85, while the resting pipes are assumed to be 0.9. Node 1 of the gas network is considered as the slack node with a pressure equal to 1000 PSIA. The compression stations are operating with only one stage and a consumption factor of 199.92 SCFD/HP. The tolerances in the iterative process are 1^{-3} in the gas infrastructure and 1^{-8} in the electrical infrastructure.

Table 3 shows the results of simulation of power generation, loads, supplies and gas demands of the coupled electricity and natural gas infrastructure. GFPPs on buses 1 and 2 produce 25.97 MW and 60.97 MW, respectively. These generators require 16.2002 MMSCFD of natural gas to provide such amount of power. On the other hand, the reference node of gas network injects 174.2916 MMSCFD of natural gas in order to achieve the system balance. In parallel, Tables 4 and 5 show the power flows and flow rates, as well as the natural gas consumption of the compression units, respectively. Moreover, the results are also reported between the LAT-NR methodology and the NR approach. Note that the mean absolute deviations are 0.25, 11.54 and 0.0024, for the flow rates in pipes, horsepower (HP) and gas consumption in compressors. As can be seen, the LAT-NR technique offers a good solution on the simulation results of coupled natural gas and electricity flows.

In Figs. 6 and 7 , the convergence of the iterative process for the calculation of the flow rate, HP and natural gas consumption for case 2 is presented. Identically to Case 1, the process was initialized under the assumption that $L_{(i,j)} = C_{(i,j)}$. Fig. 6 shows the different gas flows calculated in each iterative step (k). Here, it can be observed that during the first iterations the gas flow in certain pipes varies drastically; however, as the number of iterations advances the gas flow stabilizes. In the same way, Fig. 7a) presents the calculation of HP and Fig. 7b) shows the gas consumption for the previous calculations. Note that the natural gas consumption is a function of the compressor HP.

6. Conclusions

In this paper, a methodology has been presented to jointly analyze the coupled electricity and gas flow, where the existence of combined cycle power plants and compressors has been considered. The set of non-linear equations that represent the operation of the power system has been solved using Newton-Raphson (NR) method, while the solution of the gas nodal balance and flow rates in the pipelines and compressors on the gas network have obtained using the linear-analog approach (LAT). Two case studies have been presented to demonstrate the simplicity of the methodology proposed to analyze the interaction between gas and electricity systems. The results obtained with LAT have been verified against the Newton-Raphson method for gas networks, in order to confirm the solution reached, finding a good performance of the joint methodology applied LAT-NR. The application of the proposed approach allows the analysis of vulnerability and resilience of interdependent power and gas infrastructures. The authors are currently working in this area of research using the method described in this paper.

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Appendix A. Data for Case 1

Appendix B. Data for Case 2

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Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures

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Abstract: In this paper, we evaluate the use of statistical indexes from graph theory as a possible alternative to power-flow techniques for analyzing cascading failures in coupled electric power and natural gas transmission systems. Both methodologies are applied comparatively to coupled IEEE and natural gas test networks. The cascading failure events are simulated through two strategies of network decomposition: Deliberate attacks on highly connected nodes and random faults. The analysis is performed by simulating successive N-*k* contingencies in a coupled network, where the network structure changes with the elimination of each node. The suitability of graph-theoretic techniques for assessing the vulnerability of interdependent electric power and natural gas infrastructures is demonstrated.

Keywords: electrical grid protection; natural gas transmission networks; graph theory; cascading failures; interdependent critical infrastructure

1. Introduction

Modern society depends on increasingly complex and interdependent energy systems, such as electric power and gas networks. These systems could be at risk from various threats and faults. A disturbance or failure in one network may not be critical if the two systems are considered separately but, as these networks are coupled, any analysis must include both systems so that the potential propagation or amplification of the individual disturbance effects can be captured. Therefore, the problem of interdependence between critical infrastructure systems must be addressed [1].

Natural gas and electric power transmission networks are highly interdependent for two reasons: Natural gas is increasingly being used for the production of electricity in combined-cycle power plants, and compressors in gas networks often require electric power. These networks can fail, not only because of their technical complexity, but also because of their interdependence.

The disruption of one infrastructure could cause failures in the other infrastructure, as a result of the interdependent effects that bind these systems together, which can lead to severe economic problems and the loss of human lives [2]. For this reason, our research takes into account the effects of interdependence when conducting studies in the two joint systems. The above is a situation whose application is generally unconsidered in the scientific literature.

The literature review on natural gas and electricity infrastructures has been traditionally focused on the study of N-1 contingency events, the planning of both integrated systems, the quantification of reliability, and the evaluation of hardening strategies. For example, the references [3,4] model a stand-alone system that includes gas network restrictions on the whole energy system. The reference [5] explores the effect of the gas system on the overall efficiency of the power system, while [6] analyzes the future of electric power generation as a result of improvements in the natural gas infrastructure.

On the other hand, references [7,8] examine the reliability of the electrical system as a function of the natural gas system, while [9] studies the optimal operation of the integrated energy system via robustness studies. The works in [10,11] evaluate strategies in system hardening and smart technologies aimed at increasing resilience. The reference [12] explores the planning model of the gas-electricity network using coupled cooling heating and power systems.

Although the previous works are related to the study of the gas and electricity networks in a coupled manner, none of them quantifies the consequences of high-impact events that may interfere in the daily operation of these infrastructures. All energy networks are exposed to different types of failures or attacks, and operators must implement risk management methodologies to evaluate the degree of weakness of the system under these severe threats, assessing the vulnerability of the infrastructure.

Therefore, the current research only focuses on load flows in terms of the security of the whole integrated system. Nevertheless, flows within and between infrastructures play a significant role in the operation of both systems. On the other hand, few studies have addressed the concept of vulnerability in coupled energy networks but, in most cases, the large amount of technical information makes it difficult to carry out studies, as evidenced in [13]. In this sense, complex network theory is an emerging method that can be useful for studying and assessing the vulnerability of critical energy infrastructures [14].

The vulnerability of the integrated natural gas and power system can be defined as a lack of robustness and resilience against high impact events. Robustness indicates that the joint network continues to operate under attack or disturbance, and resilience indicates that the interdependent system can adapt and achieve a new stable condition after a contingency.

When analyzing the interdependence between natural gas and power systems, two types of vulnerability can be distinguished: Functional and structural vulnerability [14]. On one hand, functional vulnerability implies a detailed analysis of the operating conditions of the infrastructures [15]. Although the interconnection of the two systems increases the energy transfer capacity, it also implies that local disturbances spread throughout the networks. The failure of a power line can lead to the inability of distribution substations, which may cause electrical energy not to be delivered to electric compressors in the gas network. The failure of a gas pipeline, as a consequence of a deficient operation, can cause the loss of fuel for the coupled electric generators [16]. In both cases, a disturbance can spread to the other system and, ultimately, to the end users. On the other hand, structural vulnerability is related to a decrease in performance and efficiency of the integrated network after an attack [17,18].

Therefore, this article proposes the use of graph theory to assess the vulnerability of integrated gas and electricity networks and to study the performance of both systems against cascading failures. This technique allows us to overcome the problems derived from obtaining technical data in the infrastructure systems under study. Thus, this article provides an original contribution by developing a more effective proposal, in order to achieve the same results as the well-known technique of coupled load flows, but without the need to use the electrical and mechanical parameters of the infrastructures. We believe that this research will help to better investigate the performance of electricity- and natural gas-critical infrastructures.

The main contributions of this article can be summarized as follows:

1. A novel methodology, using graph theory, is proposed to assess the structural vulnerability of interdependent electricity and natural gas infrastructures.
2. The effectiveness of the graph statistical indexes is validated, versus the traditional technique of coupled natural gas and power flows.
3. New original topological representations of the natural gas and electricity systems are employed.

The paper is structured as follows. Section 2 describes the use of scale-free graphs to model electric power and gas networks. Section 3 presents the vulnerability indexes for networks. Section 4 describes the cascading failure algorithm for assessing the vulnerability of interdependent electric power and natural gas networks. Section 5 discusses the numerical results from two case studies of integrated systems represented by electrical and natural gas test networks. Section 6 summarizes the main conclusions of this paper.

2. Networks Models

In this section, we consider an infrastructure that is composed of two interdependent networks: An electrical network and a natural gas network. Here, we describe each network model and propose a novel representation using scale-free graphs. The use of scale-free graphs is significant because the structures of the graphs are similar to those of the actual networks. In addition, the use of graphs allows study of the properties and the vulnerability of various topologies, among others [19].

2.1. Electrical Network Model

An electric power system delivers the power produced in generation plants to consumers through a connected network. The electrical network is typically represented as a graph composed of nodes and links. The nodes represent points of interconnection between two or more electrical components, and the links represent transmission lines and electrical transformers [20]. In the traditional representation, the assets connected to substations, such as generation plants, loads, and compensators, are not represented separately in the graph but, rather, as a single integrated node.

Figure 1 shows our proposal of a topological representation of a four-bus electrical network, in comparison with the traditional representation than only considers nodes and links. Here, transformers, transmission lines, loads, capacitors, and reactances could be considered as assets that can be eliminated, to represent attacks or failures in the electrical network.

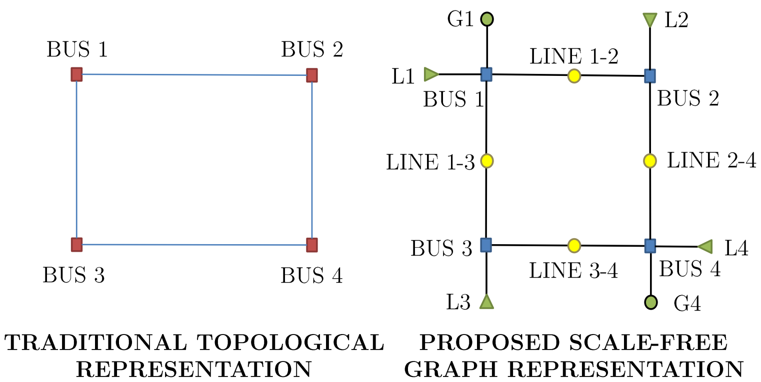

Figure 1. Proposed representation as a scale-free graph of a four-bus electrical network.

2.2. Gas Network Model

A gas network transports natural gas from production sites to consumers, where it is required for heating, industrial demand, and electricity generation [21]. The traditional topological representation is a graph composed of nodes and links. Interconnection points are represented by nodes, and compressors and pipelines are represented by links [21,22]. Gas supplies and loads are not included.

Figure 2 shows our proposal of a topological representation of a gas network consisting of eleven nodes and a compressor, in comparison with the traditional representation that considers only nodes and links. Our graph takes into account pipelines, demands, and gas supplies as nodes, that can be eliminated to represent deliberate attacks or random faults.

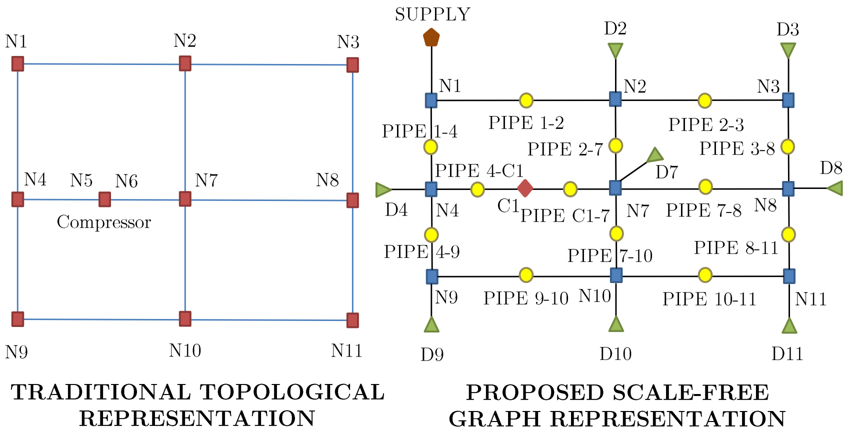

Figure 2. Proposed representation as a scale-free graph of a natural gas network.

2.3. Coupling between Networks

The coupling between gas and electrical systems occurs through interactions between certain assets in the two networks:

1. On one hand, combined-cycle power plants or gas turbine plants that consume natural gas to produce electricity;
2. On the other hand, the electrical system supplies power for the operation of compressors in the gas network.

Figure 3 represents our novel coupling proposal, where the graphs of Figures 1 and 2 are considered. The resulting network consists of 49 nodes and 55 links in total. The graph represents the links between the gas and electric power networks as nodes. In the case of natural gas supply to the combined-cycle power plants, the coupling nodes represent the gas pipelines that transport the gas to the generation plants. Similarly, the power lines supplying electricity to the compressor stations in the gas network are represented as nodes.

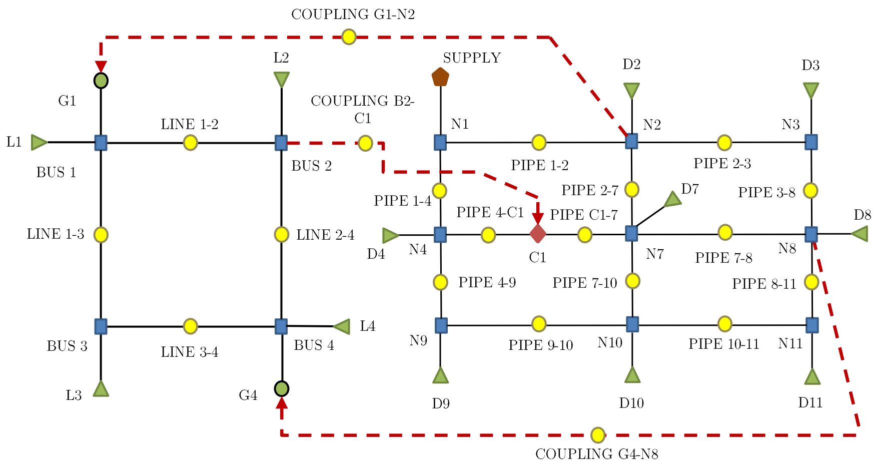

Figure 3. Scale-free graph of coupled electric power and gas networks.

This original representation, using graphs, offers a realistic topological model of the coupled networks. In addition, the nodes representing the coupling can be removed from the graph to initiate cascading failures. Previous representations in the literature have not considered this level of detail. It can be shown that the proposed models for the electric power and gas networks are scale-free graphs by calculating the cumulative distribution and its analytical equivalent with the power-law function, as given in graph theory [19]. A scale-free graph is a network in which several nodes are highly connected through a certain number of links [23,24]. This type of graph allows evaluation of the robustness of the networks against certain failure events and characterization of their topological properties using statistical measures [25].

3. Measures of Vulnerability in Networks

We use the geodesic vulnerability index ($\widetilde{v}$) and impact on connectivity (S) to measure the functionality of the combined electric power and gas network, with respect to the stable condition, when the functionality of a node is compromised. These indexes have been applied to both IEEE test networks and actual electrical networks [26,27]. Although the potential of these indexes has been shown in electrical networks, they have not been applied in coupled networks, which is the goal of this work. The geodesic vulnerability index ($\widetilde{v}$) normalizes the geodesic efficiency and balances the process of node elimination, as indicated in Equation (1):

$$\widetilde{v} = 1 - \frac{\sum_{i \neq j}(\frac{1}{d_{ij}^{LC}})}{\sum_{i \neq j}(\frac{1}{d_{ij}^{BC}})}, \tag{1}$$

where:

d_{ij}^{LC} is the geodesic distance between pairs of nodes of the scale-free graph, following the elimination of a node; and

d_{ij}^{BC} is the geodesic distance between pairs of nodes of the scale-free graph, for the base case.

The geodesic distance is defined as the shortest distance between two nodes, which is obtained by counting the minimum number of nodes that must be crossed to join them [28]. The value of $\widetilde{v}$ varies between zero and one. The greater the value is, the greater the effect on the supply disruption in the coupled network.

On the other hand, the connectivity index S, which quantifies the number of nodes that remain connected to the larger network following the elimination of a node, is defined as

$$S = 1 - \frac{N^{LC}}{N}, \tag{2}$$

where:

N^{LC} is the number of nodes that remain connected in the scale-free graph, following the elimination of a node; and

N is the total number of nodes in the scale-free graph for the base case.

The value of S varies between zero and one. The greater the value is, the greater the number of isolated nodes in the coupled electric power and gas network.

The performance of the coupled electric power and gas network is quantified by the geodesic vulnerability index in Equation (1) and the connectivity index in Equation (2), which are determined as a function of the fraction of removed nodes (f).

Although the performance analysis of cascading failures in a coupled electric power and gas network can be conducted using the evolution of the aforementioned indexes, a comparison of the effectiveness of graph theory measures with that of traditional power flow indexes, which incorporate the electrical and mechanical parameters of the network, must be demonstrated. Therefore, we propose adapting the load shedding index (LS) to measure the effect of cascading failures by running power flows [29]. The load shedding index quantifies the loads that remain connected in the coupled network, following successive interruption events.

For an electrical subnetwork, the load shedding index is defined as

$$LS = 1 - \frac{\sum_i \sqrt{(P_{Di}^{LC})^2 + (Q_{Di}^{LC})^2}}{\sum_i \sqrt{(P_{Di}^{BC})^2 + (Q_{Di}^{BC})^2}}, \tag{3}$$

where:

P_{Di}^{LC} is the total active power that remains connected in the electrical network, following the removal of a node;

Q_{Di}^{LC} is the total reactive power that remains connected in the electrical network, following the removal of a node;

P_{Di}^{BC} is the total active power in the base case; and

Q_{Di}^{BC} is the total reactive power in the base case.

For a gas subnetwork, the load shedding index is defined as

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

where:

D_i^{LC} is the total gas demand remaining connected in the gas network, following the removal of a node; and

D_i^{BC} is the total gas demand in the base case.

Note that, in Equation (4), the gas demand is normalized to the electrical equivalent, which is calculated from the calorific value and the operating pressure and temperature at each node. In this work, we assumed that 1 m^3 of natural gas is equivalent to 11.63 kWh for all the nodes of the network, as indicated in the data provided in [30].

In both the gas and electrical networks, the value of LS varies between zero and one. As the value increases, the effect on the loads connected in the coupled network also increases, where the effect is measured as a function of the fraction of removed nodes (f). The solutions obtained with this index are compared with the results obtained through the graph theory indexes given in Equations (1) and (2).

4. Algorithm to Evaluate Structural Vulnerability in Coupled Electric Power and Gas Networks

In this paper, we assess the structural vulnerability of coupled electric power and gas networks in a cascading failure event. For simplicity, IEEE test networks and natural gas test networks are used. The two networks are coupled by interdependent links that represent the bidirectional dependencies, as indicated in Figure 3. It is assumed that the electrical network has m combined-cycle natural gas power plants, which are fed from n nodes of the gas network. Identically, the gas network has p compressors that operate through an external power supply, provided by q nodes of the electrical network.

Figure 4 shows the flow chart of the proposed algorithm to evaluate the structural vulnerability against cascading failures in coupled electric power and gas networks, where the geodesic vulnerability index ($\widetilde{v}$), the connectivity index (S), and the load shedding index (LS), measured for each fraction of removed nodes (f), are used to assess the vulnerability.

Cascading failures are simulated by removing nodes to represent two types of disruptions:

1. Deliberate attack: Where the nodes with a large number of links are sequentially eliminated, in descending order of nodal degree.
2. Random faults: Where nodes are eliminated randomly (from the central limit theorem, more than 30 simulations are required to obtain a suitable statistical sample [31]).

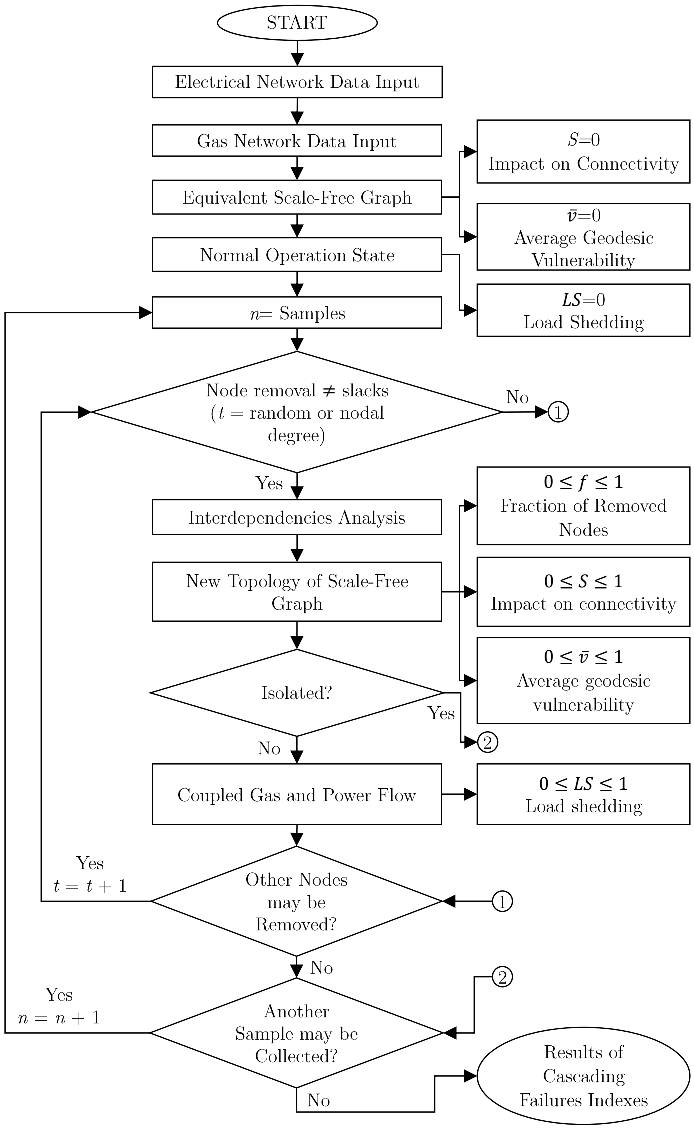

Figure 4. Flow chart for the algorithm to evaluate the structural vulnerability against cascading failures in coupled electric power and gas networks.

Successive iterations of N-k contingencies are performed on a coupled network, where the structure of the network changes as each node is removed. As it is not possible to run power flows without the existence of a slack electric generator, a gas supply injection node, and a coupling link between the slack generator and the gas network, these nodes are excluded from removal in the simulations (red boxes in Figure 5). This is because the slack generator provides the balance in the power flow equations, the gas injection node represents the gas delivery point for the coupled generator, and the coupling link represents the asset that transports natural gas between the two infrastructure systems. Thus, in order to obtain the solution to the flow equations of both networks and to give a realistic representation, the proposed algorithm in Figure 4 always keeps these nodes linked. Besides, this allows the calculation of the LS and $\widetilde{v}$ indexes to be unified during the decomposition process of interdependent networks.

In Figure 5, electric generator 14 and bus 1 are fixed references for the electrical network, node 48 represents the pipeline that transports natural gas from node 17 of the gas network to generator 14, and node 46 represents the gas supply injected into the network from node 16. It would not be possible to run power flows if these nodes were removed.

The successive removal of nodes can generate interdependent effects in the coupled network, especially if the nodes involve the natural gas supply to the generators, the electrical substations that provide electric power to the compressor units, the supply pipelines to the compressors, or the coupling links between the gas and electrical networks.

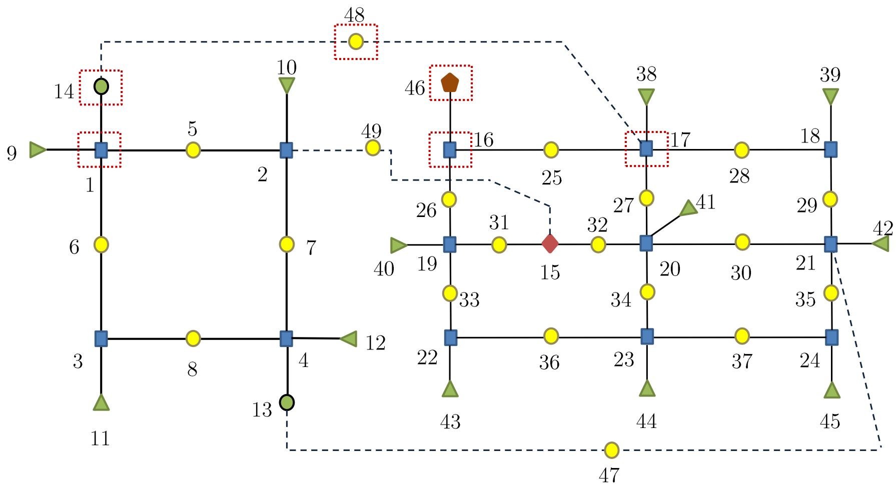

Figure 5. Scale-free coupled graph indicating the nodes that are excluded from removal.

The iterative process, detailed below in Figure 6, shows steps in the execution of the flow chart of Figure 4, applying a deliberate attack scenario to the graph shown in Figure 5. Starting with the node with the highest number of incident links and proceeding in descending order of nodal degree, in each iteration step (t) a node with a large number of links is eliminated. The geodesic vulnerability index ($\tilde{v}$), the impact on connectivity index (S), and the load shedding index (LS) are then calculated. The calculations are performed only for the largest set containing the nodes that cannot be eliminated (i.e., those indicated by the red boxes in Figure 5). This is done with the purpose of obtaining a unified computation of load shedding and geodesic vulnerability indexes. Otherwise, it could cause divergences in the results of the graph statistical index.

In Figure 6, the evolution process of the coupled natural gas and electric power network of Figure 5 is illustrated. Note that, when node 20 is initially removed at $t = 1$, the network is divided into three independent subnetworks, for which two nodes do not have links.

In the next time step ($t = 2$), the node with the next highest order, node 21, is removed from the larger subnetwork. Note that, when this node is eliminated, an interdependency effect appears in the electrical network because this node supplies natural gas to the generator represented by node 13. The interdependence in our model emerges when the coupled generator (node 13) and its connection (link 47, which represents the natural gas supply) are removed from the graph.

At $t = 3$, the attack on node 2 of the electrical network causes a new interdependence effect, now on the gas network. The loss of this asset prevents electricity from flowing to the compressor at node 15. The interdependent effect is simulated by disconnecting the affected assets (nodes 2, 49, and 15) of the coupled graph. In some cases, the node that is attacked corresponds to the input pipeline of a compressor; in those cases, it is necessary to determine whether the compressor unit is powered by electricity or by natural gas. In either case, a disruption to an inlet pipeline is equivalent to the loss of the compressor, and also of the link to the electrical network, if the unit relies on an external power supply. Similarly, the elimination of couplings causes interdependent effects on both networks. For example, the loss of node 47, which represents a natural gas transmission pipeline, causes the loss of the coupled generators. In turn, the loss of node 49, which represents the electrical transmission lines, causes the loss of the coupled gas compressors. The neighboring nodes that are affected as a result of the elimination of the links between the two networks must be eliminated from the graph.

In many cases, there are multiple nodes with the same number of connecting links. In these cases (at $t = 4$, for example), a node is chosen at random from among those with the same nodal degree.

At $t = 5$, several islands are formed when node 19 is disrupted. One of the islands contains nodes that cannot be eliminated. Therefore, in the next iteration the node to be eliminated is required to be on the same island, as can be observed in Figure 6 from $t = 6$ to $t = 9$. The algorithm ends when there are no more nodes to remove, or there are no more networks for which power flows could be obtained, in this case at $t = 10$.

The algorithm in Figure 4 was implemented in the Matlab® programming environment. The coupled natural gas and electricity flows have been calculated, using the modeling framework explained in detail in [32]. The program developed here includes graph theory algorithms, such as using the shortest path algorithm of Bellman-Ford [33] to calculate the geodesic distances in Equation (1).

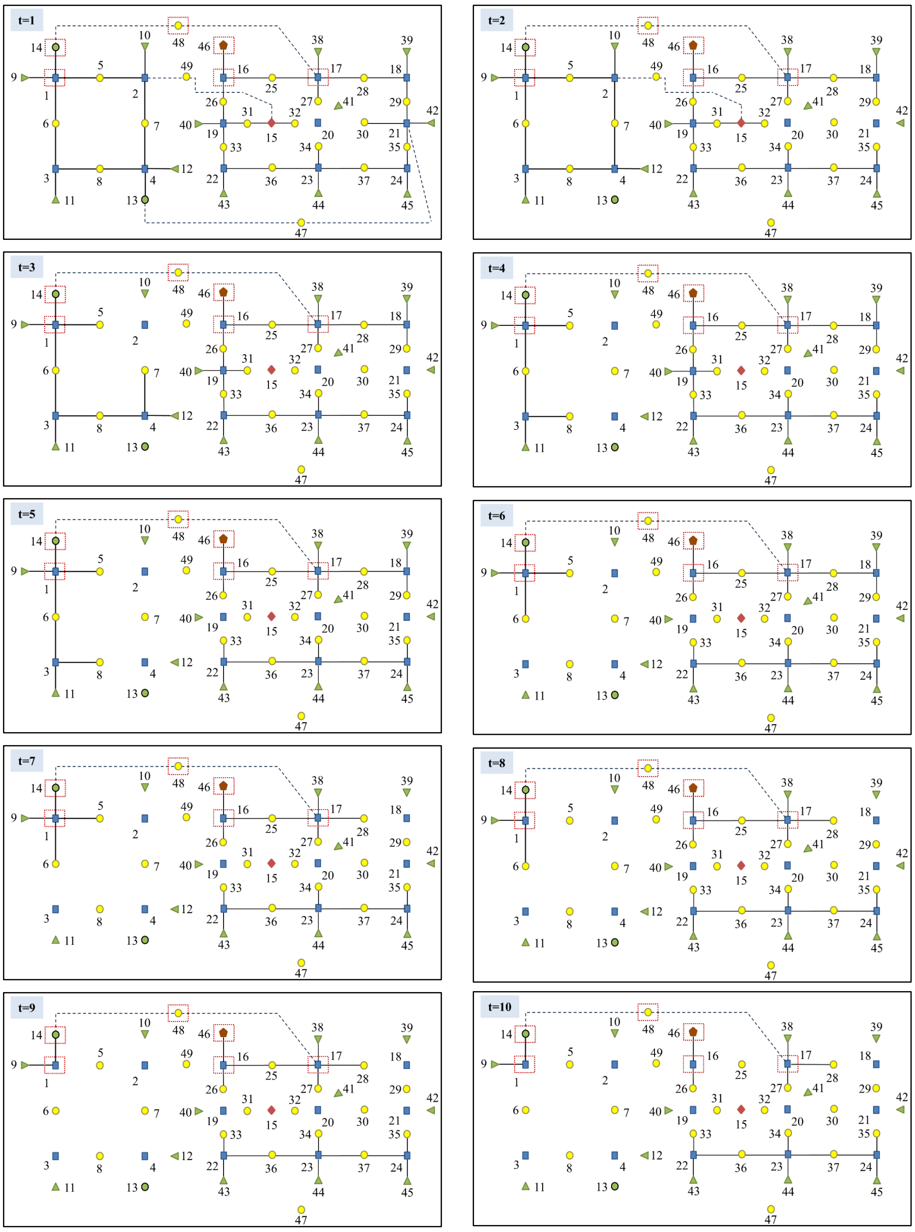

Figure 6. Evolution process of coupled electric power and gas networks using the proposed algorithm.

In this way, it is possible to evaluate the structural vulnerability of coupled electric power and gas networks to cascading failures for both deliberately induced and randomly occurring faults.

5. Case Studies

Given the novelty of the problem posed here, it was necessary to define coupled test networks of electrical and natural gas infrastructures. The systems used here are the IEEE-57 and IEEE-118 test networks, and the Osiadacz test networks of 22 and 25 nodes. The IEEE-57 and IEEE-118 Bus Test Cases represent a portion of the American Electric Power System (in the Midwestern US) [34], and the Osiadacz test networks of 22 and 25 nodes represent a gas infrastructure similar to that of Belgium [35,36]. Thus, we constructed two case studies:

1. A combined system consisting of the IEEE-57 bus network and a 22 node gas network, and
2. a combined system consisting of the IEEE-118 bus network and a 25 node gas network with 3 compressors.

The details of the networks are as follows.
Case study (1):

- The 22 node gas network consists of 19 non-electric loads, one supply, and 36 pipelines. Node 21 is assumed to be a supply. The gas system is analyzed using Weymouth's generalized gas flow equation. An average gas temperature of 495 °R is considered, and an average compressibility factor of 0.90 is assumed for illustration purposes. In this case study, the gas has a specific gravity of 0.69, and all pipelines are assumed to be horizontal with an efficiency of 1.0. The physical characteristics of gas pipelines and loads can be found in [35].
- The IEEE-57 bus network consists of 42 loads, 17 transformers, 80 lines, 3 capacitors, and 7 generators [34].
- It is assumed that generators 1, 2, 3, 6, 8, and 9 are natural gas combined-cycle power plants fed by gas network nodes 22, 14, 15, 9, 5, and 1, respectively. The operation characteristics of the coupled generators are presented in Table A1.

Case study (2):

- The 25 node gas network consists of 18 non-electric loads, 3 compressor units, 1 supply, and 35 pipelines. Node 1 is assumed to be a supply. The gas infrastructure is analyzed using the Weymouth's gas flow equation. The average fluid temperature is 520 °R with an average compressibility factor of 0.90. The gas has a specific gravity of 0.69, and all pipelines are horizontal with an efficiency of 1.0. The physical characteristics of gas pipelines and loads can be found in [35].
- The IEEE-118 bus network consist of 99 loads, 9 electrical transformers, 186 transmission lines, 14 capacitors, and 54 generators [34].
- Generators 10, 12, 18, 19, 46, 49, and 69 are assumed to be natural gas combined-cycle power stations fed by gas network nodes 20, 7, 18, 8, 9, 10, and 4, respectively. The operation characteristics of the coupled generators are presented in Table A2.
- The electrically powered compressors are supplied with power by the substations of the electrical network at nodes 26, 60, and 58. The compression units operate with consumption factors of 199.92 SCFD/HP, a suction temperature of 520 °R, average compressibility of 0.90 and a polytropic exponent of 0.90. Moreover, the compressors operate in one stage with compression ratios of 1.8.

In Figure 7, the simulation results for the two case studies are shown. Figure 7a,c,e show the results for randomly occurring faults, and Figure 7b,d,f show the results for deliberately induced faults. In the following, the results obtained with the load shedding index (LS) are compared with the results obtained with the two graph theory indexes, the geodesic vulnerability index ($\widetilde{v}$) and connectivity index (S). These indexes are dimensionless and are calculated for the eliminated nodes fraction (f), as shown in the flow chart in Figure 4.

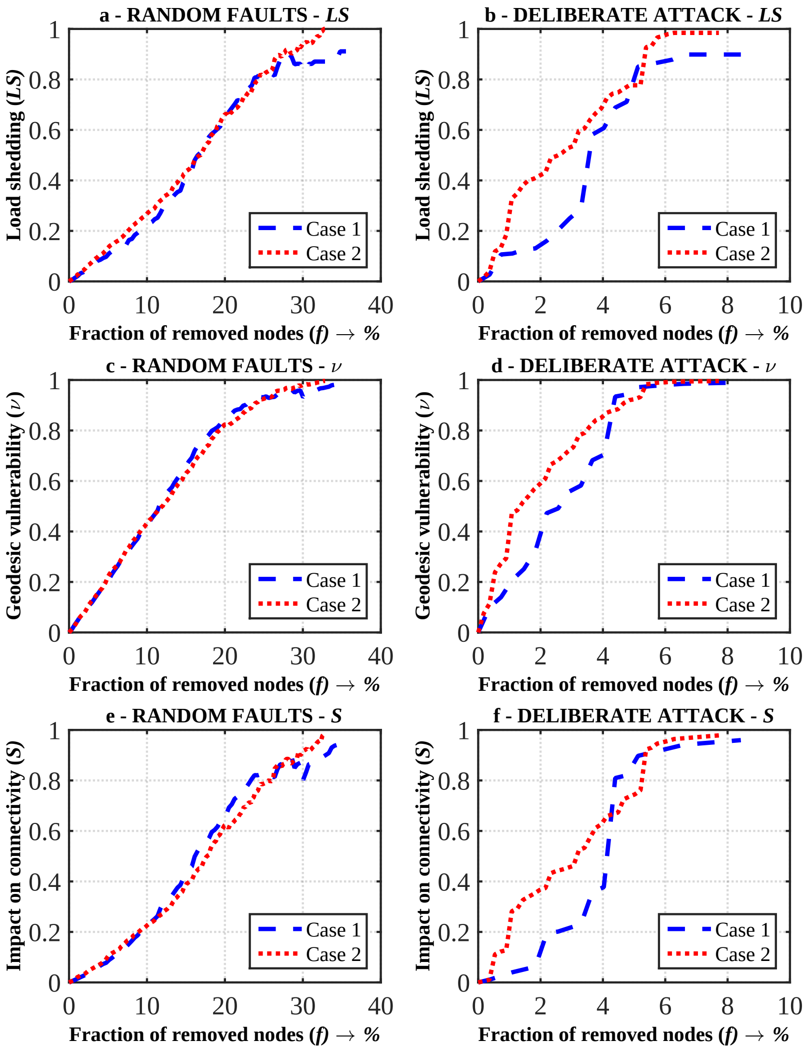

Figure 7. Simulation results for cascading failure cases.

5.1. *Load Shedding Index (LS)*

From the power flow method, it can be observed in Figure 7a that, with randomly occurring faults, the total collapse of the coupled networks occurred following the elimination of more than 30% of the nodes, which indicates that complete failure occurred gradually. The evolution of *LS* for case study 2 shows that this coupled network was more vulnerable, because there was greater load shedding for the same eliminated node fraction. In addition, the results show that the system in case study 1 collapsed at a greater eliminated node fraction.

Figure 7 shows that, under deliberate attacks, the networks collapsed with the elimination of only 7% of the nodes. The results for deliberate attacks again showed that the system in case study 2 was more vulnerable. This system has compressors powered by electricity, which results in greater dependencies between the electrical and gas networks.

Case study 2 reflects what would happen in an actual network if the nodes with strong connectivity were attacked, where the interdependent effects would cause significant economic and social disruption.

Additionally, note that the evolution in the system topology generates a slight load recovery when about 30% of the nodes are removed (Figure 7a). This can be explained by the fact that, in different samples, a circuit is connected around the largest connected component that allows the circulation of power flows, but a new iteration of these cascading failures causes a new collapse in the network.

5.2. Graph Theory Indexes

Figure 7c–f show the results obtained with the graph theory indexes $\widetilde{\nu}$ and S to randomly occurring and deliberately induced faults. These indexes can be compared with LS.

For the randomly occurring faults, the indexes $\widetilde{\nu}$ and S were consistent with the results obtained with LS: The networks collapsed, following the elimination of more than 30% of the nodes. Comparing Figure 7a,c, it can be observed that the system in case study 2 was more vulnerable. Moreover, the trend in $\widetilde{\nu}$ was very similar to that of LS. However, comparing Figure 7a,e, it can be observed that S, despite producing acceptable results, was not highly consistent with LS. These differences are evident in the deliberate attack scenarios, shown in Figure 7b,f. This difference is more evident in case study 1.

The network decomposed more rapidly with deliberate attacks than with random faults. The results, shown in Figure 7d,f, indicate that the networks became isolated when more than 7% of the nodes were eliminated.

It should be noted that, in all cases, when the value of $\widetilde{\nu}$ was nearly one, there was a greater fragmentation of the network. Similarly, the value of S was nearly one as the network was almost completely disintegrated.

Comparing the results of Figure 7a–d, it can be concluded that, when compared with LS, $\widetilde{\nu}$ more accurately represents the disintegration of the coupled networks than S.

5.3. Correlation between Indexes

The curves plotted in Figure 7 allow graphical comparisons between the different sets of results, obtained using coupled load flow techniques and the statistical indices of graph theory. However, visual representation is not desirable in most cases, and a quantitative index is needed to determine the degree of correlation of the results more accurately. The Pearson correlation coefficient ρ is a practical measure to calculate the dependence between LS and $\widetilde{\nu}$ and between LS and S. This index is obtained by dividing the covariance of each pair of variables by the product of their standard deviations σ [31].

The correlation coefficient ρ_1 between LS and $\widetilde{\nu}$ is given by

$$\rho_1 = \frac{cov(LS, \widetilde{\nu})}{\sigma_{LS}\sigma_{\widetilde{\nu}}}, \tag{5}$$

and the correlation coefficient ρ_2 between LS and S is given by

$$\rho_2 = \frac{cov(LS, S)}{\sigma_{LS}\sigma_{S}}. \tag{6}$$

Table 1 shows the values for the correlation coefficients ρ_1 and ρ_2 for the various cases. Note that, in the degradation of the coupled networks with random faults, the value of ρ_1 is closer to +1 for the two case studies, which implies a positive linear relation between LS and $\widetilde{\nu}$. This analysis shows that the statistical graph measure $\widetilde{\nu}$ is useful for determining which loads are disconnected in cascading failures.

Table 1. Correlation between power flow index (LS) and graph theory indexes ($\widetilde{\nu}$, S).

	Correlation	Case Study 1	Case Study 2
Random	ρ_1 $(LS, \widetilde{\nu})$	0.9987	0.9992
	ρ_2 (LS, S)	0.9759	0.9802
Deliberate	ρ_1 $(LS, \widetilde{\nu})$	0.9805	0.9970
	ρ_2 (LS, S)	0.9677	0.9754

The values of ρ_2 also indicate a correlation in both case studies, although the value, again, shows that S evolved slightly differently from $\widetilde{\nu}$, with respect to LS.

Similar results for ρ_2 were obtained for the cases with deliberate attacks. Therefore, the geodesic vulnerability index $\widetilde{\nu}$ is useful for comparing different topologies of coupled networks, to determine which is more vulnerable. The results obtained are consistent with the qualitative relations observed in Figure 7a,c for random faults, and in Figure 7b,d for deliberate attacks.

Table 2 shows the execution times of the algorithm of Figure 4 in the two case studies and for both node removal strategies, either running coupled load flow and, alternatively, using graph indexes. It is observed that the centrality measures of graphs are more computationally efficient than the coupled load flow on the gas and electricity networks, since the computation times were reduced by more than 80%. Therefore, the geodesic vulnerability index is a measure that can very well characterize the structural vulnerability of different interdependent electricity and natural gas infrastructure topologies.

Table 2. Computation time of the algorithm of Figure 4.

Node Removal Strategy	Computational Time	IEEE 57–Gas 22 (min)	IEEE 118–Gas 25 (min)
Deliberate	Coupled gas and power flow	2	6.2
	Graph theory indexes	0.3	1.12
Random	Coupled gas and power flow	150	345
	Graph theory indexes	18	42

The importance of the proposed geodesic vulnerability index is that it can be used for analyzing coupled electric power and gas networks without detailed knowledge of the system's electrical and mechanical parameters. Moreover, this method can provide the operators of electric power and gas systems a new tool for analyzing the interdependencies in these networks. Also, in broader terms, the methodology developed here may be useful for studying network expansion plans, from the viewpoint of structural vulnerability and robustness. In other words, thanks to the proposed statistical measure, each of the different investments in the network could be evaluated. The results obtained would provide an overview of how different assets could improve or worsen the response behavior of the coupled infrastructure in the face of undesirable events.

6. Conclusions

In this paper, a methodology, based on graph theory, has been proposed to analyze the structural vulnerability of coupled natural gas and electricity networks. New topological representations of both infrastructures, as scale-free graphs, have been defined to consider the interdependence effects of four assets: The gas network facilities that supply fuel to the combined cycle plants, the electrical substations that provide power to the compressors, the compressor inlet lines, and the coupling links between both networks. Vulnerability has been quantified, using the results obtained from the traditional indices of coupled load flow (LS) and, alternatively, from two statistical indices from graph theory, $\widetilde{\nu}$ and S, applied to two case studies. In the latter, a statistical analysis has shown a strong correlation between the load shedding (LS) index and the $\widetilde{\nu}$ geodesic vulnerability index. Thus, for the first time, a statistical measure of geodesic vulnerability has been validated, surpassing the traditional indices which require a detailed knowledge of the electrical and hydraulic parameters of the systems. The results have clearly shown that the graph index is more efficient from a computational standpoint than the load flow measurement, because the computation time needed to perform the studies was reduced by more than 80%. As a result, a new method has been established to estimate the structural vulnerability of joint electricity and gas systems, using the proposed geodesic vulnerability index.

Our future research will apply this methodology to identify critical assets more susceptible to cascading failures, and to study optimal strategies for network recovery.

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Appendix A

Table A1. Operation characteristics of the combined cycle power plants for Case 1.

Generator	Coefficient of Gas Consumption (MM^3/MW) K_0	K_1	K_2	$P_{G_{min}}$ (MW)	$P_{G_{max}}$ (MW)
1				0	575.88
2				0	100
3	0	0.00555	0	0	140
6				0	100
8				0	550
9				0	100

Table A2. Operation characteristics of the combined cycle power plants for Case 2.

Generator	Coefficient of Gas Consumption (MM^3/MW) K_0	K_1	K_2	$P_{G_{min}}$ (MW)	$P_{G_{max}}$ (MW)
10				0	550
12				0	185
18				0	100
19	0	0.00516	0	0	100
46				0	119
49				0	304
69				0	805.2

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Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures

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Abstract: Electricity and natural gas networks are critical infrastructure for society, but the robustness of coupled networks has not been evaluated, even though both systems have strong interactions. This article proposes a novel graph theory-based methodology to assess the structural robustness of the coupled natural gas and electricity transmission networks in Spain while considering their interdependencies. Cascading failures were simulated in 22 case studies with different topologies, and the performance against random failures was evaluated. The results show that the investment programme proposed by both network operators ultimately improves the robustness of the interdependent electricity and natural gas infrastructure in Spain compared to the current system.

Nomenclature

G	graph
V, N	vertices or nodes
E	links or edges
i	index for the upstream node
j	index for the downstream node
k	nodal degree
$\bar{k}$	average nodal degree
$\bar{l}$	average shortest path length
$d_{i,j}$	shortest geodesic distance between nodes i and j
d	network diameter
$\bar{e}$	geodesic efficiency
$\bar{v}$	geodesic vulnerability
$d_{i,j}^{\mathrm{LC}}$	shortest geodesic distance between nodes i and j following the elimination of a node
$d_{i,j}^{\mathrm{BC}}$	shortest geodesic distance between nodes i and j for the base case

1 Introduction

Electricity and natural gas networks are fundamental for the daily operations of any country. These complex and interdependent systems are prone to failures and threats that can cause serious interruptions to the services provided. Directive 2009/72/EC of the European Parliament emphasises the importance of having a safe and reliable supply of electricity [1]. Energy supply security involves assessing the robustness of networks against various contingencies to address their weaknesses. However, the high complexity of the energy systems poses major challenges [2]. This is evident in Spain, where the significant integration of the electricity and gas networks creates many challenges for analyses [3]. As such, these networks have recently become a subject of study by academics and researchers.

In recent years, several approaches have been proposed to analyse interdependent networks [4], including the approach based on networks or graph theory, which has been widely validated [5]. This method allows the robustness of systems to be assessed considering their topological properties through centrality measures.

The electrical infrastructure consists of several facilities, such as generators, transmission lines, loads, and electrical transformers. The natural gas infrastructure consists of compression stations, pipelines, underground facilities, compressors, and other facilities. These systems can be described by graph theory as a network of nodes and links [6]. The networks can be disintegrated through deliberate or random failures characterised by centrality indexes. This disintegration process is analogous to cascading failures. In this context, Motter and Lai [7] proved that premeditated attacks can collapse electrical networks. Therefore, the simulation of these events involves the use of indexes such as the clustering coefficient and geodesic distance [8, 9]. However, other scholars have used other indexes, such as the nodal degree, network diameter, and efficiency [10].

In addition, several authors, such as [11, 12], have created methodologies that used the geodesic vulnerability index to evaluate the structural vulnerability of the electrical networks of Mexico, Spain, and Colombia. These studies analysed the expansion plans for the networks and concluded that the investments made do not improve their vulnerability to deliberate attacks. However, the investments result in a considerable improvement when random failures are considered.

The studies discussed above were based only on the topology of the networks and did not consider the electrical or mechanical characteristics of the networks. Therefore, Chen *et al.* [13] evaluated an electrical network using the geodesic efficiency index and considering the operational characteristics of the system. Likewise, Wang *et al.* [14] used the maximum load and capacity of the generators as well as the betweenness index. Other researchers have used hybrid models of graph theory and game theory [15].

On the other hand, some research studies have created synthetic electrical networks in order to evaluate the impact of topology, generators, and re-dispatch policies on the power grid [16]. The conclusions show that the above factors should be improved to reduce energy losses within the electrical infrastructure when cascading failures occur. Similarly, in [17], a model that estimates the efficiency of IEEE test networks and synthetic networks using graph indexes has been proposed. Here, it is shown that the robustness of the power system could be subject to the average shortest path length measure and the location of the generators. Other researchers, such as [18, 19], have included risk assessments and stochastic variables to assess the vulnerability of the power system, respectively.

The indexes used in studies on gas networks include the average geodesic distance, efficiency, betweenness, and maximum flow [20, 21]. Other studies have calculated the load flows and geodesic efficiency in parallel [22]. An attack on the links of the networks has also been considered to analyse how to achieve long-term topology improvements [23, 24]. Finally, several studies have used Monte Carlo simulation techniques and economic and technical models [25, 26].

More recently, other academics have evaluated the electricity and natural gas infrastructures in a coupled manner. For instance, stochastic models have been proposed for the joint planning of both systems [27, 28] and for the improvement of operational security [29, 30]. In addition, scholars have developed algorithms to enhance resilience against natural disasters and malicious attacks [31, 32]. Some remaining works have used computer programs and two-stage optimisation methods [33, 34] and the interruption of electric generators and power transmission lines has also been considered [35].

In summary, the research works described above have employed different methods and techniques in order to study the coupled electricity and natural gas systems. However, the lack of studies evaluating the robustness of the expansion plans of the two networks has been observed. In this manuscript, emphasis is placed on the importance that both energy critical infrastructures should be addressed as coupled networks due to their strong interactions. A disturbance on a system may not be critical if the infrastructures are separated, but since both networks are interdependent, the resulting impact could cause failures on the other system. Interdependencies increase the impact of disturbances.

In this article, graph theory has been proposed as a novel approach for the robustness assessment of the expansion plans of joint 400 kV electrical infrastructure and 80 bar high-pressure natural gas infrastructure in Spain. This research uses this technique because, as previously mentioned, it has been proved as a very useful tool to analyse the structural characteristics and performance under cascading failures of interdependent networks [4]. Here, robustness is the ability of the coupled system to resist multiple attacks or failures. The major contributions of this work can be summarised as follows:

i. A representation of the coupled electricity and natural gas infrastructures in Spain with a high level of detail has been proposed.
ii. A novel procedure with graph theory has been developed for the robustness assessment of the expansion plans of coupled electricity and natural gas systems. Here, four effects of interdependencies have also been taken into account.

To achieve the last objective, 22 case studies with different topologies of the infrastructure under study have been considered.

The remainder of this article is organised as follows. Section 2 presents the methodology used for assessing the structural robustness of the coupled electricity and natural gas network in Spain and describes the topological indexes used in this article. Section 3 reports all of the case studies, and Section 4 presents the numerical results obtained from the simulation of cascading failures. Finally, Section 5 presents the main conclusions of this study.

2 Methodology for assessing the structural robustness of coupled electricity and natural gas network

Power system security is the ability of the electric power system to withstand sudden disturbances or contingencies. Several categories and corresponding indicators can be considered in this definition when planning the power system: adequacy, quality of supply, stability, reliability, voltage, collapse etc.

Reliability indexes have been usually employed to assess *N*–1 or *N*–2 contingencies, analysing the continuity of the operations of the power grid in the case of failure of any asset through metrics as frequency and duration of power outages, expected energy not supplied, among others.

On the other hand, vulnerability or robustness indexes have been used to study the weakness of electrical infrastructure under *N*–*k* contingencies, traditionally using load flows [36]. In this case, a model in steady state is more recommended in order to analyse cascading failures on the systems under study. However, graph theory is emerging as an assessment method for cascading failures on interdependent electricity and natural gas infrastructures. This technique consists on mapping the topologies of the energy systems by converting each of the facilities to nodes (generators, substations, loads, gas storages, compressors, ...) and power lines and pipelines to links [5]. Next, centrality measures are calculated following each step of disintegration of the joint system. Some of these indexes show strong correlation with the load disconnected in the cascading failures process and let characterise the structural robustness of different topologies of the coupled electricity and natural gas network [37].

2.1 Graph theory indexes

Electricity and natural gas networks are represented as an ordered graph $G\ (V,\ E)$, where the links are ordered pairs of the form (i, j) such that $(i, j) \in E$ [6]. In this context, several graph indexes describe the topological characteristics of these networks [38]. This study uses the nodal degree, shortest path length, network diameter, geodesic efficiency, and geodesic vulnerability as indexes. The first four indexes are used to characterise the current topology of the coupled network in Spain, and the last index measures the structural robustness against cascading failures.

The nodal degree (k) is the number of links of a node. The average nodal degree $(\bar{k})$ can also be estimated. These indexes provide a relative measure of how meshed the network is

$$\bar{k} = 2 \cdot \frac{E}{V} \tag{1}$$

The average shortest path length $(\bar{l})$ measures the accessibility of a node relative to another, which is the path from a given node to another node in the network

$$\bar{l} = \frac{1}{N \cdot (N-1)} \sum_{i \neq j} d_{i,j} \tag{2}$$

The network diameter (d) is the longest path length as measured by the number of links. A large network diameter indicates that the flow circulates through a greater number of links. This study uses the Bellman–Ford algorithm to obtain the shortest geodesic distance $d_{i,j}$ [39]

$$d = \max_{(i,j)} d_{i,j} \tag{3}$$

The geodesic efficiency ($\bar{e}$) quantifies the information exchange efficiency within a network. The flow between two nodes is assumed to occur through the shortest geodesic distance [13]. A low-efficiency value indicates that the flow travels between many nodes

$$\bar{e} = \frac{1}{N \cdot (N-1)} \sum_{i \neq j} \frac{1}{d_{i,j}} \tag{4}$$

The geodesic vulnerability ($\bar{v}$) is an index that measures the performance of the network against contingencies, and it normalises (4) in relation to its base case [40]. This index ranges between zero and one; the greater the index is, the greater its impact on the network

$$\bar{v} = 1 - \frac{\sum_{i \neq j} \left(1/d_{i,j}^{\mathrm{LC}}\right)}{\sum_{i \neq j} \left(1/d_{i,j}^{\mathrm{BC}}\right)} \tag{5}$$

This index has proved to be useful for quantifying the load that is disconnected due to disintegration processes caused by cascading failures [11, 12, 37]. The geodesic vulnerability index is also used in this study to evaluate the structural robustness of the coupled electricity and natural gas network.

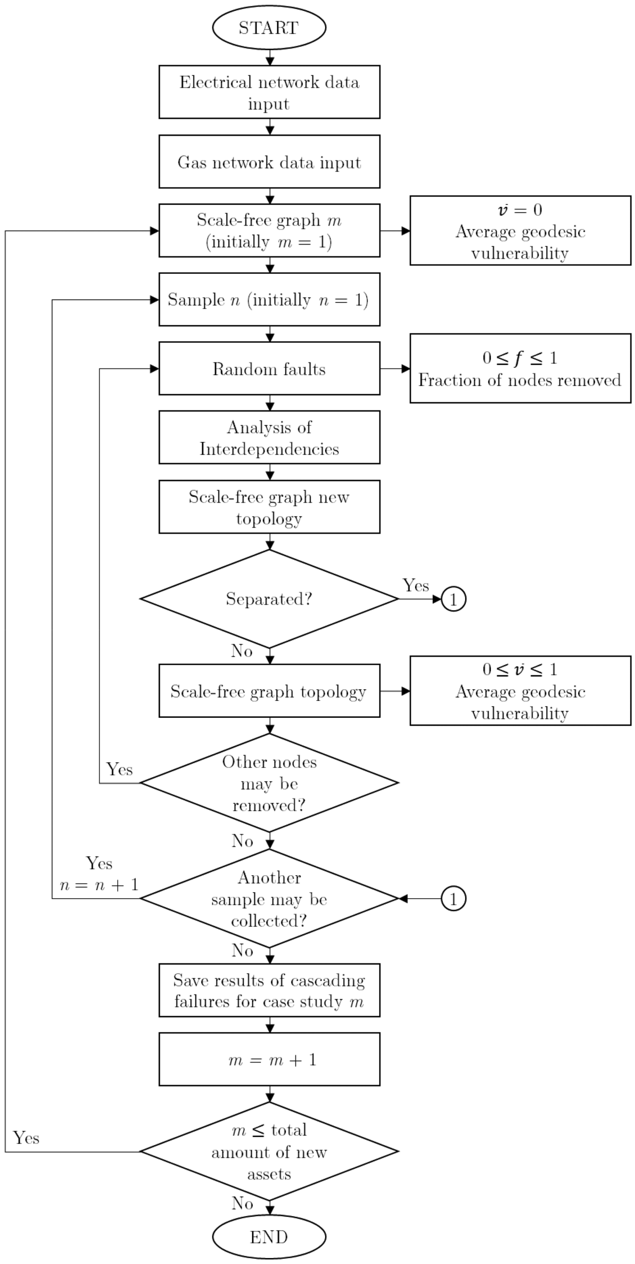


Fig. 1 *Algorithm for assessing the structural robustness of electricity and natural gas networks*

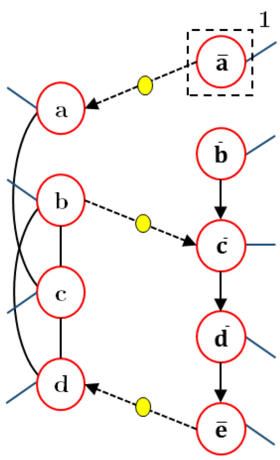


Fig. 2 *Analysis of interdependencies. Base case*

2.2 Algorithm for assessing the structural robustness of coupled networks against cascading failures

The electricity and natural gas networks of Spain are coupled through combined cycle plants that use natural gas to produce electricity. These networks are also coupled through compressors in the gas network that demand a reliable supply of electrical power. These interactions are represented by nodes and links that describe the exchange of energy between the two infrastructure systems.

Fig. 1 shows the proposed algorithm used to assess the structural robustness against cascading failures in coupled electricity and gas networks. This algorithm uses the evolution of the geodesic vulnerability index ($\bar{v}$) measured in terms of the fraction of nodes removed (f).

Previous studies validated that using network topology in combination with centrality measures is an efficient tool for adequately assessing the performance of energy systems [11, 12, 37]. Therefore, for an appropriate methodological application of the algorithm shown in Fig. 1, it is necessary to know the topological structure of the studied networks in detail. Likewise, the use of the geodesic vulnerability index in (5) is proposed to quantify the load that is disconnected from the interdependent electricity and natural gas infrastructure during the process of cascading failures.

The first step in the algorithm shown in Fig. 1 is to create a scale-free graph of the coupled electricity and natural gas network. A scale-free graph is a grid in which several nodes are highly connected through a certain number of links [38, 41]. This type of graph allows the robustness of networks against certain failure events to be assessed and their topological properties to be characterised using the indexes described above [42].

Researchers have simplified the representation of these two systems. Most studies only consider some facilities in the electricity and gas networks, such as substations, power lines, compressors, and pipelines [9, 22]. This representation is incomplete because not all of the assets of the networks are considered. This study proposes using a more complete original model that considers all assets and facilities.

In the algorithm shown in Fig. 1, the events used to simulate cascading failures are created by randomly removing nodes. The removal of a node involves removing all of the links connected to it, which represents one iteration in the process of disintegration of the network. This study uses the central limit theorem, which suggests repeating a random experiment at least 30 times for appropriate statistical processing [11]. Each sample contains the set of results obtained by the successive execution of contingencies $N-k$.

The structural robustness is quantified by calculating the geodesic vulnerability index using (5). This index is a function of the number of nodes that are left isolated (f). The iterative process ends once no more nodes can be removed from the graph.

2.3 Analysis of interdependencies

The removal of some of the nodes from a network may have interdependent effects on the other interconnected network. We classify the assets that interconnect the gas and electricity systems into four types:

i. facilities in the gas network that supply fuel to power generation plants;
ii. electrical substations that provide power to compressors;
iii. inlet lines of the compressors;
iv. coupling links between both networks.

The algorithm shown in Fig. 1 considers the random disintegration of the various assets of the gas and electricity infrastructure and allows the elimination of the four types of coupling facilities described above. Figs. 2–4 show the strategy used in this study for the case in which the coupling facilities are removed by the algorithm.

Circles a, b, c, and d in Fig. 2 represent the nodes of an electrical network, and circles $\bar{a}$, $\bar{b}$, $\bar{c}$, and $\bar{d}$ represent the nodes of a gas network. The nodes in yellow indicate couplings between the two networks. The lines are internal connections between the networks. The boxes indicate facilities 1, 2, 3, and 4, respectively.

Fig. 2 shows the base case of a simple coupled network. In Fig. 3*a*, an interdependence effect towards the electrical network is produced when facility 1 is removed because this node supplies natural gas to generator a. This methodology considers removing node a and its coupling on the graph (yellow node), which represents the loss of fuel supply. In Fig. 3*b*, an interdependence towards the gas network is produced when facility 2 is removed because this node provides power to the compressor $\bar{c}$. The interdependent effect can be observed when the affected facilities are disconnected from the combined scale-free graph, including all of the links adjacent to the substation, the coupling node, and coupled compressor. In some simulation cases (e.g. Fig. 4*a*), the removed node could correspond to facility 3; in such cases, it must be determined if the compressor runs on electricity or on natural gas from the network. In both cases, an attack on an inlet line results in the loss of the compressor, and if it runs on an external power supply, the coupling link to the electrical network is lost as well. Likewise, the removal of the couplings causes interdependent effects between the two networks. The removal of the couplings in Fig. 4*b* causes the loss of compressor $\bar{c}$ and coupled generator d. In all cases, the nodes whose supply is affected by the removal of links between the two systems must also be removed from the scale-free graph.

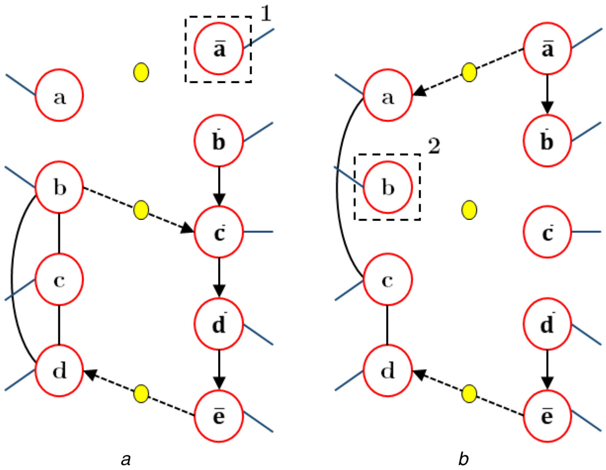


Fig. 3 *Analysis of interdependencies. Process 1*

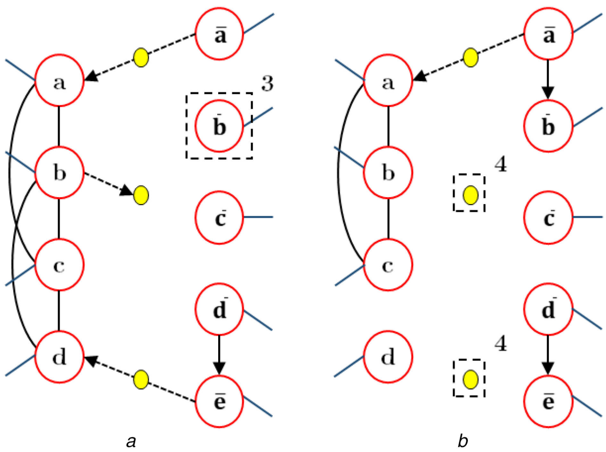


Fig. 4 *Analysis of interdependencies. Process 2*

3 Case studies

This section presents the case studies. The current topology of the coupled electricity and natural gas network in Spain is described first, and the cases evaluated in this study are then presented.

3.1 Current topology of the coupled electricity and natural gas network in Spain

The 400 kV high-voltage power network and the 80 bar high-pressure natural gas network are considered in this study. The high-voltage power network features >21,000 km of high-voltage power lines, >1000 substations, and >80,000 MVA of transformation capacity [43]. In addition, the high-pressure natural gas network features >11,000 km of piping and a set of facilities for the optimal operation of the infrastructure [44].

Fig. 5 shows the scale-free graphs that represent the electricity and gas networks and the coupled network of both systems. This representation considers all of the assets of both systems based on the open source information provided by the operators in [44–47].

The 400 kV high-voltage power network is composed of electrical substations, generators, electrical loads, power lines, and transformers. Here, the data to build the scale-free graph of Fig. 5*a* are extracted from the network map of the transmission system operator [45]. In addition, the 80 bar high-pressure natural gas network of Fig. 5*b* contains 6 regasification terminals, 19 compression stations, 3 underground storage facilities, 2 gas fields, 6 international connections, 32 connection points for direct lines, 57 transmission–transmission connection points, and 294 transmission–distribution connection points. The data are extracted from the gas system operator [44, 46, 47].

The natural gas combined cycle thermal power plants and the electric compressors serve as couplings for the networks described above. This study evaluates 26 combined cycle power plants connected to 400 kV electrical substations [45, 47]. In addition, the natural gas network includes 14 compressors that require a power supply [44]. Finally, Fig. 5 represents the coupled network that we consider as the base case. Section 4.1 describes some of the

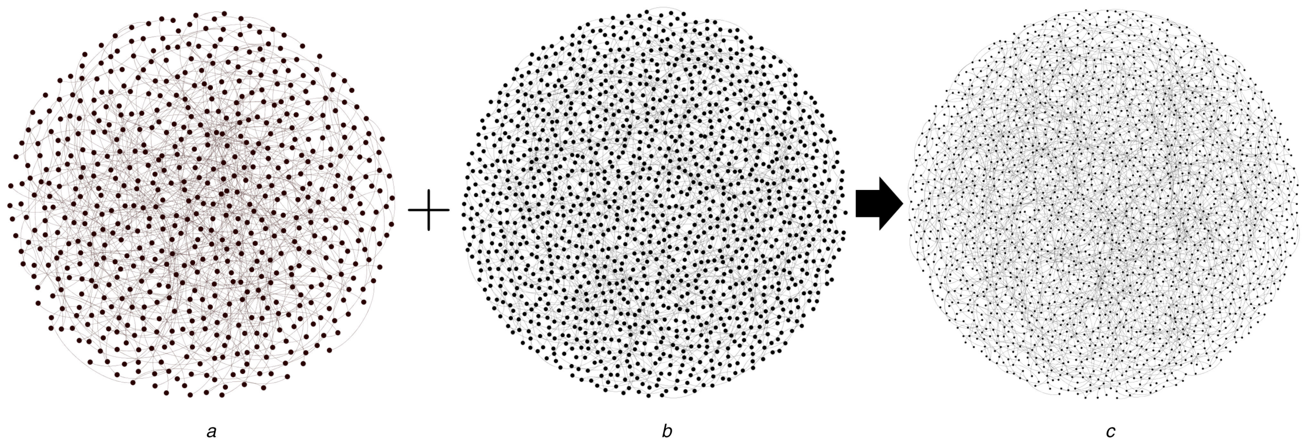


Fig. 5 *Scale-free graphs of the electricity and natural gas infrastructure in Spain*
(a) Four hundred kilovolt electrical network, ***(b)*** Eighty bar natural gas network, ***(c)*** Coupled network

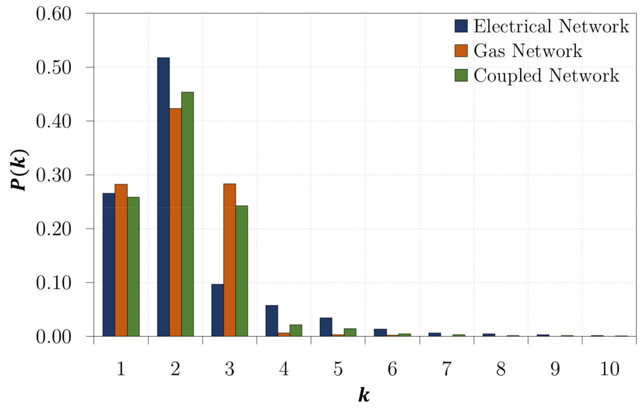


Fig. 6 *Nodal degree distributions of the base case*

topological characteristics of these systems using the indexes described in (1) through (4).

3.2 Description of the case studies

The network operators have expansion plans to improve the security of the electricity and gas supplies to users. The report by Ministerio de Industria, Energia y Turismo [3] considers the case of Spain; it describes the proposed network investments for 2015–2020 and provides information about the construction of new power lines, substations, pipelines, compression stations, and other facilities. The investments proposed through 2017 are currently ongoing and consequently are considered in the base case shown in Fig. 5. Therefore, this study considers case studies related to the construction of new 400 kV high-voltage power lines and 80 bar high-pressure gas pipelines from 2018 until 2020. Table 1 summarises the 22 cases analysed according to the planned investments.

The cases follow the chronological order of construction proposed by the operators of both networks. It should be noted that every new case includes the previous improvements. Table 1 shows that a new power line is added in each instance except in case 19, where a new pipeline is added to the gas network. The last two cases, 21 and 22, correspond to the extension of the natural gas network.

4 Simulation

This section presents the simulation results of the implementation of the algorithm shown in Fig. 1. The algorithm was implemented in the Matlab®2017 programming environment using a computer with an Intel®Core i7 processor, 3.40 GHz CPU and 32 GB of RAM. First, several topological characteristics of the base case are described.

4.1 Topological characteristics of the base case

The nodal degree distribution allows standardising graphs in which several nodes with a large number of connections transform into key points of the network. Fig. 6 shows the nodal degree distributions ($P(k)$) for the networks shown in Fig. 5. The nodal degree distribution $P(k)$ is the probability that a randomly selected node has exactly k connections.

In the case of the individual networks, the electrical network has a distribution ($P(k) > 0.25$) for ($k = 1$); namely, the probability that a node has a single link is >25%. The gas network has a probability of 28%. Therefore, the results indicate that the electrical network contains fewer assets with a single link than the gas network.

However, for ($k = 2$), the distributions of the natural gas network and the electric network are ($P(k) > 0.40$) and ($P(k) > 0.50$), respectively; the natural gas network contains fewer assets with only two links.

For the nodes with the strongest connections, which are key to the robustness of the infrastructure, the electric network has nodes with a high degree of connection ($k = 10$), but the natural gas network only has nodes up to ($k = 6$).

Table 1 Case studies

Case study	Electrical network	Gas network
base case	current topology	current topology
case 1	new power line	—
case 2	new power line	—
case 3	new power line	—
case 4	new power line	—
case 5	new power line	—
case 6	new power line	—
case 7	new power line	—
case 8	new power line	—
case 9	new power line	—
case 10	new power line	—
case 11	new power line	—
case 12	new power line	—
case 13	new power line	—
case 14	new power line	—
case 15	new power line	—
case 16	new power line	—
case 17	new power line	—
case 18	new power line	—
case 19	new power line	new pipeline
case 20	new power line	—
case 21	—	new pipeline
case 22	—	new pipeline

The analysis of the coupled electric and gas network (Fig. 6) shows that the probability of having a node ($k = 2$) is ($P(k) > 0.40$). This means that >40% of the nodes have only two connections with other nodes in the network. The value ($k = 2$) corresponds to pipelines and electricity transmission lines. In addition, almost 25% of the nodes have a connection degree of ($k = 3$). These nodes represent compressors and substations where three power lines meet. The value ($k = 1$) corresponds to nodes with a single link, which usually corresponds to generators, loads, regasification terminals, international connections, underground storage facilities, and gas fields.

Fig. 6 shows that the topology of the coupled network has a structure that is similar to the gas network in the lower nodal degrees ($k = 1$ to $k = 6$) but also incorporates the high connectivity nodes of the electricity network ($k = 6$ to $k = 10$). In addition, by comparing the cumulative distributions of the nodal degrees and the power law function [41], Fig. 7 demonstrates that the networks analysed correspond to scale-free graphs. Both results show that $P(k \geq 1) = 1$, which means that all of nodes in the graph contain at least one connection. Additionally, the probability of having nodes with at least two connections ($k \geq 2$) is high in all cases with a probability close to 1 and successively with the other nodal degrees $\forall k_i \in [1, 10]$.

Table 2 shows other topological characteristics of the base case, and the main results are listed below:

i. The electrical network has the largest average nodal degree $\langle k \rangle$. This demonstrates that the electrical network's structure is more meshed than that of the gas network. Furthermore, the average nodal degree of the coupled network is between those of the gas and electricity networks.
ii. The maximum nodal degree (k_{max}) of the electricity network is 10; therefore, the coupled network has the same maximum value. The electrical network contains nodes with large numbers of connections.
iii. The natural gas network contains 1402 links and a very high network diameter ($d = 210$), but this does not mean that it is a meshed network. As shown in Table 2, for the natural gas network, an increase in the network diameter (d) causes a

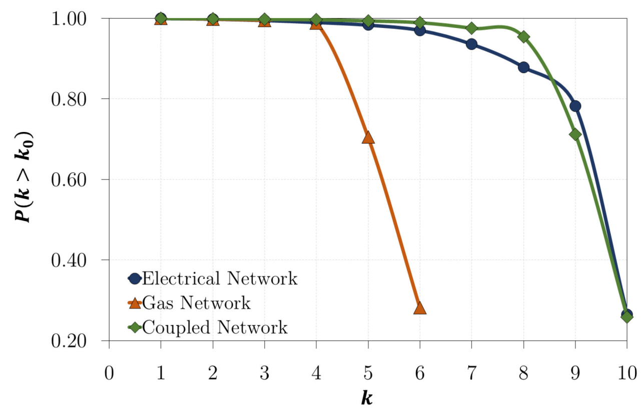
reduction in the efficiency ($\bar{e}$); as the number of nodes increases, the flow in the network must travel through a greater number of links.

The indexes shown above provide a better understanding of the topology structure of the gas and electricity networks as well as that of the coupled network.

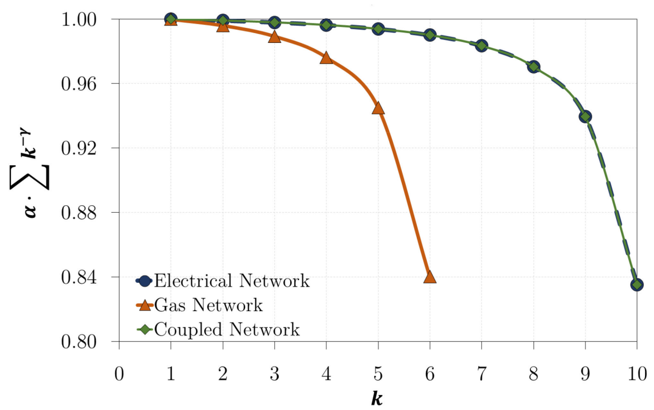
4.2 Numerical results of the coupled network

In accordance with the methodology described in Section 2, Table 3 shows the results for the different case studies corresponding to the removal of certain numbers of nodes in the coupled network (f), its impact on the loads disconnected from the system through the geodesic vulnerability index ($\bar{v}$), and the maximum value of disintegration ($f_{\max}$). For example, for the base case, the geodesic vulnerabilities are 0.1696, 0.3294, 0.5771, 0.7893, and 0.8762 for the removal of 2, 4, 6, 8, and 10% of the nodes, respectively. In addition, the values for the 22 case studies in which a new asset is added are shown. Considering the values in Table 3 for ($f = 10\,\%$) for case 22, the structural robustness increases by 6% compared to that of the base case.

Fig. 8 shows the results of the cascading failure simulations for the coupled electrical and natural gas networks for the base case, case 5, case 15, and case 22. All of the graphs also show the base case. The tolerance against random failures is obtained by averaging 100 samples of computational results. The computation



a



b

Fig. 7 *Equivalent analysis of the cumulative distributions of nodal degrees and a power law function*
(a) Scale-free graph cumulative distribution, ***(b)***Power law function

time for the most comprehensive case study (case 22) was 150 min.

The graphs in Fig. 8 show the geodesic vulnerability ($\bar{v}$) as a function of the fraction of nodes removed (f). When all of the nodes in the network are initially connected, the geodesic vulnerability ($\bar{v}$) has a value of 0. Subsequently, as the network breaks down as a result of the cascading disintegration, the geodesic vulnerability ($\bar{v}$) increases until it reaches a value of 1 when the supply of electricity to all of the nodes in the system is interrupted.

Fig. 8*a* shows that the base case collapses under random failures with the removal of >12% of the nodes. Fig. 8*d* shows that the removal of 11% of the nodes in the coupled network of case 22 is sufficient to cause network collapse. The comparison of both cases shows that case 22 is more robust until ($f = 10\,\%$). However, this system collapses before the base case, which shows that it disintegrates faster.

Furthermore, the comparison of the other graphs in Fig. 8 to the base case shows that the geodesic vulnerability curves for all of the cases are very similar to that of the base case, and the differences between the behaviour of the topology of the base case network and those of the topologies with additional assets are barely noticeable. In some cases, such as in Fig. 8*c*, the values of the geodesic vulnerability overlap that of the initial case, and the improvement in the robustness of the coupled network can only be observed clearly when all of the investments in new power lines and pipelines in case 22 have been made (Fig. 8*d*).

To corroborate these results, Fig. 9 shows the geodesic vulnerability $\bar{v}$ for all of the case studies corresponding to a loss of 10% of the nodes ($f = 10\,\%$). The trend line in Fig. 9 shows that the coupled system only improves when all of the investments have been carried out (case 22). The values in Table 3 for ($f = 10\,\%$) show that the structural robustness improves by 6% because the geodesic vulnerability changes from 0.8762 to 0.8232 for case 22.

In addition, the results show that cases 6, 17, and 21 can be considered to be good investments in the system because in these situations, the vulnerabilities change from 0.9537, 0.9288, and 0.9014 to 0.9069, 0.8562, and 0.8418, respectively. Conversely, cases 14 and 20 are identified as the worst investments from a robustness standpoint because they cause the vulnerabilities to decrease from 0.8434 and 0.8522 to 0.9033 and 0.9014, respectively.

Case 19 shows a singular scenario where a power transmission line and a gas pipeline are simultaneously built. This case evidences similar conclusions to those previously obtained for comparison of base case and case 22, as the robustness of the coupled system improves slightly with respect to the previous case 18 for fractions until $f = 10\%$ but with faster disintegration when cascading failures process goes ahead.

5 Conclusions

This study has developed a novel methodology to assess the structural robustness of the coupled electrical and natural gas network in Spain. The physical interdependencies between the two systems have been evaluated considering four asset types for the interconnections between the infrastructures. The algorithm has been formulated using the graph theory approach and the centrality measure of the geodesic vulnerability. The case studies corresponded to the main proposed investments of the operators of the systems in 2015–2020. The results demonstrate that the construction of some assets for the expansion of the gas and electricity networks does not improve the structural robustness of the coupled network; however, a relative improvement of 6% to the base case occurs when the entire investment programme is

Table 2 Topological characteristics of the electrical and gas networks in Spain

Network	V	E	$(\bar{k})$	$(k_{\max})$	(d)	$(\bar{e})$	$(\bar{l})$
electrical	611	672	2.20	10	55	0.077	18.41
gas	1380	1402	2.03	6	210	0.026	67.03
coupled	2031	2154	2.12	10	84	0.042	31.53

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Table 3 Simulation results for random errors as a function of the fraction of nodes removed

Network	(f = 2 %)	(f = 4 %)	(f = 6 %)	(f = 8 %)	(f = 10 %)	Collapse (f_{max})
base case	0.1696	0.3924	0.5771	0.7893	0.8762	12.30
case 1	0.1969	0.3904	0.6129	0.7368	0.8903	14.02
case 2	0.2063	0.4480	0.6264	0.7917	0.8970	11.36
case 3	0.1901	0.4017	0.6123	0.7575	0.9292	11.16
case 4	0.1841	0.3946	0.5898	0.8081	0.9321	13.12
case 5	0.2008	0.3960	0.6355	0.7826	0.9537	12.22
case 6	0.1974	0.4101	0.6377	0.7353	0.9069	13.15
case 7	0.1808	0.3786	0.5944	0.8005	0.9085	14.52
case 8	0.1959	0.3978	0.6030	0.7780	0.8789	12.21
case 9	0.1739	0.4354	0.6183	0.7655	0.8992	11.71
case 10	0.1878	0.4002	0.6095	0.7981	0.8669	11.95
case 11	0.1833	0.3939	0.5580	0.7904	0.8828	13.32
case 12	0.1831	0.3779	0.6132	0.7852	0.8823	13.21
case 13	0.1879	0.3690	0.5883	0.7391	0.8434	13.25
case 14	0.1889	0.3739	0.5913	0.7904	0.9033	12.90
case 15	0.1910	0.4202	0.6072	0.8009	0.8978	13.24
case 16	0.1878	0.3747	0.6007	0.7640	0.9288	12.75
case 17	0.1935	0.4014	0.6019	0.7592	0.8562	13.86
case 18	0.1848	0.4400	0.6175	0.7610	0.8299	12.00
case 19	0.1761	0.3808	0.5808	0.7503	0.8522	11.75
case 20	0.1900	0.3982	0.6225	0.7718	0.9014	12.38
case 21	0.2303	0.3856	0.5624	0.7652	0.8418	13.01
case 22	0.2003	0.3949	0.5667	0.7829	0.8232	11.34

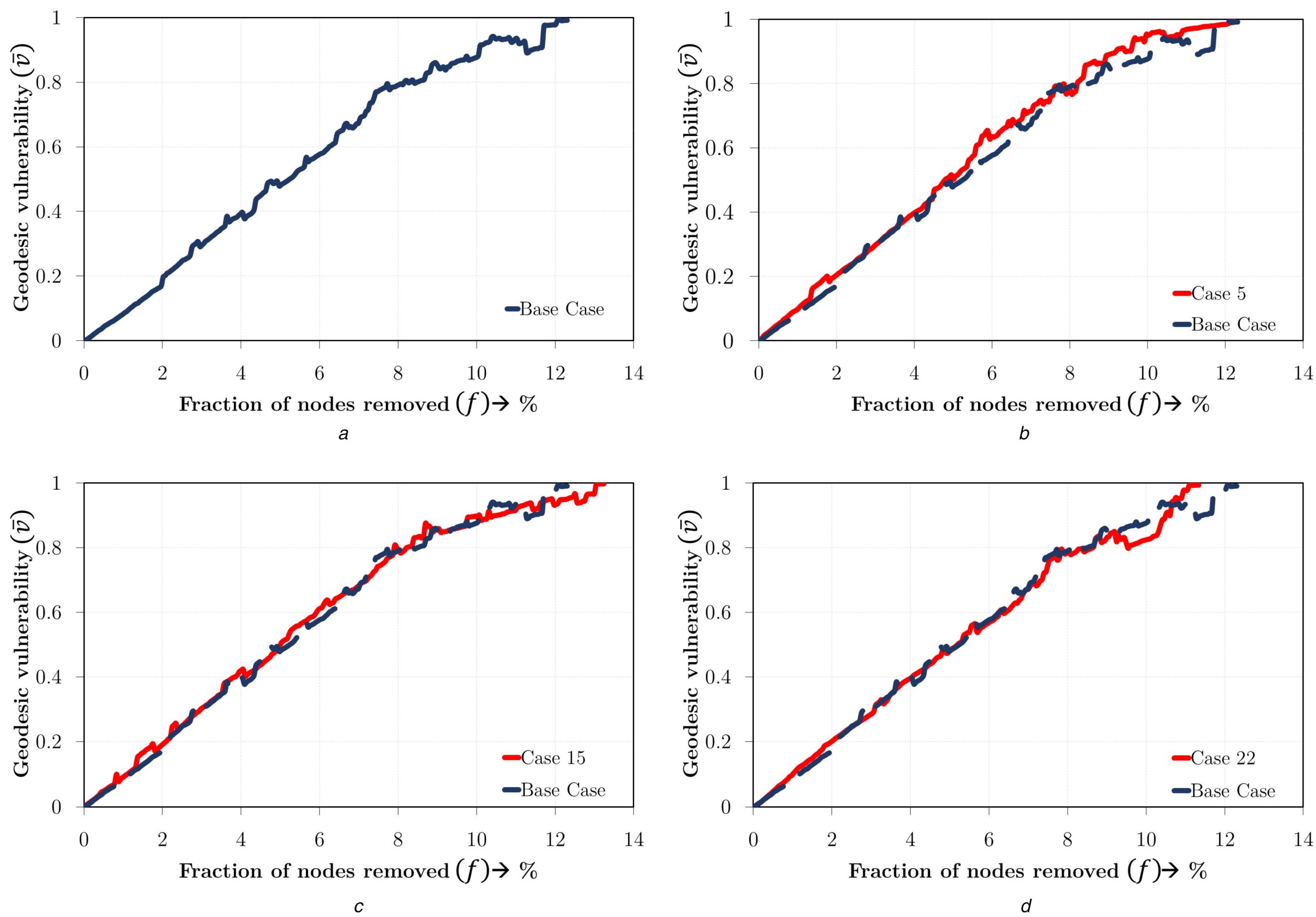

Fig. 8 *Simulation results of cascading failures for different case studies*
(a) Base case, ***(b)*** Case 5, ***(c)*** Case 15, ***(d)*** Case 22

considered. Cases 6, 17, and 21 represent examples of good investments and, on the contrary, vulnerability values in cases 14 and 20 worsen.

On the other hand, the methodology proposed in this article corroborates that the application of graph theory is appropriate to analyse assets planning of an energy critical infrastructure, only requiring the topology and the investment programme to assess the performance of the coupled network under cascading failures.

The conclusions of this study are relevant to the analysis of the robustness of the gas and electricity infrastructure, which does not

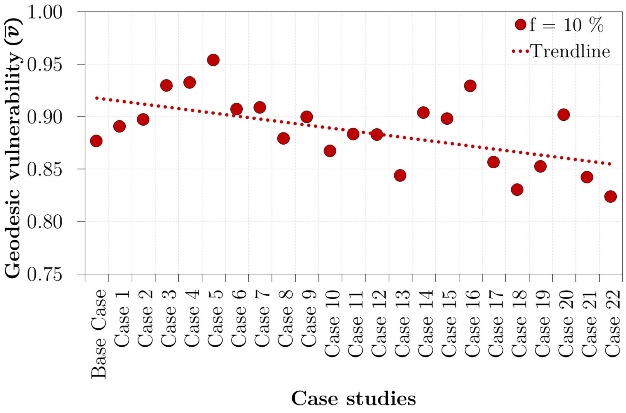

Fig. 9 *Geodesic vulnerability values for f = 10%*

discredit the planning by the operators of the transmission networks to improve the capacity of the system under other criteria and ensure their optimal technical and economic operation.

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Cascading Failures in Coupled Gas and Electricity Transmission Systems

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***Abstract*—In this article, we propose a novel methodology to study cascading failures in real interdependent electricity and natural gas networks using the graph theory approach with an efficient vulnerability analysis technique. The case study corresponds to the electricity and natural gas infrastructure of Spain. The vulnerabilities of both separate networks as well as that of the coupled network were evaluated. The simulation results show that the coupled network is more vulnerable than the electricity network to deliberate attacks and random failures.**

***Index Terms*—Cascading failures, electricity transmission networks, natural gas transmission networks, graph theory, critical infrastructures.**

I. Introduction

ELECTRICITY and natural gas networks are part of the economic prosperity of the modern world. These systems are prone to cascading failures due to natural hazards, terrorism, and deterioration of components. Adequate evaluations are important to prevent these undesirable events. However, minimizing these threats poses great analytical challenges.

Currently, most researchers analyze both types of networks individually. Nevertheless, these systems are not isolated; an event in one system may impact the other [1]. For example, combined cycle power plants require a reliable supply of natural gas. In addition, compressors in the gas network require electric power to operate. Therefore, the issue of interdependence between infrastructures must be addressed [2].

To evaluate these issues, several approaches to analyze interdependent networks have been proposed [3], of which the network-based approach, or graph theory, has been widely used. This method allows the vulnerability of systems to be evaluated by considering their topological properties through indexes or measures of centrality.

In [4], a comparative study is conducted between the physical and electrical topologies of the IEEE 300-bus network calculating the statistical parameters of the degree and clustering coefficient. In [5], the degree indices, clustering coefficient and geodesic distance are evaluated. In [6], the authors propose comparing the vulnerability and degree indices of China's electricity grid.

To determine the vulnerability of electricity grids, [7] studies the effect of deliberate attacks and random errors. Deliberate attacks are evaluated using the degree and betweenness indices.

Considering electrical networks as non-directed and weighted graphs, [8], [9] propose the electrical betweenness and electrical closeness indices. Likewise, [10], [11] suggest the measure of the electrical degree. References [12] and [13] suggest the electrical nodal robustness and electrical node significance indices.

Other scholars have developed methodologies that allow the structural vulnerability of these networks to be evaluated. References [14] and [15] use the geodesic vulnerability index to analyze electricity grids in Mexico, Spain and Colombia.

In contrast, studies on gas networks have used the average geodesic distance, efficiency, betweenness and maximum flow as indices [16], [17]. Others studies have simultaneously calculated the load flows and geodesic efficiency index [18]. In addition, attacks on the network links and how to improve the long-term topology are also studied [1], [19]. Several studies on interdependent infrastructures are reviewed in [3].

These studies do not compare the results from gas and electricity networks with those of coupled networks of both systems. Few studies have evaluated the vulnerability of coupled networks, and additional research on this subject is necessary. The interdependencies between both systems are crucial in analyzing the performance of the coupled infrastructure.

This work proposes a novel methodology to analyze cascading failures in real coupled natural gas and electricity transmission systems by applying the graph theory in complex networks. The vulnerabilities of the separate networks were evaluated before evaluating the vulnerability of the coupled network. Finally, the results from simulations are compared. The 400 kV electricity network and the 80 bar natural gas network in Spain are evaluated in this paper. This research constitutes an original contribution to the study of the vulnerability of interdependent networks.

The remainder of this article is organized as follows. Section II presents the procedure used to assess the structural vulnerability of electricity and natural gas networks. Section III

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describes the case studies and presents the simulation results. Finally, the conclusions are presented in Section IV.

II. Procedure to assess the vulnerability of electricity and natural gas systems

This section describes the methodology developed in this research. First, the graph models of each network are presented, and the algorithm developed with the graph topological index is then introduced.

The electricity and natural gas networks are represented as graphs of nodes and links using only the topology of the infrastructures instead of the electrical and mechanical parameters of both networks.

A. 400 kV electrical network

To represent the electricity network in Spain, data provided by the system operator is considered [20]. Fig. 1 a) shows the model proposed for the 400 kV electrical infrastructure in Spain. The graph features 611 nodes and 672 links. The model considers not only the bus network but also the power lines, transformers, loads, generators, and other assets. This type of network allows a detailed vulnerability analysis to be performed. In addition, all of the assets of the electrical network may be subjected to attacks.

B. 80 bar natural gas network

The topology of the high pressure natural gas network is obtained according to [21]. This system includes 6 regasification plants, 19 compression stations, 3 underground storage facilities, 2 reservoirs, 6 international connections, 32 direct line connection points, 57 transmission-transmission connection points and 294 transmission-distribution connection points. Fig. 1 b) shows the model for the high pressure natural gas infrastructure in Spain. This graph features 1380 nodes and 1402 links. This network considers all of the main assets of the natural gas infrastructure.

C. Coupling between infrastructures

Combined cycle natural gas power plants and electric compressors act as couplings for the networks described above [18]. Thus, the considerations in this study are as follows:

1) In Spain, 25% of the electric power is provided by gas power plants. The infrastructure includes a large number of these installations, which are connected to substations with different voltage levels. This study only considered those plants connected to 400 kV electrical substations. Twenty-six combined cycle power plants were considered (25 000 MW).
2) The natural gas infrastructure includes 14 compressors that operate by electricity. In this work, these assets were connected to the nearest electrical substations.

Fig. 1 c) represents the coupled electricity and natural gas network in Spain. The graph is composed of 2031 nodes and 2154 links.

Note that the model considers coupling links as nodes of the graph. Traditional representations do not consider this level of detail. The links represented as nodes become assets prone to attacks.

D. Algorithm to assess structural vulnerability in electricity and natural gas networks

This study evaluates cascading failures in coupled electricity and natural gas networks. The two systems are coupled by interdependent links as described above. The links represent bidirectional relationships between both networks. When certain assets are eliminated, interdependent effects are generated in the coupled network. Therefore, this study defines four main components and their interdependent effects:

1) Installations in the gas network that supply fuel to the electric generators: when this type of node is eliminated, an interdependence effect is caused to the electrical network because this type of node supplies natural gas to the coupled generator. This methodology considers eliminating the gas node and its coupling from the graph, which represents the loss of the fuel supply.
2) Electric substations that provide electricity to the compressors: these nodes supply electricity to the coupled gas compressor. This model also eliminates all affected installations from the graph.
3) Compressor inlet piping: for these components, the operation mode (electrical or mechanical) of the compressor is identified. In both cases, loss of this component means the loss of the compressor and, if it operates by an external power supply, the coupling link with the electricity network is also lost.
4) Coupling links between both networks: in all cases, the nodes affected by the elimination of links between both systems must also be removed from the graph.

The interdependent effects described above are iterative processes in the decomposition of the network. Therefore, the breakdown of cascading failures can be explained as follows:

Step 1 *Start*: create the equivalent graph of the coupled electricity and natural gas network based on the information presented above. This case corresponds to Fig. 1 c).

Step 2 *Types of attacks*: two node elimination strategies are considered: random or in descending order of nodal degree (number of links). Removing a node involves removing all of the links that connect to it. All of the nodes of the graph can be eliminated except the nodes that represent the slack generator, its coupling link and the coupled gas node. It is also necessary to consider the four interdependent effects described above. Additionally, the central limit theorem, which suggests repeating each experiment at least 30 times in case of random errors, was used [22].

Step 3 *Identification of islands*: the disintegration process generates subgraphs in the coupled network. In those cases, it is necessary to consider that the next node to be eliminated must be in the larger set. The subgraph with the slack generator, its coupling link and the coupled gas node was identified.

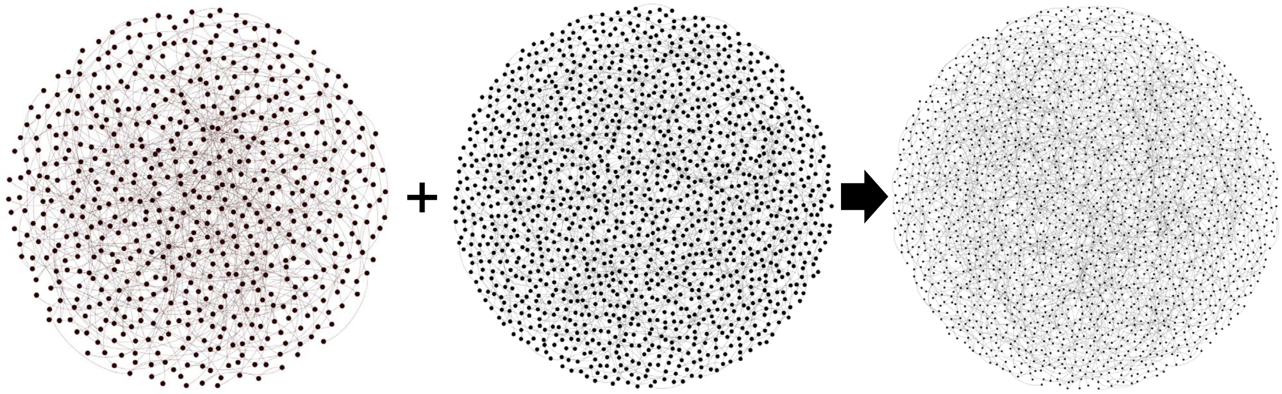

Fig. 1. Graphs of the electricity and natural gas networks in Spain.

Step 4 *Calculation of the vulnerability*: in each step of the disintegration of the network, the geodesic vulnerability index for the largest component was calculated. This index is a function of the number of nodes that are isolated (f). The iterative process ends once it is not possible to eliminate more nodes from the graph or if both networks are decoupled. If there are still nodes in the network, return to Step 2.

The proposed procedure can be applied efficiently and accurately in any real critical electricity and natural gas infrastructure. The algorithm was implemented in the Matlab®2017 programming environment using a computer with a 3.40 GHz Intel®Core i7 *CPU* and 32 GB of RAM.

E. Geodesic vulnerability index

As presented in Section I, several metrics can be used to study cascading failures in power networks using graph theory. However, among the indices proposed in the scientific literature in recent years, metrics based on the geodesic efficiency have shown greater correlations with the actual functioning of power transmission networks for the analysis of n-k contingencies [16], [18]. The geodesic vulnerability index is one of the most innovative of these metrics.

The geodesic vulnerability index ($\widetilde{\nu}$) measures the operation of a network against contingencies by normalizing the geodesic efficiency ($\widetilde{e} = \frac{1}{N \cdot (N-1)} \sum_{i \neq j} \frac{1}{d_{ij}}$) to its base case [15]. Previous research validated that this index is directly related to the disconnected load in the network before a cascading failure process [23]. The geodesic vulnerability index varies between zero and one; the greater the index value is, the greater the impact on the network is. This index is presented in (1)

$$\widetilde{\nu} = 1 - \frac{\sum_{i \neq j} (\frac{1}{d_{ij}^{LC}})}{\sum_{i \neq j} (\frac{1}{d_{ij}^{BC}})} \tag{1}$$

where:

d_{ij}^{LC}: geodesic distance between pairs of nodes of the graph after each iteration of the elimination of a node, and

d_{ij}^{BC}: geodesic distance between the node pairs of the graph for the base case.

III. Case studies

The case studies evaluated in this research are described below. The conditions of the case studies are described first, and the simulation results are then presented graphically and numerically. Finally, the conclusions of the comparative analysis are discussed.

A. Case description

The structural vulnerability of Spain's electricity and natural gas network is evaluated by first considering the separate systems and then the coupled system. Thus, the following cases were analyzed:

- Simulations of cascading failures in each of the separate electricity and natural gas networks (Case 1 and Case 2).
- Simulations of cascading failures in the coupled electricity and natural gas network (Case 3 and Case 4).

The interdependent effects are not considered in the simulation of cascading failures in the separate networks (Case 1 and Case 2) but are considered in the coupled network (Case 3 and Case 4). The results for deliberate attacks on the networks and for random failures will be presented.

B. Simulation results

Fig. 2 shows the simulation results of cascading failures for the electricity (Case 1) and natural gas (Case 2) networks and for the coupled network (Case 3). Figs. 2 a), c) and e) show the results for random failures, whereas Figs. 2 b), d) and f) correspond to deliberate failures. Random errors correspond to random events, such as human errors, adverse weather conditions, and equipment failures. In contrast, deliberate attacks correspond to terrorism, cyber-attacks, malicious acts, and other events.

To comply with the requirement of the central limit theorem, which guarantees a suitable statistical sample with random errors, the results are obtained by averaging a set of 100 tests with a computing time of 150 minutes. In contrast, deliberate attacks only require eliminating the most strongly connected nodes in descending order of the nodal degree, taking only 2 minutes to obtain the results.

The graphs in Fig. 2 show the geodesic vulnerability value ($\widetilde{\nu}$) as a function of the fraction of eliminated nodes (f). When all of the nodes of the network are initially connected, the geodesic vulnerability ($\widetilde{\nu}$) is equal to 0. As the network breaks down because of cascading disintegration, the value of the geodesic vulnerability ($\widetilde{\nu}$) increases until it equals 1 when the power supply to all of nodes in the system has been interrupted.

Fig. 2 a) shows that the electrical network collapses in the face of random failures with the elimination of approximately 20% of the nodes. Fig. 2 b) shows that in the same electrical network but in the case of deliberate failures, the elimination of less than 2% of the nodes is sufficient to cause network collapse. This shows that targeted attacks on high connectivity nodes are an effective tactic to rapidly disintegrate networks.

In contrast, Fig. 2 c) shows that the natural gas network collapses completely in the face of random failures when approximately 3% of the nodes are eliminated. The results show that this system is more vulnerable than the electrical network. In the case of deliberate failures, the elimination of 0.7% of the nodes causes the disintegration of the network, as shown in Fig. 2 d). The simulations verify that the natural gas network is less robust than the electrical network, which is explained by the different structure of the networks; the natural gas system has a less meshed topology than the electrical system.

The analysis of the coupled network (Case 3) shows that the network collapses after approximately 14% of the nodes are removed in the case of random failures, as shown in Fig. 2 e). In contrast, Fig. 2 f) shows that removing 1% of the nodes is sufficient to completely collapse the network in the case of deliberate failures.

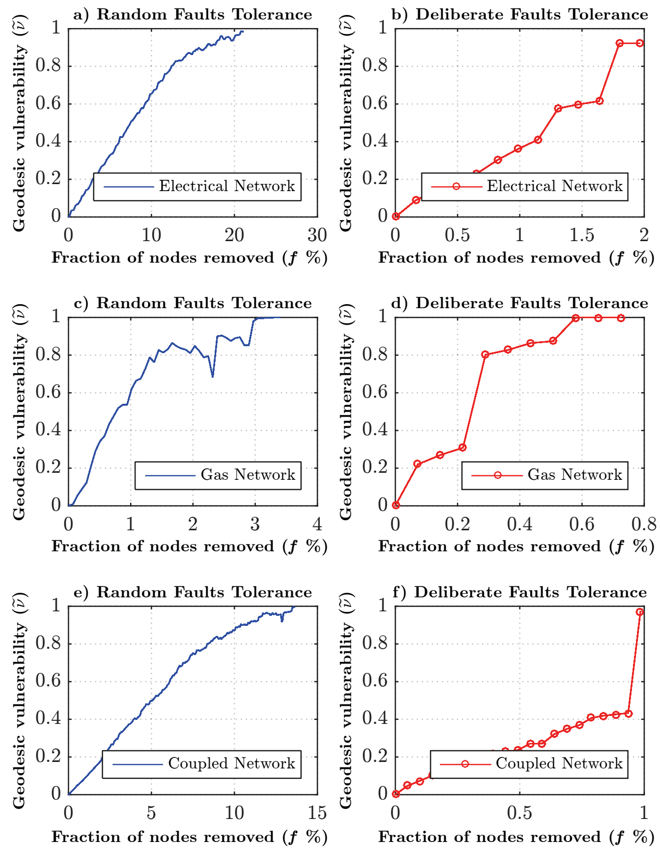

Fig. 2. Results of the simulations of cascading failures.

C. Discussion

These results lead to several conclusions about the operation of the coupled natural gas and electricity network in Spain.

The results show that the coupled network is more vulnerable than the electrical network to random and deliberate failures. However, the coupled network is less vulnerable than the natural gas network.

TABLE I shows the sequence of nodes removed from the networks against deliberate failures in four different cases:

- Electrical network (Case 1): using the nodal degrees of the nodes of the electrical network in descending order.
- Gas network (Case 2): using the nodal degrees of the nodes of the gas network in descending order.
- Coupled network (Case 3): using the nodal degrees of the most connected nodes of the electrical network in descending order and then the most connected nodes of the gas network.
- Coupled network (Case 4): using the nodal degrees of the nodes of the coupled network in descending order.

The results show that the total number of iterations required for the disintegration of the separate networks (Case 1 and Case 2) is equal to those necessary to decouple the joint network (Case 3). Thus, when the coupled network in Case 3 disintegrates following the same order of attack of the nodes of the electricity and gas networks in Case 1 and Case 2, the collapse of the coupled system occurs quickly.

In contrast, in Case 4, a different order of attack of the nodes was established using the nodal degree of the coupled network as a strategy; namely, determining the number of links of each node of the coupled network and ordering them according to their connectivity from highest to lowest.

Fig. 3 graphically shows a comparison of the results of Case 3 and Case 4. The disintegration of the coupled network for Case 4 is more gradual because it requires eliminating approximately 3% of the nodes of the network, whereas only 1% is necessary in Case 3. This demonstrates that for the disintegration of the interdependent network, the combination of the sequences of nodal degrees of the separate networks is a more efficient attack strategy than using the sequence resulting from the nodal degrees of the joint system.

IV. Conclusions

In this article, a cascading failure methodology was developed for coupled interdependent natural gas and electricity systems. The real transmission networks for electricity and

TABLE I
ORDER OF NODES ELIMINATED FOR DELIBERATE ATTACKS

Iteration	Electrical network (Case 1)	Gas network (Case 2)	Coupled network (Case 3)	Coupled network (Case 4)
1	64	647	64	64
2	23	658	23	23
3	65	713	65	65
4	30	686	30	157
5	86	655	86	30
6	157	680	157	86
7	14	632	14	14
8	38	634	38	38
9	94	968	94	94
10	153	1128	153	99
11	4		4	148
12	201		201	153
13			647	4
14			658	22
15			713	71
16			686	102
17			655	129
18			680	144
19			632	647
20			634	658
21			968	713
22			1128	25
23				26
24				32
25				43
26				46
27				53
28				96
29				97
30				110
31				139
32				141
33				146
34				164
35				171
36				184
37				185
38				191
39				650
40				686
41				718
42				34
43				35
44				36
45				44
46				48
47				57
48				58
49				169
50				170
51				655
52				680
53				37
54				39
55				40
56				196
57				632

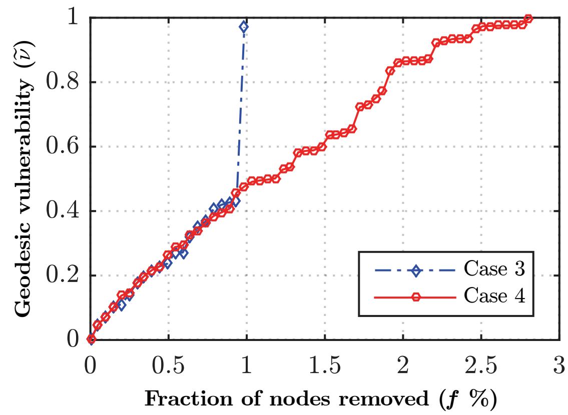

Fig. 3. Graphical representation of Case 1 vs. Case 2.

natural gas in Spain were evaluated. The results showed that the natural gas system is less robust than the electrical system and that the coupled network is more vulnerable than the electrical network to random and deliberate failures. In addition, the combination of the nodal degrees of the independent networks is an effective attack strategy for rapidly collapsing interdependent coupled networks. The use of graph theory as a methodology for vulnerability analysis has been shown to be efficient and can be applied to any real critical infrastructure system.

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3. Memoria

Esta sección describe los objetivos de investigación, las aportaciones del doctorando, la metodología utilizada y las conclusiones finales.

3.1 Objetivos de la investigación

El objetivo principal de esta tesis doctoral es como sigue:

1. Desarrollar y validar una metodología de análisis de vulnerabilidad de la topología de infraestructuras energéticas interdependientes de electricidad y gas natural.

El objetivo general se aborda mediante el planteamiento de tres objetivos específicos como sigue:

1. Obtener una representación topológica conjunta de la red de transmisión de electricidad y gas natural que incorpore todos los activos de ambos sistemas como nodos de un grafo, comprobando las propiedades del grafo resultante como red de libre escala.
2. Proponer una metodología de análisis de la vulnerabilidad conjunta de redes eléctricas de transmisión en alta tensión y de redes de transporte de gas natural, seleccionando indicadores estadísticos del grafo que expliquen el comportamiento de la red conjunta ante errores aleatorios o intencionados y justificando la sustitución de flujos de potencia clásicos para el análisis de fallos en cascada por modelos basados en redes complejas.
3. Realizar una aplicación de la metodología desarrollada en redes reales y obtener conclusiones sobre la efectividad de las inversiones en la topología de las infraestructuras energéticas, según la aplicación de los planes de expansión propuestos por los correspondientes gestores de las redes de electricidad y gas.

3.2 Metodología utilizada

La metodología usada para alcanzar los objetivos propuestos en este trabajo doctoral es la siguiente:

1. Revisión bibliográfica de los diferentes métodos y modelos matemáticos para obtener la solución en estado estacionario de los flujos de electricidad y gas natural acoplados.
2. Revisión bibliográfica de las principales técnicas de modelado de infraestructuras críticas interdependientes.
3. Revisión bibliográfica de los modelos basados en teoría de grafos para sistemas de transmisión de gas y electricidad conjuntos.
4. Estrategias de representación para la incorporación de los activos e instalaciones de las redes acopladas en forma de dos grafos interconectados, considerando las líneas eléctricas y los gasoductos como activos de la red sujetos a posibles fallos o amenazas y comprobando las propiedades resultantes de la red como un grafo de libre escala.
5. Desarrollo e implementación de un método de flujo de carga acoplado que permita calcular los flujos en estado estacionario de los sistemas eléctricos y de gas conjuntos.
6. Comprobación del enfoque de flujos propuesto mediante la comparación de los resultados con el método tradicional de Newton-Raphson.
7. Desarrollo de una metodología de análisis de la vulnerabilidad conjunta de redes eléctricas de transporte en alta tensión y de redes de transporte de gas natural, mediante el estudio de distintas medidas estadísticas que permitan analizar la desintegración de las redes, es decir, su evolución ante la eliminación sucesiva de nodos.
8. Propuesta del índice estadístico de vulnerabilidad geodésica adaptado a la red conjunta interconectada para validar la equivalencia del uso de los grafos de libre escala respecto de las técnicas de flujos de carga en el análisis de vulnerabilidad de las redes de energía.
9. Propuesta del índice de desconexión de cargas, calculado a partir de los resultados obtenidos con la ejecución de los flujos de potencia, para medir el impacto en la cantidad de demanda de gas y electricidad no suministrada como consencuencia de las contigencias sucesivas generadas por los fallos en cascada.

10. Aplicación de los dos indicadores anteriores en redes de prueba IEEE junto con redes de transporte de gas de prueba de la misma escala, calculando por un lado el flujo de potencia conjunto y por otro lado los índicadores estadísticos del grafo. Se desarrollan casos de simulación teniendo en cuenta perturbaciones aleatorias y deliberadas.
11. Estudio de la existencia de correlación entre los resultados de medida de vulnerabilidad de los modelos de flujos de potencia y las medidas obtenidas a partir de la teoría de grafos, calculando el coeficiente de correlación de Pearson entre ambos conjuntos de resultados.
12. Aplicación de la metodología desarrollada sobre las redes de gas natural y electricidad de España, modelando los sistemas interconectados como una red compleja, sometiendo la topología de las redes a fallos en cascada y analizando la robustez de los respectivos planes de expansión.
13. Aplicación de la metodología a las redes reales de transporte de energía eléctrica y gas natural de España separadas y acopladas, determinando el grado de relación entre los sistemas y estimando cuál de las dos redes es afectada antes por la propagación de los fallos en cascada.

3.3 Revisión Bibliográfica

Esta sección muestra las diferentes propuestas y metodologías encontradas en el estado del arte para los temas que componen los artículos presentados en esta tesis por compendio de publicaciones, incluyendo desde los métodos para el cálculo de flujos de electricidad y gas natural acoplados hasta los enfoques usados para evaluar la operación integrada de ambas infraestructuras energéticas.

3.3.1 Linear-analog transformation approach for coupled gas and power flow analysis

La simulación computacional de los sistemas de gas natural y electricidad requiere la solución de ecuaciones algebraicas no lineales debido a su complejo comportamiento. En este sentido, la mayoría de las metodologías disponibles en la literatura se basan en el método Newton-Raphson [46]. En el caso del análisis de los sistemas de potencia, las tensiones en las redes de transmisión o distribución están generalmente cercanas a sus valores nominales, lo que en muchos casos resulta en la convergencia del método Newton [47]. Sin embargo, en el caso de las redes de gas natural, la solución de las ecuaciones no lineales depende en gran medida de la aproximación inicial. Estos fenómenos fueron ampliamente estudiados por Li et al. [48], quienes discutieron la formulación del problema de dos maneras diferentes, teniendo en cuenta los nodos (método Newton-nodal) y los lazos (método de Newton-lazo) de la topología correspondiente.

La formulación *Newton-nodal* se basa en la suma de los flujos en cada nodo, mientras que el método *Newton-lazo* utiliza la suma de las caídas de presión alrededor de cada lazo. Dado que la formulación del lazo es casi cuadrática debido al comportamiento complejo de los flujos, el método Newton-lazo ofrece una buena convergencia cuando se compara con su contraparte. Sin embargo, el lazo o bucle analizado se debe seleccionar adecuadamente, de lo contrario, la formulación del problema se vuelve difícil. De lo contrario, el uso de métodos numéricos para calcular la matriz Jacobiana puede facilitar la implementación computacional de los dos métodos al evitar la derivación matemática requerida de una manera analítica.

En otras propuestas, Martínez-Mares y Fuerte Esquivel [28] incorporaron la influencia de los cambios en la temperatura del gas natural en el gasoducto, un aspecto que no se considera a menudo para mantener la simplicidad del modelo. Erdener et al. [34] implementaron una técnica basada en la formulación *Newton-*

lazo-nodal combinada con el algoritmo de Búsqueda en Anchura (BFS - Breadth First Search por sus siglas en inglés). Como el conjunto de ecuaciones bajo estudio es altamente no lineal, se utilizó el algoritmo BFS para encontrar una solución inicial al problema algebraico.

Por otro lado, con el gran interés en los recursos de gas natural, específicamente en las áreas urbanas, Shabanpour-Haghighi y Seifi [49] desarrollaron un modelo para incorporar una red de calefacción urbana en el sistema de electricidad y gas integrado, teniendo en cuenta los circuitos hidráulicos y térmicos en la ecuación de balance. Wang et al. [50] desarrollaron el método implícito desacoplado para la simulación eficiente de redes (DIMENS por sus siglas en inglés), que utiliza la técnica de dividir y conquistar para aumentar la velocidad de cálculo. DIMENS divide la red de gas en subsistemas que luego se analizan en su totalidad. Dyachenko et al. [51] propusieron la técnica de dividir al operador basándose en la solución de un conjunto de ecuaciones diferenciales parciales hiperbólicas no lineales para describir el comportamiento hidrodinámico del sistema de gas. Como característica más importante, la técnica es estable y precisa, así como eficiente desde el punto de vista computacional.

Recientemente, Ayala y Leong [41], [42] propusieron el concepto análogo-lineal para reducir la complejidad de las ecuaciones algebraicas utilizadas para evaluar el desempeño de las redes de gas natural. Este método se basa en la aplicación del enfoque de transformación análogo-lineal (LAT) al modelo de cada activo de la red de gas. A diferencia de las otras propuestas, en el enfoque LAT los supuestos iniciales de presiones y flujos no son necesarios y solo se requiere un conjunto de ecuaciones algebraicas que pueden resolverse mediante métodos numéricos estándar.

Como se puede notar, los trabajos discutidos anteriormente muestran que las redes de electricidad y gas natural están bien estudiadas por separado, sin embargo, se observa un margen de mejora en el desarrollo de nuevas técnicas para analizar la operación integrada de ambos sistemas de infraestructura crítica. Este artículo presenta una metodología que permite obtener la solución en estado estacionario de los flujos de electricidad y gas natural acoplados utilizando el novedoso método análogo-lineal para resolver el problema del flujo de gas. En este último, se conservan las ventajas del enfoque tradicional de Newton que utiliza sólo ecuaciones nodales, pero se simplifica la formulación, se elimina el cálculo de derivadas y se reduce el coste computacional [41], [42].

3.3.2 Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures

La revisión de la literatura relacionada con las infraestructuras de gas natural y electricidad está enfocada tradicionalmente en el estudio de eventos de contingencias N-1, la planificación de ambos sistemas integrados, la cuantificación de la fiabilidad y la evaluación de estrategias de endurecimiento. Por ejemplo, las referencias [52], [53] modelan un sistema independiente que incluye las restricciones de la red de gas sobre el sistema energético completo. La referencia [54] explora el efecto que tiene el sistema de gas en la eficiencia general del sistema de potencia, mientras que [55] analiza el futuro de la generación de energía eléctrica como resultado de las mejoras en la infraestructura de gas natural.

Por otro lado, las referencias [56], [57] examinan la fiabilidad del sistema eléctrico como una función del sistema de gas natural, mientras que [58] estudia la operación óptima del sistema energético integrado mediante estudios de robustez. La referencias en [59], [60] evalúan estrategias de endurecimiento de los sistemas y técnicas inteligentes destinadas a aumentar la resiliencia. La referencia [61] explora el modelo de planificación de las redes de electricidad y gas usando un sistema de calefacción y energía acoplado.

Aunque los trabajos anteriores están relacionados con el estudio de las redes de gas y electricidad en una manera acoplada, ninguno de ellos cuantifica las consecuencias de sucesos o eventos devastadores que puedan interferir en la operación cotidiana de estas infraestructuras. Todas las redes de energía están expuestas a diferentes tipos de fallos o ataques, y los operadores deben implementar metodologías de gestión de riesgos para evaluar el grado de debilidad del sistema ante estas graves amenazas, evaluando la vulnerabilidad de la infraestructura.

La investigación actual se enfoca únicamente en los flujos de carga en términos de seguridad de todo el sistema integrado; no obstante, los flujos dentro de las infraestructuras y entre ellas desempeñan un papel importante en el funcionamiento de ambos sistemas. Así, pocos estudios han abordado el concepto de vulnerabilidad en las redes de energía acopladas ya que, en la mayoría de los casos, la gran cantidad de información técnica dificulta llevar a cabo los estudios como se evidencia en [62]. En este sentido, la teoría de redes complejas es un método emergente que puede ser útil para estudiar y evaluar la vulnerabilidad de las infraestructuras críticas de energía [63].

Cuando se analiza la interdependencia entre los sistemas de potencia y gas natural, se pueden distinguir dos tipos de vulnerabilidad: funcional y estructural

[63]. Por un lado, la vulnerabilidad funcional implica un análisis detallado de las condiciones de operación de las infraestructuras [64]. Aunque las interconexiones de los dos sistemas incrementan la capacidad de transferencia de energía, también implica que los disturbios locales se propaguen a través de las redes. El fallo de una línea eléctrica puede provocar la incapacidad de las subestaciones de distribución, lo que puede provocar que la energía eléctrica no llegue a los compresores eléctricos de la red de gas. El fallo de un gasoducto, como consecuencia de un funcionamiento deficiente, puede provocar la pérdida de combustible de los generadores eléctricos acoplados [65]. En ambos casos, una perturbación puede propagarse al otro sistema y, en última instancia, a los usuarios finales. Por otro lado, la vulnerabilidad estructural está relacionada con la disminución del desempeño y eficiencia de la red integrada después de un ataque [66], [67].

Por lo tanto, este artículo propone el uso de la teoría de grafos para evaluar la vulnerabilidad de las redes de gas y electricidad integradas y estudiar el desempeño de ambos sistemas frente a fallos en cascada. Esta técnica permite superar los problemas derivados de la obtención de datos técnicos en los sistemas de infraestructura bajo estudio. Así, este artículo aporta una contribución original al desarrollar una propuesta más efectiva, con el fin de conseguir los mismos resultados que la bien conocida técnica de flujos de carga acoplados, pero sin necesidad de usar los parámetros eléctricos y mecánicos de las infraestructuras.

3.3.3 Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures

La infraestructura eléctrica está compuesta de instalaciones, tales como generadores, líneas de transmisión, cargas, transformadores eléctricos, etc. Por otro lado, la infraestructura de gas natural la componen estaciones de compresión, tuberías, instalaciones subterráneas, compresores, entre otros. Estos sistemas se pueden describir como una red de nodos y enlaces según la teoría de grafos [68].

Las redes pueden desintegrarse mediante fallos deliberados o aleatorios caracterizados por índices de centralidad. Este proceso de desintegración es una analogía de los fallos en cascada reales. En este contexto, en [69], se ha demostrado que los ataques premeditados pueden colapsar las redes eléctricas. Por tanto, simular estos eventos implica que los estudiosos han usado índices como coeficiente de agrupamiento y distancia geodésica [70]–[73]. Otros en cambio han utilizado el índice de grado nodal, diámetro de red y eficiencia [74].

Por otro lado, algunos autores han llegado más lejos al crear metodologías que permiten evaluar la vulnerabilidad estructural de estas redes. Tal es el caso de los trabajos encontrados en las referencias [75], [76] que han empleado el índice de vulnerabilidad geodésica sobre las redes eléctricas de México, España y Colombia. Estos trabajos han analizado los planes de expansión de las redes y han concluido que las inversiones realizadas no mejoran la vulnerabilidad cuando se analizan ataques deliberados. No obstante, se ha observado una notable mejora cuando se estudian fallos aleatorios.

Las referencias de arriba han estado basadas solamente en la topología de las redes sin considerar sus características eléctricas o mecánicas. Debido a eso, en [77], han ponderado la red eléctrica con el índice de eficiencia geodésica tomando en cuenta las características operacionales del sistema. De manera similar, en [78], han usado la demanda máxima de carga y la capacidad de los generadores junto con el índice de intermediación. Otros modelos han utilizado modelos híbridos de teoría de grafos y teoría de juegos [79].

Por otro lado, se han creado redes eléctricas sintéticas para evaluar el impacto de la topología, los generadores y las políticas de re-despacho en la red eléctrica [80]. Las conclusiones han mostrado que los factores anteriores deben mejorarse para reducir las pérdidas de energía dentro de la infraestructura eléctrica cuando se producen fallos en cascada. Del mismo modo, en [81], se ha propuesto un modelo que estima la eficiencia de las redes de prueba IEEE y de las redes sintéticas utilizando índices de grafos. Aquí, se ha evidenciado que la robustez del sistema eléctrico podría estar sujeta al índice estadístico de camino más corto y a la ubicación de los generadores. Otros investigadores, como [82], [83], han incluido evaluaciones de riesgo y variables estocásticas para evaluar la vulnerabilidad del sistema de potencia, respectivamente.

En los estudios sobre la red de gas se han empleado los índices de distancia media geodésica, eficiencia, intermediación y flujo máximo [84]–[86]. Otros han calculado paralelamente flujos de carga e índice de eficiencia geodésica [34]. También se ha considerado atacar los enlaces de las redes y estudiar cómo mejorar la topología a largo plazo [35], [87]. Trabajos restantes han utilizado técnicas de simulación Monte-Carlo, modelos económicos y técnicos [14], [88], [89].

Más recientemente, otros académicos han evaluado las infraestructuras de electricidad y gas natural de manera acoplada. Por ejemplo, se han propuesto modelos estocásticos para la planificación conjunta de ambos sistemas [52], [90] y para la mejora de la seguridad operacional [61], [91]. Además, los estudiosos han desarrollado algoritmos para mejorar la resiliencia frente a desastres naturales y ataques maliciosos [92], [93]. Algunas obras restantes han utilizado programas informáticos y métodos de optimización en dos etapas [58], [94] y también se ha considerado la interrupción de los generadores eléctricos y las líneas de transmisión de energía [95].

Los trabajos de investigación descritos anteriormente han empleado diferentes métodos y técnicas para estudiar los sistemas de electricidad y gas natural acoplados. Sin embargo, se ha observado la falta de estudios que evalúen la robustez de los planes de expansión de las dos redes. En este manuscrito, se hace hincapié en la importancia de que ambas infraestructuras energéticas críticas sean tratadas como redes acopladas debido a sus fuertes interacciones. Una perturbación en un sistema puede no ser crítica si las infraestructuras están separadas, pero como ambas redes son interdependientes, el impacto resultante podría causar fallos en el otro sistema. Las interdependencias aumentan el impacto de las perturbaciones.

En este artículo, se ha propuesto la teoría de grafos como un enfoque novedoso para la evaluación de la robustez de los planes de expansión de la infraestructura eléctrica de 400 kV y la infraestructura de gas natural de alta presión de 80 bar en España. Esta investigación utiliza esta técnica porque, como ya se ha mencionado anteriormente, ha demostrado ser una herramienta muy útil para analizar las características estructurales y el desempeño bajo fallos en cascada de las redes interdependientes.

3.3.4 Cascading failures in coupled gas and electricity transmission systems

Para estudiar y analizar redes interdependientes se han propuesto diferentes enfoques como se puede encontrar en [8]. Entre ellos, el enfoque basado en redes o teoría de grafos ha sido ampliamente usado. Este método permite evaluar la vulnerabilidad de los sistemas tomando en cuenta sus propiedades topológicas a través de índices o medidas de centralidad.

En [43], se ha realizado un estudio comparativo entre la topología física y eléctrica de la red IEEE de 300 buses calculando parámetros estadísticos de grado y coeficiente de agrupamiento. Idénticamente, en [96], se han calculado los índices de grado, coeficiente de agrupamiento y distancia geodésica. Usando la red eléctrica de China, en [97], se ha propuesto comparar los índices de vulnerabilidad y grado.

Con el objetivo de determinar la vulnerabilidad de las redes eléctricas, en [98], se ha estudiado el efecto de los ataques deliberados y errores aleatorios. Los ataques deliberados se obtienen mediante los índices de grado e intermediación.

Considerando las redes eléctricas como grafos no dirigidos y ponderados, los trabajos [99], [100], han propuesto los índices de intermediación eléctrica y cercanía eléctrica. De manera similar, [101], [102], han sugerido la medida de grado eléctrico. Mientras tanto, las referencias [103], [104], han planteado el índice de importancia eléctrica.

Por otro lado, otros trabajos han empleado los índices de distancia media geodésica, eficiencia, intermediación y flujo máximo [84], [86]. Otros han calculado paralelamente los flujos de carga e índices de eficiencia geodésica [34]. También se han considerado atacar los enlaces de las redes y estudiar cómo mejorar la topología a largo plazo [35], [87]. Una variedad de estudios restantes sobre infraestructuras interdependientes pueden ser consultados en [8].

Nótese que los trabajos aquí mencionados no comparan los resultados en las redes de gas y electricidad con los resultados de la red conjunta de ambos sistemas. Poco trabajo se realiza en evaluar la vulnerabilidad de la red conjunta y en este artículo se considera que un mayor estudio en este tema debe ser realizado. Las interdependencias entre ambos sistemas juegan un papel crucial para analizar el desempeño de la infraestructura acoplada. Debido a eso, se ha aplicado la teoría de grafos como un método novedoso para evaluar la vulnerabilidad estructural de redes acopladas de gas y electricidad.

En este trabajo, se ha propuesto una metodología novedosa para analizar fallos en cascada en redes de electricidad y gas natural acopladas reales. Primero se estudia la vulnerabilidad de las redes separadas y, posteriormente, se evalúa la vulnerabilidad de la red conjunta. Finalmente, se comparan los resultados obtenidos en las diferentes simulaciones. El caso de estudio corresponde a la red de electricidad de 400 kV y la red de gas natural de 80 bar de España.

3.4 Metodología empleada en cada artículo

3.4.1 Linear-analog transformation approach for coupled gas and power flow analysis

El objetivo principal de este trabajo ha sido desarrollar un mejor enfoque para calcular el flujo de carga conjunto de las redes de energía eléctrica y gas natural, centrándose en la simulación computacional de ambas infraestructuras como un sistema integrado. La solución unificada del flujo de electricidad y gas natural acoplado se ha obtenido combinando los modelos eléctricos e hidráulicos de ambos sistemas de infraestructura. La principal fuente de problemas es la no linealidad de la conductividad de la tubería (debido a la física del gas natural) y este trabajo ha hecho grandes esfuerzos para desarrollar una propuesta más efectiva con el fin de reducir la complejidad de las ecuaciones algebraicas utilizadas para evaluar el desempeño de las redes de gas natural.

Para lograr el objetivo antes expuesto, en este artículo se han utilizado los últimos avances en el modelado de la red de gas expuestos en [41], [42] y se han combinado con el enfoque tradicional de Newton-Raphson (NR) del sistema de potencia.

En términos generales, las dos redes están unidas mediante enlaces interdependientes que representan el intercambio de flujo entre los dos sistemas. La red eléctrica tiene centrales eléctricas a gas conectadas a sus buses que se alimentan desde nodos determinados de la red de gas. De manera similar, el sistema de gas tiene compresores que operan con energía externa suministrada por ciertos buses de la red eléctrica.

Básicamente se ha recopilado la información requerida para simular las infraestructuras de potencia y de gas natural asumiendo los enlaces bidireccionales descritos anteriormente. Luego, se ha resuelto el problema de flujo de carga en la red eléctrica mediante el método NR para calcular las magnitudes y ángulos de fase en todos los buses de la infraestructura en función de las cargas y generaciones de potencia definidas. A continuación, se han obtenido los flujos de potencia activa y reactiva a través de las líneas de transmisión. Dado que las pérdidas de transmisión de potencia en la red eléctrica no pueden determinarse sin conocer primero el flujo de potencia, se ha asignado un generador de referencia con su magnitud de tensión y ángulo de fase definidos para suministrar el desajuste de la generación de potencia. En algunos casos, el generador de referencia podría acoplarse a la infraestructura de gas. Una vez que se ha completado el estudio del flujo de carga, la potencia producida por cada generador se ha usado para estimar la cantidad de gas natural. A continuación, la demanda de gas natural se ha incorporado como una carga en la red de gas y, después, se ha ejecutado el estudio del flujo de carga de gas que incorpora la ecuaciones análogas-lineales de las estaciones de compresión. Aquí, se ha utilizado la cantidad de gas requerida para la producción de electricidad y el comportamiento de las estaciones de compresión para estimar los valores correspondientes de los suministros y demandas de gas. La Tabla I describe un resumen detallado de la metodología seguida.

La implementación computacional del enfoque propuesto se ha implementado en dos casos de estudio y los resultados se han comparado contra el enfoque tradicional Newton-Raphson encontrando un error máximo entre los resultados del 1.21%.

3.4.2 Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures

La metodología de esta investigación se ha ejecutado a través de la comparación de índices clásicos de flujo de carga contra índices de teoría de grafos. Para lograr el objetivo antes expuesto, este artículo ha iniciado considerando una infraestructura interdependiente compuesta de dos redes: una red eléctrica y una red de gas natural. Aquí, se ha descrito el modelo de cada red y se ha propuesto una representación original como grafos de libre escala. La importancia de representar estas infraestructuras como grafos de libre escala ha sido debido a que este tipo de redes tienen más semejanza con la realidad de las infraestructuras [105].

La Fig. 2 muestra la propuesta de representación topológica de una red eléctrica de cuatro buses, en comparación con la representación tradicional. Tanto los transformadores, las torres eléctricas de las líneas de transmisión, las cargas eléctricas, así como capacitores y reactores han sido tenidos en cuenta como activos susceptibles de ser eliminados como resultado de ataques o fallos en la red eléctrica. En la representación tradicional los activos conectados a las subestaciones, por ejemplo, centrales de generación, cargas, compensadores, etc., no se consideran en el grafo, sino que quedan integrados en un solo nodo.

Tabla I Descripción de la metodología

Procedimiento para el cálculo de los flujos de carga en el sistema de potencia	**Procedimiento para el cálculo de los flujos en la red de gas**
DATOS DE ENTRADA **1.-** Ingresar el valor base para el sistema de potencia, los valores por unidad de tensiones, así como el valor de tolerancia "ε" el cual el algoritmo debe satisfacer. **2.-** Ingresar la clasificación de los nodos de acuerdo a su tipo (*PQ, PV* y *Slack).* **3.-** Especificar las potencias de los generadores *PV.* **4.-** Especificar la conectividad de las líneas con sus respectivos valores de impedancias, así como la conectividad y valores del TAP de los transformadores, si es el caso. **5.-**Inicializar las variables P_i, Q_i, V_i, δ_i con valores conocidos para buses *PQ* y *PV.* **CÁLCULOS INICIALES** **6.-** Calcular las corrientes nodales iniciales I_i. **7.-** Calcular las potencias P_i y Q_i de todos los buses, con el fin de determinar los cambios en las potencias ΔP y ΔQ. **8.-** Si los cambios en las potencias están por encima del valor de tolerancia "ε" el proceso iterativo inicia. **PROCESO ITERATIVO** **9.-** Formar y calcular la matriz Jacobiana del sistema. **10.-** Se determinan los cambios en las magnitudes de las tensiones nodales V_i y ángulos δ_i, y los nuevos valores son actualizados mediante el uso de la ecuación 20. $$\begin{bmatrix}\Delta\delta \\ \Delta V\end{bmatrix} = [J]^{-1} \cdot \begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (20)$$ **11.-** Utilizando los nuevos valores de tensiones, recalcular las nuevas corrientes nodales I_i, determinar los nuevos valores de potencias P_i y Q_i, y encontrar los desajustes en ΔP y ΔQ en cada bus. **12.-** Repetir los pasos del 9 al 12 hasta que cada valor de desajuste de las potencias nodales sea menor a la tolerancia "ε" definida en el paso 1. **DATOS DE SALIDA** **13.-** Tensiones nodales V_i y ángulos δ_i. **14.-** Las potencias P_i y Q_i que fluyen en cada línea. **15.-** Se determina las potencias P_i y Q_i generadas por el bus *slack.* **16.-** Se calculan las pérdidas de potencias P_i y Q_i en el sistema. **17.-** Se determina el consumo de gas natural necesario para satisfacer la demanda de potencia activa en los generadores acoplados gas natural-electricidad mediante la ecuación 21. $$e_i(P_{G,i}) = K_{2,i}P_{G,i}^2 + K_{1,i}P_{G,i} + K_{0,i} \quad (21)$$	**DATOS DE ENTRADA** **1.-** Ingresar los datos de los nodos y clasificarlos de acuerdo a su tipo (*Cargas, Presión definida, Nodos de succión y descarga de compresores y Nodo de suministro)* con sus respectivos datos nodales, las alturas con respecto al origen e indicar los nodos en la red que presenten un acoplamiento gas-electricidad. **2.-** Si es el caso, ingresar los valores de eficiencia, razón de compresión, temperatura de succión, número de etapas, exponente politrópico y tipo de operación (a base de gas natural o con electricidad) de los compresores. **3.-** Ingresar la conectividad de las tuberías en la red indicando su longitud, diámetro, eficiencia y temperatura media del fluido. **4.-** Ingresar las propiedades del fluido como son gravedad específica, factor medio de compresibilidad, temperatura y presión en condiciones estándar. **5.-** Seleccionar la expresión del factor de fricción que se desea utilizar de acuerdo a la Tabla I. **6.-** Formular el vector de suministros/demandas **(S)** tomando en consideración el paso 1 de este procedimiento, y el paso 17 del "*Procedimiento para el cálculo de los flujos de carga en el sistema de potencia".* **7.-** Establecer el valor de tolerancia "ε" que debe satisfacer el algoritmo. **CÁLCULOS INICIALES** **8.-** Calcular los parámetros de elevación "*s*" de las tuberías mediante la ecuación 22. $$s = 0.0375\left(\frac{SG_G \cdot \Delta H}{Z_{av} \cdot T_{av}}\right) \quad (22)$$ **9.-** Calcular la longitud equivalente "L_e" de las tuberías de acuerdo a la ecuación 23. $$L_e = \left(\frac{e^s - 1}{s}\right) \cdot L \quad (23)$$ **10.-** Calcular el factor de fricción "f_F" de acuerdo a la Tabla I. **11.-** Determinar la conductividad de las tuberías para la ecuación de flujo de gas generalizada "C_{ij}" mediante la ecuación 24. $$C_{ij} = \frac{\sigma_G}{\sqrt{SG_G T_{av} Z_{av}}}\left(\frac{T_{sc}}{p_{sc}}\right)\sqrt{\frac{1}{f_F}} \cdot \frac{d^{2.5}}{L_e^{0.5}} \quad (24)$$ **12.-** Si es el caso, calcular la constante de los compresores "k_c" utilizando la ecuación 25. $$k_c = 0.0857\left(\frac{n_{st} \cdot n_p}{n_p - 1}\right)T_i(Z_{av})\left(\frac{1}{\eta}\right) \quad (25)$$ A continuación, calcular la constante final del compresor "C_{cij}" mediante la ecuación 26. $$C_{cij} = \frac{1}{k_c\left[(r_{cij})^{\frac{n_p-1}{n_{st} \cdot n_p}} - 1\right]} \text{ [MMscf/D/HP]} \quad (26)$$ **PROCESO ITERATIVO**

13.- Calcular la conductividad de las tuberías análoga-lineal "L_{ij}" mediante la ecuación 27.

$$L_{ij} = T_{ij} \cdot C_{ij} \quad (27)$$

14.- Formular y calcular la matriz característica **"K"** de la red.

15.- Formar el vector de incógnitas de presiones **"P"** de la red. En el caso que se tengan compresores, el vector **"P"** incluirá el consumo de los HP de los compresores en la fila correspondiente al nodo de descarga del compresor, es decir:

$$P = \begin{bmatrix} p_i \\ \vdots \\ HP \\ \vdots \\ p_n \end{bmatrix} \text{ donde } \forall i \in N_n \quad (28)$$

Adicionalmente, las presiones que se encuentren definidas en el sistema, se ubicaran directamente en la posición correspondiente al nodo en cuestión en el vector "**P".**

16.- Ingresar el vector de suministros/demandas **"S"** calculado en el paso 6.

17.- Obtener la solución al sistema de ecuaciones **KP=S,** mediante cualquier método de solución de ecuaciones algebraicas. No se requiere el método de Newton-Raphson.

18.- Con las presiones calculadas en el paso 15 determinar las relaciones de presión r_{ij} mediante la ecuación 29.

$$r_{ij} = \frac{p_i}{e^{\frac{s_{ij}}{2}} p_j} \quad (29)$$

En el caso que se tengan compresores, determinar la presión de descarga del compresor mediante la expresión 30.

$$r_{cij} = \frac{p_j}{p_i} \quad (30)$$

19.- Determinar las transformadas de las conductividades análogas "T_{ij}" mediante la ecuación 31.

$$T_{ij} = \sqrt{1 + \frac{2}{r_{ij} - 1}} \quad (31)$$

20.- Repetir los pasos del 13 al 20 hasta que cada valor de las presiones nodales sea menor a la tolerancia "ε" definida en el paso 7.

DATOS DE SALIDA

21.- Presiones nodales y HP de los compresores.

22.- Se determinan los flujos en la red de gas (q_{Gij}) mediante la ecuación 32.

$$q_{Gij} = L_{ij}\left(p_i - e^{\frac{s_{ij}}{2}} p_j\right) \quad (32)$$

23.- Se determina el caudal de gas necesario que aporta el *"Nodo de suministro"*.

24.- Se determina el gas consumido por la turbina de los compresores mediante la ecuación 33, si es el caso.

$$g_k = Cf * HP \quad (33)$$

25.- Se confirma la ecuación 34 de balance de flujo en los nodos del sistema.

$$\sum L_{ij} \cdot (p_i - p_j) + S - D - D_g - g_k \quad (34)$$

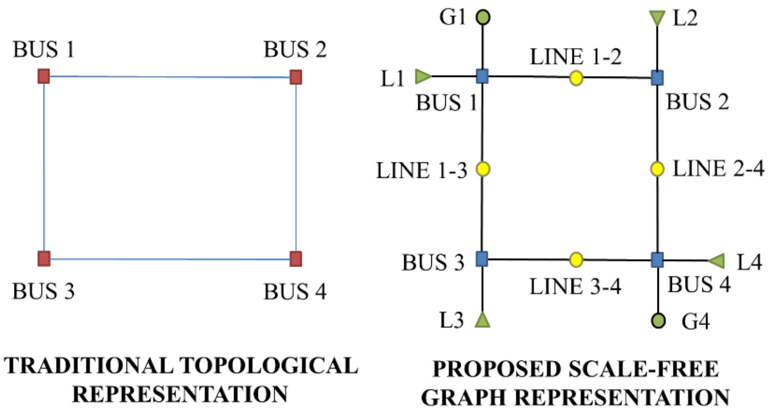

Fig. 2 Representación propuesta como grafo de libre escala de una red eléctrica de cuatro buses.

Por otro lado, la Fig. 3 muestra la propuesta de representación topológica de una red de gas de once nodos y un compresor, en comparación con la representación tradicional que solo considera nodos y enlaces. El grafo de libre escala considera las tuberías, demandas y suministros de gas como nodos del sistema que pueden ser atacados como resultados de ataques deliberados o errores aleatorios. Mientras tanto, la representación topológica tradicional considera únicamente como nodos a los puntos de interconexión, y los compresores y tuberías como enlaces. Aquí no se considera la existencia de suministros y demandas de gas.

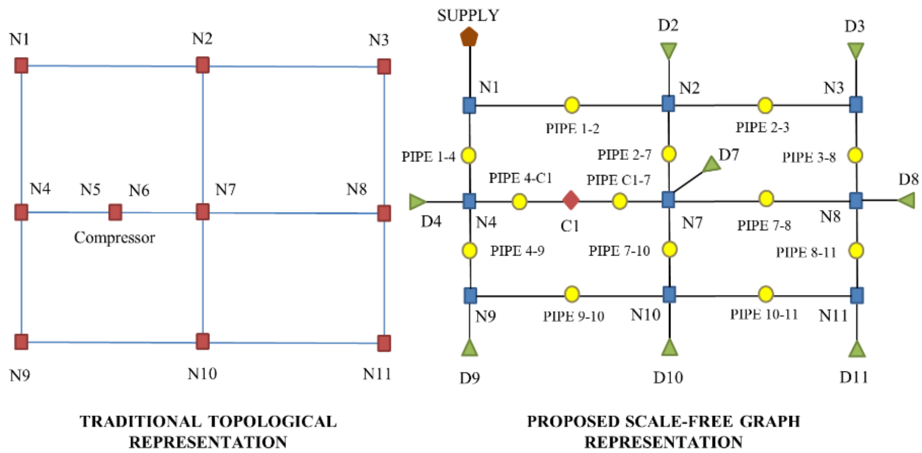

Fig. 3 Representación propuesta como grafo de libre escala de una red de gas natural.

El acoplamiento real entre ambos sistemas se ha realizado mediante la interacción entre determinados activos de ambas redes:

- Por un lado, las centrales de ciclo combinado que usan gas natural para producir electricidad.
- Por otro lado, mediante el suministro de energía eléctrica para el funcionamiento de los compresores de la red de gas.

La Fig. 4 representa la propuesta original de acoplamiento donde se han considerado los grafos de libre escala de las Fig. 2 y Fig. 3. La representación mostrada ha incluido los enlaces de acoplamiento entre las redes de gas y electricidad como nodos del grafo. En el caso del suministro de gas natural a las centrales eléctricas de ciclo combinado, los nodos del acoplamiento representaron los gasoductos que transportan el gas a las centrales de generación. Por otro lado, en el acoplamiento de la red eléctrica a la estación de compresión de la red de gas, las torres de transmisión de electricidad también se representaron como un nodo.

Esta propuesta original como grafo de libre escala ha ofrecido un modelo topológico más realista de ambas redes acopladas. Además, ha permitido que los nodos que representaban el acoplamiento se eliminen para iniciar un proceso de fallos en cascada. Hasta el momento, las representaciones tradicionales en la literatura científica no han considerado el nivel de detalle expuesto en esta metodología. Adicionalmente, se ha comprobado que los modelos propuestos para las redes de electricidad y gas correspondieran a grafos de libre escala, mediante el cálculo de la distribución acumulada y su equivalente analítico como ley de potencias según la teoría de grafos [105], [106].

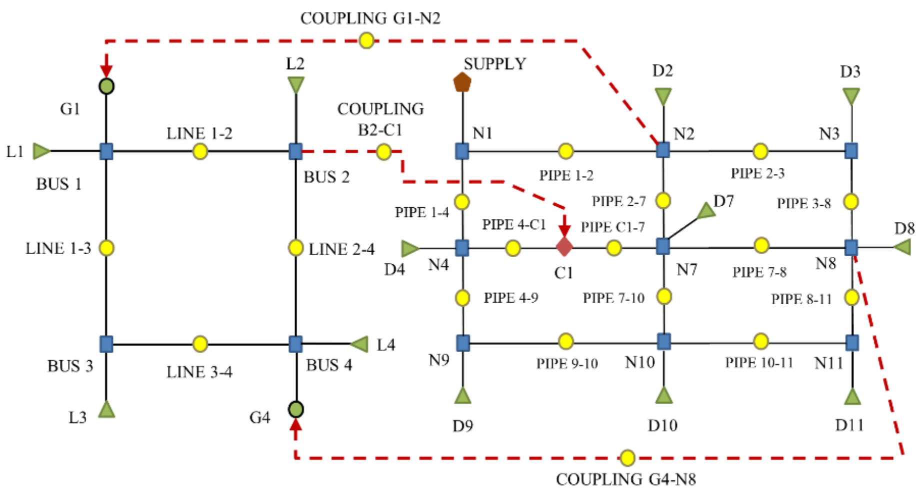

Fig. 4 Grafo de libre escala acoplado de electricidad y gas.

Por otro lado, la vulnerabilidad es un concepto que se utiliza para caracterizar la falta de robustez y resiliencia de un sistema cuando está sujeto a peligros y amenazas [70], [107]. En esta situación, la robustez significa que la infraestructura mantiene su función intacta cuando se expone a perturbaciones, y la resiliencia implica que puede adaptarse para recuperar una nueva posición estable después de una contingencia [70]. Así, para poder evaluar el desempeño de ambas redes acopladas cuando están sujetas a una contingencia debido a la interrupción de un nodo, en este artículo se han usado los índices de vulnerabilidad geodésica $(\bar{v})$ e impacto en la conectividad (S). Estos índices ya han sido validados en redes de prueba IEEE [108] y posteriormente aplicados en redes eléctricas reales [76]. Los resultados obtenidos con estos índices han demostrado su potencial en redes eléctricas aisladas, sin embargo, no han sido aplicados en redes acopladas. Relación que se ha pretendido demostrar en este trabajo.

La vulnerabilidad geodésica $(\bar{v})$ permite normalizar la eficiencia geodésica y hacer un balance en el proceso de evolución de eliminación de nodos, como se indica en (1):

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

Donde:
d_{ij}^{LC}: Distancia geodésica entre los pares del nodo del grafo de libre escala, después de cada iteración de eliminación de un nodo.
d_{ij}^{BC}: Distancia geodésica entre los pares de nodos del grafo de libre escala, para el caso base.

La distancia geodésica se describe como la menor distancia directa entre dos nodos, mediante el conteo del número mínimo de nodos que deben recorrerse para unirlos [71]. El índice $\bar{v}$ varía entre cero y uno, cuanto mayor sea este índice mayor será el impacto en la interrupción del suministro en la red acoplada.

El índice S permite cuantificar el número de nodos que permanecen conectados a la red de mayor tamaño después de cada proceso de eliminación:

$$S = 1 - \frac{N^{LC}}{N} \tag{2}$$

Donde:
N^{LC}: Número de nodos que permanecen conectados en el grafo de libre escala después de una interrupción del nodo.

N: Número total de nodos en el grafo de libre escala para el caso base.

El índice S varía entre cero y uno, cuanto más grande sea este índice mayor será el número de nodos aislados en la red acoplada de electricidad y gas.

El desempeño de la red acoplada de electricidad y gas, cuantificada mediante los índices de vulnerabilidad geodésica en (1) e impacto en la conectividad en (2), se determinan como funciones de la fracción de nodos eliminados (f).

Asimismo, aunque el análisis del desempeño de la red acoplada de electricidad y gas ante fallos en cascada se puede realizar con la sola evolución de los índices descritos arriba, en este artículo se ha querido demostrar que es posible comparar la efectividad de estas medidas de teoría de grafos contra índices clásicos de flujos de carga que incorporan parámetros eléctricos y mecánicos de las redes. Para este caso, se ha propuesto adaptar el índice de desconexión de cargas (LS) aplicado en redes eléctricas [109] para determinar el impacto de los eventos de fallos en cascada, mediante la cuantificación de las cargas que permanecen conectadas en la red acoplada después de sucesivos eventos de interrupción.

Para el caso de la subred eléctrica:

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

Donde:

P_{Di}^{LC}: Potencia activa total que permanece conectada en la red eléctrica después de cada eliminación de un nodo.

Q_{Di}^{LC}: Potencia reactiva total que permanece conectada en la red eléctrica después de cada eliminación de un nodo.

P_{Di}^{BC}: Potencia activa total en el caso base.

Q_{Di}^{BC}: Potencia reactiva total en el caso base.

Para el caso de la subred de gas:

$$LS = 1 - \frac{\sum_i D_i^{LC}}{\sum_i D_i^{BC}} \tag{4}$$

Donde:

D_i^{LC}: Demanda de gas total que permanece conectada en la red de gas después de cada eliminación de un nodo.

D_i^{BC}: Demanda de gas total en el caso base.

La ecuación (4) ha requerido normalizar las unidades de demanda de gas en su equivalente eléctrico, calculado a partir del poder calorífico, presiones y temperaturas de operación en cada uno de los nodos de la red [110]. Por tal motivo, se ha considerado a modo de ilustración el equivalente de 1 m^3 de gas natural igual a 11.63 kWh para todos los nodos de la red, de acuerdo a los datos recogidos en [110].

Las soluciones obtenidas con este índice han sido comparadas con los resultados conseguidos mediante los índices de teoría de grafos de las ecuaciones (1) y (2).

La simulación de fallos en cascada se ha realizado mediante dos estrategias distintas de eliminación de nodos:

- *Ataques deliberados*: se han eliminado sucesivamente los nodos más fuertemente conectados en orden descendente de grado nodal.
- *Errores aleatorios*: se han eliminado nodos al azar. De acuerdo al teorema del límite central, ha sido necesario repetir más de 30 veces cada experimento para obtener una muestra estadística idónea [108].

Del mismo modo, cuando ciertos activos se eliminan se generan efectos interdependientes en la red conjunta. Debido a eso se han clasificado cuatro componentes principales y sus efectos interdependientes:

- *Instalaciones en la red de gas que suministran combustible a los generadores eléctricos*: cuando se elimina este nodo se ocasiona un efecto de interdependencia hacia la red eléctrica porque este nodo suministra gas natural al generador acoplado. La metodología ha considerado eliminar del grafo el nodo de gas y su acoplamiento. Esto representa la pérdida de suministro de combustible.
- *Subestaciones eléctricas que proporcionan electricidad a los compresores*: este nodo suministra electricidad al compresor acoplado. Nuevamente el modelo ha eliminado del grafo todas las instalaciones afectadas.
- *Tubería de entrada de los compresores*: en estos casos se ha identificado el modo de operación (eléctrico o mecánico) del compresor. En ambos casos equivale a la pérdida del compresor y, si este opera por suministro eléctrico externo, al enlace de acoplamiento con la red de electricidad.
- *Enlaces de acoplamiento entre ambas redes*: en todos los casos, los nodos que se han visto afectados como consecuencia de la remoción de los enlaces entre ambos sistemas se han eliminado también del grafo.

Todo lo anterior ha sido programado en el software de Matlab®. Aquí, se ha empleado la metodología de flujos de carga acoplados desarrollada en el artículo

«*Linear-analog transformation approach for coupled gas and power flow analysis*». El programa desarrollado también ha incorporado una amplia variedad de rutinas para resolver algoritmos de teoría de grafos.

Finalmente, para mostrar el desempeño del modelo propuesto y comprobar la utilidad de los modelos de teoría de grafos en contraste con la técnica de flujos de carga en redes acopladas de electricidad y gas, se han aplicado dos casos de estudio:

1) en un sistema conjunto de la red de 57 nodos IEEE junto con una red de gas de 22 nodos.
2) en un sistema conjunto de la red de 118 nodos IEEE junto con una red de 25 nodos y 3 compresores.

3.4.3 Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures

En este artículo se ha propuesto como metodología la aplicabilidad de los avances obtenidos en el artículo «*Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures*». El sistema bajo estudio ha correspondido a la red eléctrica de alta tensión de 400 kV y la red de gas natural de alta presión de 80 bar de España.

La red eléctrica de alta tensión la componen más de 21 000 km de líneas eléctricas en alta tensión, más de 1 000 posiciones de subestaciones y más de 80 000 MVA de capacidad de transformación [111]. Por su parte, la red de gas natural de alta presión la integran más de 11 000 km de tuberías y un conjunto de instalaciones que permiten la operación óptima de la infraestructura [112].

En la Fig. 5 se han representado las redes de electricidad y gas, y la red acoplada de ambos sistemas como grafos de libre escala. La representación aquí propuesta ha tomado en cuenta la totalidad de activos de ambos sistemas según la información proporcionada por los operadores en [112]–[115].

La red eléctrica de alta tensión de 400 kV está compuesta por subestaciones eléctricas, generadores, cargas eléctricas, líneas eléctricas y transformadores. Los datos para construir el grafo sin escala de la Fig. 5 a) se han extraído del mapa de red del operador del sistema de transmisión [113]. La red de gas natural de alta presión de 80 bar de la Fig. 5 b) contiene 6 terminales de regasificación, 19 estaciones de compresión, 3 instalaciones de almacenamiento subterráneo, 2 yacimientos, 6 conexiones internacionales, 32 puntos de conexión para líneas directas, 57 puntos de conexión de transmisión-transmisión y 294 puntos de conexión de transmisión-distribución. Los datos se han extraído del operador del sistema gasista [112], [114], [115].

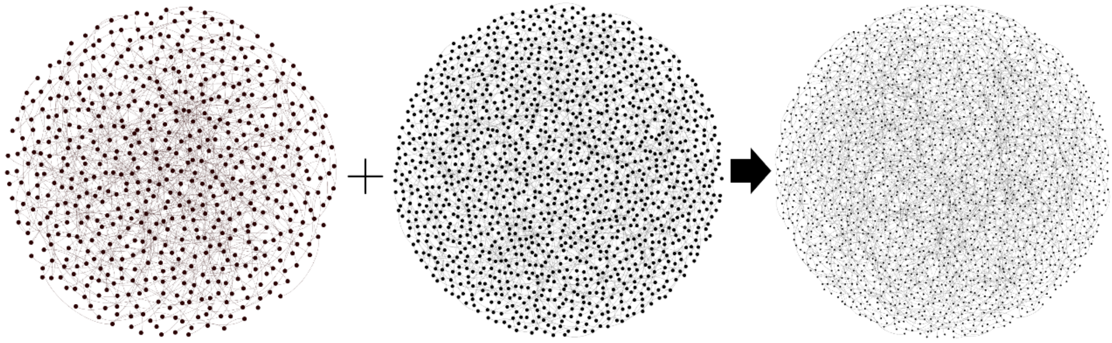

Fig. 5 Grafos de libre escala de infraestructuras de electricidad y gas natural en España.

Del mismo modo que el artículo dos, las centrales térmicas de ciclo combinado de gas natural y los compresores eléctricos han actuado como acoplamiento para las redes descritas arriba. En este trabajo se han considerado 26 centrales de ciclo combinado conectadas a subestaciones eléctricas de 400 kV. Paralelamente, la red de gas natural ha contado con 14 compresores que requieren de un suministro eléctrico. Esta representación ha constituido el caso de estudio base.

Los operadores de las redes cuentan con planes de expansión para mejorar la seguridad del suministro de electricidad y gas a los usuarios. Para el caso de España se ha tomado en cuenta el informe [116] que describe las propuestas de inversiones en las redes para los años 2015-2020, de donde se ha obtenido la información sobre la construcción de nuevas líneas eléctricas, subestaciones, gasoductos, estaciones de compresiones, entre otros. Las inversiones propuestas hasta 2017 se encuentran actualmente en operación, por lo que han sido ya tenidas en cuenta en el caso base de la Fig. 5. Por tanto, en este trabajo se han considerado los casos de estudio correspondientes a la construcción de nuevas líneas eléctricas de alta tensión de 400 kV y gasoductos de alta presión de 80 bar entre 2018 y 2020.

El algoritmo de evaluación propuesto utiliza el planteamiento validado en el artículo dos, evaluando la robustez estructural ante fallos en cascada mediante la evolución del índice de vulnerabilidad geodésica ($\bar{v}$).

En suma, la aplicación de la metodología se ha llevado a cabo sobre 22 casos de estudio, donde los casos han seguido el orden cronológico de construcción de nuevas líneas eléctricas y gasoductos propuesto por los operadores de ambas redes. Aquí, cada nuevo caso de estudio contiene la ampliación anterior.

3.4.4 Cascading failures in coupled gas and electricity transmission systems

En este artículo de conferencia se ha estudiado la vulnerabilidad estructural de las redes de gas y electricidad conjuntas de España, tanto de manera separada como acoplada. Se ha utilizado la metodología de evaluación de vulnerabilidad basada en teoría de redes complejas, validada en el artículo dos. Las redes de gas y electricidad para este estudio se corresponden con el caso base del artículo tres. Así, se han planteado los siguientes casos:

- Simulación de fallos en cascada en cada una de las redes de electricidad y gas natural separadas nombrados como casos 1 y 2.
- Simulación de fallos en cascada en la red acoplada de electricidad y gas natural nombrados como casos 3 y 4.

Los efectos interdependientes no se han tenido en cuenta en la simulación de fallos en cascada en las redes por separado, sino únicamente en la red acoplada. Los resultados han sido presentados para ataques deliberados y errores aleatorios.

Con base en los resultados obtenidos, se pueden obtener conclusiones sobre el funcionamiento de la red acoplada de gas natural y electricidad en España. Los resultados han evidenciado que la red acoplada es más vulnerable que la red eléctrica ante fallos aleatorios y deliberados. Sin embargo, la red conjunta es menos vulnerable que la red de gas natural.

También, se ha analizado la secuencia de los nodos eliminados de las redes ante fallos deliberados en cuatro casos distintos:

- Red eléctrica (caso 1): utilizando en orden descendente el grado nodal de los nodos de la red eléctrica.
- Red de gas (caso 2): utilizando en orden descendente el grado nodal de los nodos de la red de gas.
- Red acoplada (caso 3): utilizando, para la red acoplada, el grado nodal en orden descendente de los nodos más conectados de la red eléctrica y, a continuación, los nodos más conectados de la red de gas.
- Red acoplada (caso 4): utilizando en orden descendente el grado nodal de los nodos de la red acoplada.

Los diferentes casos anteriores han demostrado que, para la desintegración de la red interdependiente, la combinación de las secuencias de los grados nodales de las redes por separado es una estrategia de ataque más eficiente que utilizar la secuencia resultante de los grados nodales del sistema conjunto.

3.5 Aportaciones del doctorando

3.5.1 Linear-analog transformation approach for coupled gas and power flow analysis

Las aportaciones realizadas por el doctorando fueron las siguientes:

- Realicé una extensa revisión bibliográfica sobre diversos modelos y técnicas para obtener la solución de los flujos de electricidad y gas natural acoplados.
- Mantuve conversaciones con diversos especialistas en el estudio de redes de gas.
- Programé en el software de Matlab® todas las ecuaciones que simulan la interacción entre ambas redes.
- Propuse la elaboración de un artículo científico.
- Participé en la escritura, planteamiento y objetivo del artículo.
- Definí los casos de estudio, realicé los cálculos y analicé los resultados.
- Participé en la obtención de conclusiones.

3.5.2 Applying Complex Network Theory to the Vulnerability Assessment of Interdependent Energy Infrastructures

Las aportaciones realizadas por el doctorando fueron las siguientes:

- Realicé una extensa revisión bibliográfica sobre las técnicas de modelado y simulación de infraestructuras críticas interdependientes.
- Participé en el planteamiento y objetivo del problema a estudiar.
- Participé en la elaboración del grafo de libre escala de las infraestructuras de gas natural y electricidad.
- Participé en la propuesta y estudio de las interdependencias entre las infraestructuras de electricidad y gas natural.
- Colaboré durante todo el desarrollo de la propuesta metodológica.
- Programé la herramienta de simulación de fallos en cascada para redes interdependientes.
- Participé en la escritura, planteamiento y objetivo del artículo.
- Definí los casos de estudio, realicé los cálculos y analicé los resultados.
- Participé en la obtención de conclusiones.

3.5.3 Robustness assessment of the expansion of coupled electric power and natural gas networks under cascading failures

Las aportaciones realizadas por el doctorando fueron las siguientes:

- Realicé una extensa revisión bibliográfica sobre trabajos que evalúen los planes de expansión de las redes desde el punto de teoría de grafos.
- Realicé un amplio estudio de los planes de expansión de las redes de electricidad y gas natural de España.
- Extraje toda la información topológica de los sistemas acoplados de electricidad y gas natural de España.
- Elaboré los grafos de libre escala de las infraestructuras energéticas.
- Programé la herramienta de simulación de fallos en cascada.
- Participé en la escritura, planteamiento y objetivo del artículo.
- Definí los casos de estudio, realicé los cálculos y analicé los resultados.
- Participé en la obtención de conclusiones.

3.5.4 Cascading failures in coupled gas and electricity transmission systems

Las aportaciones realizadas por el doctorando fueron las siguientes:

- Sugerí la elaboración del artículo con propósitos de divulgación.
- Programé la herramienta de simulación de fallos en cascada tanto para errores aleatorios como ante ataques deliberados.
- Participé en la escritura, planteamiento y objetivo del artículo.
- Definí los casos de estudio, realicé los cálculos y analicé los resultados.
- Participé en la obtención de conclusiones.

3.6 Resultados y conclusiones finales

La falta de metodologías y técnicas de análisis que permitan evaluar la vulnerabilidad estructural de infraestructuras energéticas de electricidad y gas natural interdependientes ha constituido la principal motivación para abordar este trabajo de investigación. A lo largo de este documento se ha dejado en evidencia la necesidad de desarrollar una mejor estrategia de estudio de las ecuaciones combinadas de ambas redes acopladas, de proponer una metodología de estudio de la vulnerabilidad estructural con menor cantidad de información técnica de las redes, pero manteniendo precisión en los resultados y, de corroborar y aplicar los resultados obtenidos sobre redes de energía reales, todo lo cual no se ha abordado en trabajos de investigación previos.

Por tal motivo, en esta tesis doctoral se ha presentado inicialmente una metodología para analizar conjuntamente el flujo de electricidad y gas acoplado, donde se ha considerado la existencia de centrales de ciclo combinado y compresores. El conjunto de ecuaciones no lineales que representan la operación del sistema de potencia se ha resuelto utilizando el bien conocido método de Newton-Raphson (NR por sus siglas en inglés), mientras que la solución del balance nodal de gas y los caudales a través de los gasoductos y compresores de la red de gas se han obtenido utilizando el enfoque análogo-lineal (LAT por sus siglas en inglés). Se han presentado dos casos de estudio para demostrar la simplicidad de la metodología propuesta para analizar la interacción entre los sistemas de gas y electricidad. Los resultados obtenidos mediante LAT han sido verificados contra el método NR para redes de gas, con el fin de confirmar la solución alcanzada, encontrando un buen desempeño de la metodología conjunta aplicada LAT-NR. La aplicación del enfoque propuesto ha permitido llevar a cabo análisis de la vulnerabilidad y la resiliencia de las infraestructuras de electricidad y gas conjuntas.

En lo referente a la evaluación integrada de ambos sistemas, también se ha propuesto y desarrollado una metodología para analizar la vulnerabilidad estructural de las redes de energía eléctrica y gas acopladas, considerando y proponiendo interdependencias en el proceso de fallos en cascada. La vulnerabilidad se ha evaluado con los resultados obtenidos del índice de desconexión de carga del método tradicional de flujo de potencia y de dos índices de la teoría de grafos, la vulnerabilidad geodésica y el impacto en la conectividad. El análisis estadístico ha mostrado una fuerte correlación entre el índice de desconexión de carga y el índice de vulnerabilidad geodésica. Por lo tanto, los métodos de la teoría de grafos pueden utilizarse en lugar de los métodos de flujo de carga que requieren un conocimiento más detallado de los parámetros eléctricos y mecánicos de los sistemas y son computacionalmente más intensivos que los métodos estadísticos de grafos. Como resultado, se ha propuesto un nuevo método para estimar la vulnerabilidad de las redes de energía eléctrica y gas conjuntas utilizando el índice de vulnerabilidad geodésica. En términos más generales y precisos, este método ha simplificado enormemente las comparaciones de diferentes topologías de redes de gas y energía eléctrica interdependientes.

Por otro lado, la aplicabilidad de los avances obtenidos en este documento ha terminado en la propuesta de una novedosa metodología para evaluar la robustez estructural de la red eléctrica y de gas natural acoplada en España. Las interdependencias físicas entre los dos sistemas se han evaluado considerando cuatro tipos de activos para las interconexiones entre las infraestructuras. La metodología en combinación con su algoritmo ha utilizado el enfoque de grafos y la medida de centralidad de vulnerabilidad geodésica. Los estudios de casos han correspondido a las principales inversiones propuestas por los operadores de los sistemas en 2015-2020. Los resultados han demostrado que la construcción de algunos activos para la expansión de las redes de gas y electricidad no mejoran la robustez estructural de la red acoplada; sin embargo, cuando se tiene en cuenta todo el programa de inversión se produce una mejora relativa de hasta un 6% con respecto al caso base.

Por otra parte, la metodología propuesta en este artículo ha corroborado que la aplicación de la teoría de grafos es adecuada para analizar la planificación de activos de una infraestructura energética crítica, requiriendo únicamente la topología y el programa de inversiones para evaluar el desempeño de la red acoplada en caso de fallos en cascada. Las conclusiones de este estudio son relevantes para el análisis de la robustez de la infraestructura de gas y electricidad, lo que no desacredita la planificación de los operadores de las redes de transporte para mejorar la capacidad del sistema bajo otros criterios y asegurar su óptimo funcionamiento técnico y económico.

También, se ha terminado estudiando el comportamiento de las redes de electricidad y gas natural de España, tanto de manera separada como conjunta. Los resultados han mostrado que el sistema de gas natural es menos robusto que el sistema eléctrico y que la red acoplada es más vulnerable que la red eléctrica ante fallos aleatorios y deliberados. Además, eliminar los nodos más fuertemente conectados de los dos sistemas independientes ha sido una estrategia de ataque eficaz para el rápido colapso de las redes acopladas interdependientes. Nuevamente, el uso de la teoría de grafos como metodología para el análisis de vulnerabilidad ha demostrado ser eficiente y que puede aplicarse a cualquier sistema de infraestructura crítica real.

Finalmente, esta tesis doctoral ha puesto de relieve la importancia de que los sistemas energéticos se aborden como redes acopladas debido a sus fuertes interacciones. Una perturbación en un sistema puede no ser crítica si las infraestructuras están separadas, pero dado que ambas redes son interdependientes, el impacto resultante podría causar fallos en el otro sistema. En otras palabras, las interdependencias aumentan el impacto de las perturbaciones.

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Anexos

Factor de impacto de las revistas y áreas temáticas correspondientes a las publicaciones que se recogen en la tesis.

Anexo A. Electric Power Systems Research

Fuente: InCites Journal Citation Reports / Web of Science / THOMSHON REUTERS

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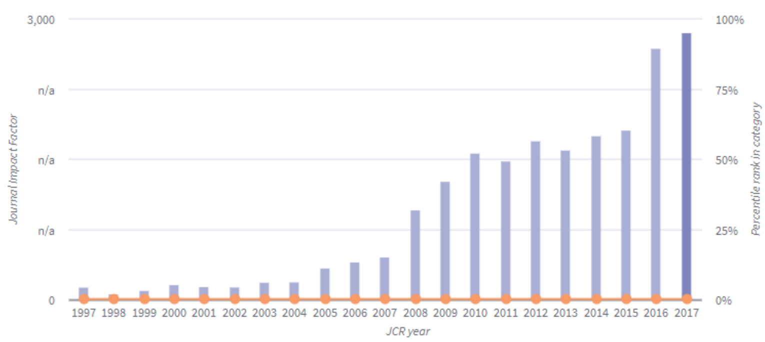

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2016	73/262	Q2	72.328
2015	85/257	Q2	67.121
2014	83/249	Q2	66.867
2013	91/248	Q2	63.508
2012	70/243	Q2	71.399
2011	82/245	Q2	66.735
2010	69/247	Q2	72.267
2009	91/246	Q2	63.211
2008	126/229	Q3	45.197
2007	151/227	Q3	33.700
2006	149/206	Q3	27.913
2005	159/208	Q4	23.798
2004	176/209	Q4	16.029
2003	176/205	Q4	14.390
2002	180/203	Q4	11.576
2001	167/200	Q4	16.750
2000	169/204	Q4	17.402
1999	179/205	Q4	12.927
1998	182/208	Q4	12.740
1997	157/193	Q4	18.912

Anexo B. Energies

InCites Journal Citation Reports

Clarivate Analytics

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Energies

ISSN: 1996-1073
eISSN: 1996-1073
MDPI
ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND
SWITZERLAND

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TITLES
ISO: Energies
JCR Abbrev: ENERGIES

CATEGORIES
ENERGY & FUELS - SCIE

LANGUAGES
English

PUBLICATION FREQUENCY
12 issues/year
Open Access from 2008

InCites Journal Citation Reports

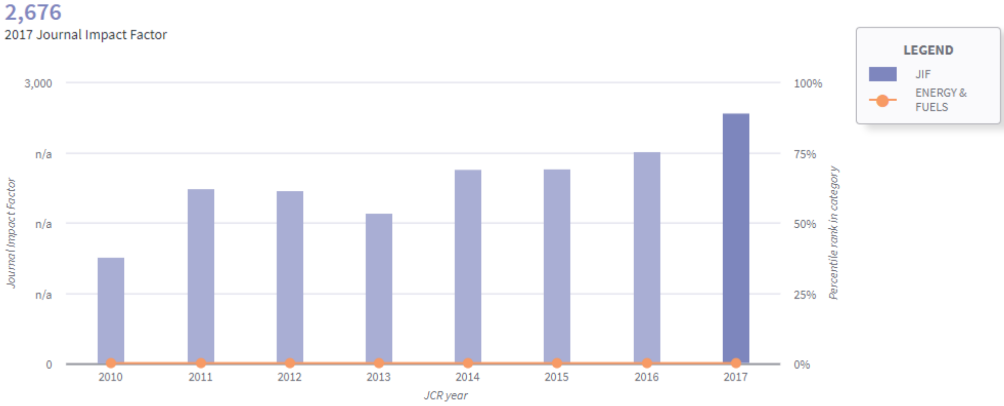
Clarivate Analytics

2017 journal performance data for: Energies

Click here to print current page

2017Journal Impact Factor & percentile rank in category for:Energies

2,676
2017 Journal Impact Factor



JCR Impact Factor

JCR Year	ENERGY & FUELS Rank	Quartile	JIF Percentile
2017	48/97	Q2	51.031
2016	45/92	Q2	51.630
2015	43/88	Q2	51.705
2014	43/89	Q2	52.247
2013	43/83	Q3	48.795
2012	38/81	Q2	53.704
2011	35/81	Q2	57.407
2010	42/79	Q3	47.468

Anexo C. IET Generation, Transmission & Distribution

InCites Journal Citation Reports

Clarivate Analytics

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IET Generation Transmission & Distribution

ISSN: 1751-8687
eISSN: 1751-8695
INST ENGINEERING TECHNOLOGY-IET
MICHAEL FARADAY HOUSE SIX HILLS WAY STEVENAGE, HERTFORD SG1 2AY, ENGLAND
ENGLAND

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TITLES
ISO: IET Gener. Transm. Distrib.
JCR Abbrev: IET GENER TRANSM DIS

View TitleChanges

CATEGORIES
ENGINEERING, ELECTRICAL & ELECTRONIC - SCIE

LANGUAGES
English

PUBLICATION FREQUENCY
12 issues/year

InCites Journal Citation Reports

Clarivate Analytics

2017 journal performance data for: IET Generation Transmission & Distribution

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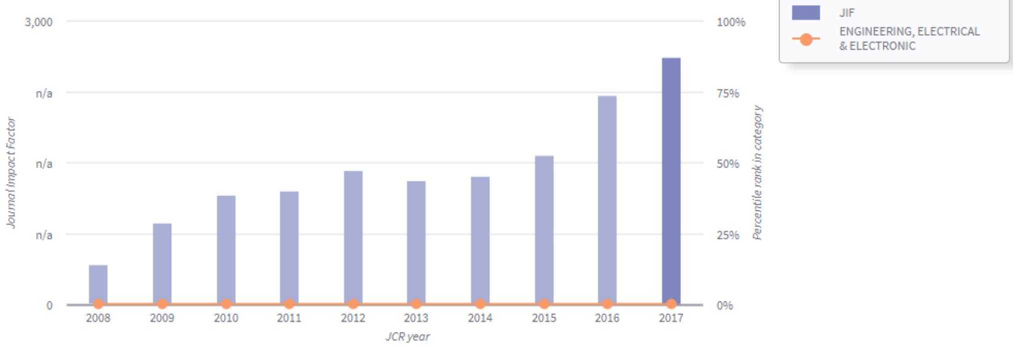
2017Journal Impact Factor & percentile rank in category for:IET Generation Transmission & Distribution

2,618
2017 Journal Impact Factor



JCR Impact Factor

JCR Year	ENGINEERING, ELECTRICAL & ELECTRONIC		
	Rank	Quartile	JIF Percentile
2017	87/260	Q2	66.731
2016	104/262	Q2	60.496
2015	103/257	Q2	60.117
2014	112/249	Q2	55.221
2013	114/248	Q2	54.234
2012	91/243	Q2	62.757
2011	109/245	Q2	55.714
2010	109/247	Q2	56.073
2009	134/246	Q3	45.732
2008	183/229	Q4	20.306

Anexo D. Artículo de conferencia indexado al IEEEXplore.

Product Description

Title:	2018 IEEE ANDESCON
Desc:	Proceedings of a meeting held 22-24 August 2018, Santiago de Cali, Colombia.
Prod#:	CFP1861J-POD
ISBN:	9781538683736
Pages:	591 (1 Vol)
Format:	Softcover
Notes:	Authorized distributor of all IEEE proceedings
TOC:	View Table of Contents
Publ:	Institute of Electrical and Electronics Engineers (IEEE)
POD Publ:	Curran Associates, Inc. (Jan 2019)