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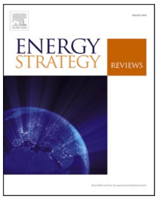

Optimal cooperative model for the security of gas supply on European gas networks

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ABSTRACT

Natural gas infrastructures play a key role in the transition towards the new energy model, with a high share of renewable energies, both ensuring the firm capacity of electric power systems and integrating all energy vectors. The European Union (EU) strongly depends on external natural gas suppliers and is thus particularly vulnerable. In the event of supply problems due to natural phenomena, technical failures or other threats, cooperation between EU countries would be essential to best solve a supply crisis. This study proposes an EU cooperative model to meet the gas demand over a fourteen-day crisis, using a mathematical optimisation approach for resources and infrastructure. The model considers the dynamic management of underground gas storage facilities, limiting daily withdrawal based on the amount of working gas available in each storage facility. The ability of the model to make quick decisions is illustrated in six gas-demand case studies of the European cold wave in January 2017 and hypothetical supply disruptions.

1. Introduction

As part of the new international policy to reduce pollutant emissions, most developed countries are closing coal-fired power stations. These power stations are being replaced by other, more modern, power production technologies, which mainly use natural gas and renewable energy sources. The International Energy Agency estimates that replacing coal-with gas-fired power stations could reduce up to 1.2 gigatons of CO_2 because the latter emit 50% less pollutants than the former [1]. The creation of international emissions markets and regulations has remarkably raised the cost of coal-fired power generation, rendering gas-fired power generation increasingly attractive. In fact, low natural gas prices have accelerated this trend in 2020 [2].

While many countries are setting ambitious decarbonisation targets for 2030 and 2050, the transition towards 100% renewable energy requires power generation technologies that provide electric power systems with firm capacity. Until commercially viable, large-scale electricity storage technologies are available, electric power systems will depend on predictable and reliable energy generation sources like gas-fired power plants [3]. In addition, gas infrastructures do allow seasonal energy storage, which also provides significant value in ensuring electricity supply through combined-cycle gas plants. Therefore, these stations play a key role in the security of electricity supply.

Notwithstanding the importance of natural gas as a transition fuel for supporting renewable energy development in the short and medium term, the demand for gas is expected to decline in the long term [4,5]. This perspective can limit future investments in new gas transmission and storage infrastructure projects even though the gas sector is promoting alternatives for the use of existing networks with new energy vectors, such as hydrogen, to address its decreasing importance from 2030 [6,7].

As the world's largest importer of natural gas and, therefore, highly dependent on other countries, the European Union (EU) is a very unique case. Its annual consumption is approximately 500,000 million m^3, and its dependence on external suppliers reached 90% in 2019 [8]. Russia is the main natural gas supplier to the EU (45%), followed by Norway (21%) and Algeria (12%) [9]. Liquefied natural gas (LNG) imports to the EU increased for geopolitical reasons of supply diversification, reaching 22% of total gas imports in 2019. However, pipeline gas imports remain the main source of foreign gas entry into the EU, and some major projects for new international gas pipelines running from Russia and Caspian countries to Europe are under development, such as Nord Stream 2, TurkStream and TANAP-TAP (Trans-Anatolian Natural Gas Pipeline - Trans Adriatic Pipeline).

In addition to improving the natural gas supply infrastructures, the EU has proposed new cooperative mechanisms to reduce the impact of supply crises by increasing cross-border pipeline gas exchange when

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Nomenclature

$C_{i,d}$	daily gas demand satisfied in country i (GWh/d)
$P_{i,d}$	daily gas production of country i (GWh/d)
$ST_{i,d}$	daily working gas available in storage every day in country i (GWh)
$SWR_{i,d}$	daily gas storage withdrawal from underground storage in country i (GWh/d)
$IMP_{i,d}$	daily gas pipeline imports from third-party countries to country i (GWh/d)
$LNG_{i,d}$	daily gas injected from regasification plants into the pipes of country i (GWh/d)
$X_{ij,d}$	daily gas flow through cross-border pipelines between countries i and j (GWh/d)

necessary [10,11]. These regulations do not aim to replace the national energy policies, but rather to facilitate mutual support between natural gas-producing countries, LNG-importing countries, pipeline gas transit countries and the other EU countries. Similar cooperative mechanisms have also been proposed for risk-preparedness in the electricity sector [12].

Intentional attacks, cold waves, or technical failures can affect gas supply. However, when operators of national transmission systems face these crises, they usually make decisions considering their endogenous resources, overlooking possible collaborative actions with neighbouring countries. In turn, given the dynamic nature of gas production, storage and flows in networks, establishing contingency plans for all possible scenarios during an energy supply crisis is practically impossible. In addition, such a crisis may require continuously updating the interventions in the infrastructure, especially if the crisis lasts for a long period.

Thus, this study proposes a novel approach to developing strategies to optimally respond to possible crises, beyond the classical simulation approach for risk assessment. For this purpose, mathematical optimisation tools are used to apply cooperative strategies towards meeting as much as possible the demand in all EU-28 member states and in some neighbouring countries. The mathematical problem is formulated considering the daily production and storage capacities, cross-border interconnections and third-party country LNG or gas pipeline imports of each country. The EU network model of gas transmission infrastructures captures the different characteristics of national systems and manages gas exchange between countries to determine the best possible solution for global EU supply.

Another novelty of this research is the application of the proposed mathematical model to identify the best strategy for a two-week winter gas supply crisis by calculating the most adequate daily use of resources and infrastructures while maximising the satisfied demand over the entire fourteen-day period. The effects of emptying gas reservoirs and reducing the daily withdrawal with the decrease in stored working gas volume are analysed. The two-week case study is a common research strategy in studies simulating the security-of-supply of natural gas conducted by the European Network of Transmission System Operators for Gas (ENTSO-G) in Europe because this design makes it possible to capture the effect of a cold wave on gas supply and, especially, on gas storage [13].

This article is organised as follows: Section 2 presents a review of the main gas system models. Section 3 describes the optimisation model proposed to determine the optimal management of a fourteen-day natural gas supply crisis in the EU. Section 4 presents six case studies based on possible supply outages in the European gas transmission network. Section 5 discusses the findings, and, last, Section 6 outlines the main conclusions of this paper.

2. Modelling of gas systems for the security of supply: state of the art

The most widely used approach in risk assessment studies for interconnected natural gas systems is the set of probabilistic methods known as Monte Carlo. The Monte Carlo method has been used to evaluate the behaviour of natural gas networks in different events [14,15]. This method is based on repetitive simulations of how the system operates under different assumptions of accidental or intentional contingencies in gas supply and transportation infrastructures. Each possible contingency is assigned a specific probability. Hence, the method makes it possible to evaluate all possible consequences by estimating the input uncertainties of the model, running the model under different values of input parameters and by describing the consequences in statistical terms [16].

The risk assessment studies for interconnected gas systems frequently rely on a simplified mass balance model in which the equations are obtained by applying the principle of mass conservation at each network node [14,15], rather than on a dynamic hydraulic model of the gas transmission system [17] since the latter requires extensive knowledge of the parameters and technical characteristics of the networks. If this information would be available, specific software programs such as SAInt can simulate the dynamic operation of gas networks for assessing the security of supply [18].

While simulation models analyse the consequences of different system contingencies, there is a lack of research providing strategies to optimally respond to possible gas supply crises. Using mathematical optimisation rather than probability-based approaches may be appropriate if the time frame for making decisions about available resources is limited because traditional probabilistic simulation models used to determine the impact of disturbances on gas supply take a long time to run. Therefore, a mathematical optimisation approach makes it possible to obtain the best possible operation of an interconnected gas infrastructure under different supply disruption conditions.

Some models apply optimisation in gas systems, but they aim to examine how markets function, to reduce costs or to analyse the impact of different changes in regulatory frameworks on market participants. Among these, the GASMOD model is formulated as a two-stage game of natural gas exports and wholesale trade within Europe [19]. Other works propose multilevel models for the gas market, including infrastructure constraints under perfect competition and assuming interaction between the operator and traders [20]. Similarly, the European Gas Market Model (EGMM) is a market equilibrium model for analysing the production, trade, storage, and natural gas consumption in Europe [21]. Meanwhile, the Global Gas Model is a model for studying European gas markets, which maximises the profit of market players and the behaviour of operators, and includes security of supply concerns [22,23]. Additionally, a minimum cost dispatch for the gas supply chain can be found in Ref. [24].

On the other hand, other studies propose models based on mathematical programming techniques to evaluate investments in new infrastructure within the EU. For example, the GASTALE model uses game theory, and the EUGAS and MAGELAN models use dynamic programming to optimise investments in production and infrastructure capacity on a yearly basis [25,26]. Likewise, the COLUMBUS model optimises production, transport and storage capacities based on monthly resolution [27], the TIGER model minimises supply-demand transmission costs also with monthly granularity [28,29], and the GASMOPEC model enhances the decision-making process from a market perspective [30].

Despite analysing gas markets and infrastructures, these optimal models do not solve supply crises in the short term, but rather aim to assess the adequacy of the infrastructure in the long term. Therefore, it is essential to propose an optimal cooperative management model for the security of supply, which allows establishing the best strategies for dealing with crisis scenarios in case of disruptions in gas supply to the EU.

3. Proposed mathematical model

Contingency plans to recover critical energy infrastructure after a severe failure are developed primarily at the national level. However, European energy infrastructures are interconnected between countries, and intentional attacks, natural hazards or limited third-party country supply can lead to restrictions on demand. In these cases, cooperative strategies may be implemented, instead of individual solutions, to jointly meet as much as possible the demand of all countries.

The EU has proposed regulations to prepare and establish preventive and emergency action plans, seeking a cooperative approach among member states to reduce the impact of severe disruption scenarios. Regulation (EU) 2017/1938 on measures to safeguard the security of gas supply is currently being implemented to develop joint measures and facilitate the bi-directional capacity of cross-border interconnections under a cooperation framework between EU countries [11].

Given the dynamic nature of gas production flows, storage and networks, establishing contingency plans for all possible scenarios during a power supply crisis is practically impossible. In addition, infrastructure interventions may require updating, especially if the crisis lasts for a long period. This study proposes a formulation for managing interconnected natural gas infrastructures towards improving resilience when facing a supply crisis, that is, maintaining the maximum amount of gas supply to consumers during a two-week study period. Gas storage facilities and exchange between countries play a key role in this problem because they can extend gas supply for more days if used optimally. Using mathematical optimisation techniques instead of probabilistic approaches is appropriate when decisions concerning available resources need to be quick since traditional probabilistic simulation models used for determining the disturbance impact on gas supply are more time-consuming.

The proposed model maximises the daily coverage of the natural gas demand for fourteen days in a group of interconnected countries by providing collaborative solutions to supply crises due to technical, political or natural phenomena. Later, in Section 4, this model is applied to a series of case studies in the European gas transmission network. The mathematical equations of the model are derived by applying the principle of mass balance at each node of the network. Each country is represented by a node in a graph, following the Monte Carlo-based Gas Energy Network for Europe, Russia, and the Commonwealth of Independent States (MC-GENERCIS) and Gas Emergency Flow (GEMFLOW) models proposed by the Joint Research Centre of the European Commission [14,31]. Such models can be applied to draw significant conclusions about gas system capacities even when a hydraulic model of the system is not used. They are used to assess the security of natural gas supply in the event of disruptions in the external supply of natural gas to the EU through cooperative mechanisms between member countries. Hydraulic models cannot be used due to the lack of detailed information on the infrastructures of these countries.

In the model presented here, each country i is represented as a node in the natural gas transmission system. The resources involved every day d are the demand, $C_{i,d}$, the production, $P_{i,d}$, the daily storage facility's withdrawal rate, $S_{i,d}$, natural gas pipeline imports, $IMP_{i,d}$, LNG shipping, $LNG_{i,d}$, and the interconnection capacities between neighbouring countries $X_{ij,d}$.

The mathematical model uses the available capacities of each country once the internal demand has been met to identify the best solution for the fourteen days of the case study, that is, to get as close as possible to meeting the demand of the countries belonging to the interconnected natural gas system. Cross-border interconnections have a physical capacity that limits the flow and they can be uni-o bi-directional. Previous optimisation models for this problem have only solved gas supply for one day, and without sharing gas stored in the countries [32].

The mathematical optimisation problem is defined by the objective function of eq. (1) and by the set of constraints that are shown in eqs. (2)–(10). $C_{i,d}^{max}$ is the natural gas demand that the system seeks to meet every day, d, in each country, i, and $C_{i,d}$ is the demand that is actually met.

The maximum technical capacity for endogenous natural gas production in each country ($P_{i,d}^{max}$) is a value which generally remains relatively stable over time and which is not affected in the two-week case study. The withdrawal rate of gas storage in each country results from solving the mathematical problem, and a different value is calculated for each day of the fourteen-day study period.

The amount of third-party country pipeline natural gas imports is defined as the daily maximum available technical capacity from gas pipelines, in the direction of entry, to the countries in the network.

The countries of the system with access to the sea may have receiving terminals and regasification plants for liquefied natural gas (LNG) supply. The possibility of using the nominal capacity of a regasification plant ($LNG_{i,d}^{max}$) to supply the gas entry to natural gas transmission networks for fourteen days depends on the ability to maintain the supply flow to the terminal through LNG tankers because the storage capacity of LNG maritime terminals is usually limited to a few days.

$$max \sum_{d=1}^{14} \sum_{i=1}^{n} C_{i,d} \tag{1}$$

when

$$0 \leq C_{i,d} \leq C_{i,d}^{max} \tag{2}$$

$$0 \leq P_{i,d} \leq P_{i,d}^{max} \tag{3}$$

$$0 \leq IMP_{i,d} \leq IMP_{i,d}^{max} \tag{4}$$

$$0 \leq LNG_{i,d} \leq LNG_{i,d}^{max} \tag{5}$$

The amount of natural gas exchanged between countries helps to solve the possible shortage of domestic gas supply in some countries. The may vary with the direction of gas flow, as indicated in eq. (6). Balancing all possible gas resources in each country is expressed in eq. (7).

$$-X_{ji,d}^{max} \leq X_{ij,d} \leq X_{ij,d}^{max} \tag{6}$$

$$P_{i,d} + SWR_{i,d} + IMP_{i,d} + LNG_{i,d} - C_{i,d} - \sum X_{ij,d} = 0 \tag{7}$$

Gas storage is a strategic resource for each country. However, under a cooperative scheme, gas storage can be decisive in supporting other countries in the system during a crisis. The underground gas storage capacity differs considerably between countries because it depends on the geological conditions and on the investments in infrastructure. There are three main types of underground storage: aquifer, salt cavern and depleted gas reservoir. The amount of gas available each day from an underground gas storage is characterised by the maximum withdrawal rate, $SWR_{i,d}^{max}$, and varies with the amount of working gas, $ST_{i,d}$, available in storage every day. In this model, the relationship between $SWR_{i,d}^{max}$ and $ST_{i,d}$ was estimated by linear regression, as mathematically expressed in eq. (9). The daily storage balance is indicated in eq. (10).

$$0 \leq SWR_{i,d} \leq SWR_{i,d}^{max} \tag{8}$$

$$SWR_{i,d}^{max} = a_i ST_{i,d} + b_i \tag{9}$$

$$-SWR_{i,d-1} + ST_{i,d-1} - ST_{i,d} = 0 \tag{10}$$

The mathematical optimisation problem defined in eqs. (1)–(10) is linear because the objective function is linear, the constraints are linear, and all variables are continuous. The optimisation problem is programmed and solved using the Optimisation Toolbox™ of MatlabR2019a by applying the linear programming function *linprog* and the

Table 1
Mean data from the European natural gas system from the 14th to the 27th of January of 2017, and peak gas consumption on the 18th of January of 2017 (GWh/d).

	Daily averages from the 14th to the January 27, 2017				UGS		Cross-border capacity		Gas demand on the January 18, 2017
	C^{max}	P^{max}	IMP^{max}	LNG^{max}	$ST_{d=1}$	$SWR_{d=1}$	X_{ij}^{max}	X_{ji}^{max}	C^{max}
Austria	517	44	0	0	23,657	998	2382	2290	550
Belgium	929	0	488	225	2046	170	2380	2658	988
Bosnia	10	0	0	0	0	0	0	15	11
Bulgaria	142	3	766	0	1463	36	158	362	151
Croatia	150	37	0	0	1383	58	0	129	159
Czechia	511	5	0	0	9358	682	1923	1690	543
Denmark	135	170	0	0	3075	194	33	61	144
Estonia	21	0	48	0	0	0	0	63	22
Finland	101	0	249	0	0	0	0	0	107
France	2964	0	570	615	33,638	2205	695	1667	3152
Germany	4347	189	3280	0	65,072	6657	5111	5384	4623
Greece	215	0	49	75	0	0	0	109	229
Hungary	598	68	605	0	16,781	812	270	283	636
Ireland	181	120	0	0	0	0	0	432	192
Italy	3840	171	1695	272	46,894	2703	41	1807	4084
Latvia	62	0	179	0	6380	287	128	68	66
Lithuania	89	0	325	61	0	0	68	65	95
Macedonia	15	0	0	0	0	0	0	27	16
Netherlands	1960	1936	0	218	37,700	2400	4288	2009	2084
Poland	745	74	1336	79	8300	528	932	194	792
Portugal	222	0	0	178	893	78	80	144	236
Romania	624	314	370	0	8165	315	364	73	664
Serbia	83	15	0	0	1133	52	15	142	88
Slovakia	268	0	2080	0	9002	436	2285	1111	285
Slovenia	45	0	0	0	0	0	75	141	48
Spain	1412	3	732	956	7905	129	369	245	1502
Switzerland	206	0	0	0	0	0	635	828	219
UK	3612	2007	1499	823	12,703	1324	1062	1297	3841

Table 2
Capacity of the cross-border interconnections of the European natural gas system in January of 2017.

			Capacity max	Capacity min				Capacity max	Capacity min
Unidirectional	Belgium	France	870	0	Bidirectional	Spain	France	225	−165
	Germany	France	571.8	0		Spain	Portugal	144	−80
	France	Switzerland	260.4	0		Belgium	Germany	313.1	−320.1
	Belgium	Netherlands	122	0		Netherlands	Germany	889.7	−1615.9
	Germany	Switzerland	554.4	0		UK	Belgium	630.1	−803.4
	Switzerland	Italy	634.7	0		Germany	Austria	581.3	−638.7
	Netherlands	Germany	1466.8	0		Czechia	Slovakia	696.8	−400.4
	Netherlands	UK	494	0		Latvia	Lithuania	65.1	−67.6
	Netherlands	Belgium	1041.5	0		Austria	Slovakia	320.2	−1684.7
	UK	Ireland	431.7	0		Belgium	Netherlands	271.2	−396
	Germany	Austria	24.2	0		Italy	Slovenia	28.5	−21.5
	Slovenia	Croatia	53.3	0		Germany	Denmark	60.6	−32.7
	Austria	Italy	1150.5	0		Germany	Poland	166.3	−931.6
	Austria	Slovenia	112.5	0		Hungary	Romania	51.5	−2.5
	Austria	Hungary	153.1	0		Slovakia	Czechia	73.1	−93.9
	Latvia	Estonia	63	0		Bulgaria	Romania	21.6	−1.6
	Czechia	Germany	906.9	0		Germany	Czechia	135.5	−197.5
	Hungary	Croatia	76	0					
	Hungary	Serbia	142.1	0					
	Romania	Bulgaria	751.2	0					
	Bulgaria	Greece	109.3	0					
	Bulgaria	Macedonia	27.4	0					
	Serbia	Bosnia	15	0					
	Germany	Czechia	1081.2	0					
	Czechia	Poland	28	0					
	Slovakia	Hungary	127	0					
	France	Belgium	270	0					
	Italy	Switzerland	12.9	0					
	Austria	Germany	6.9	0					

interior-point algorithm. The simulation framework runs on a computer with a 3.40 GHz CPU Intel® Core™ i7 processor and with 16 GB of RAM.

The data on the technical capacities of different variables are subjected to a pre-treatment before solving the optimisation problem. In reality, each country tries to meet its demand by first using its own resources and then, under the cooperative scheme of the proposed model, making its surplus capacities available to the other countries in the system. Usually, the countries use their own resources in the following order: production, imported LNG and imported pipeline gas. Gas in underground storage is always the last resort since it is a more strategic resource.

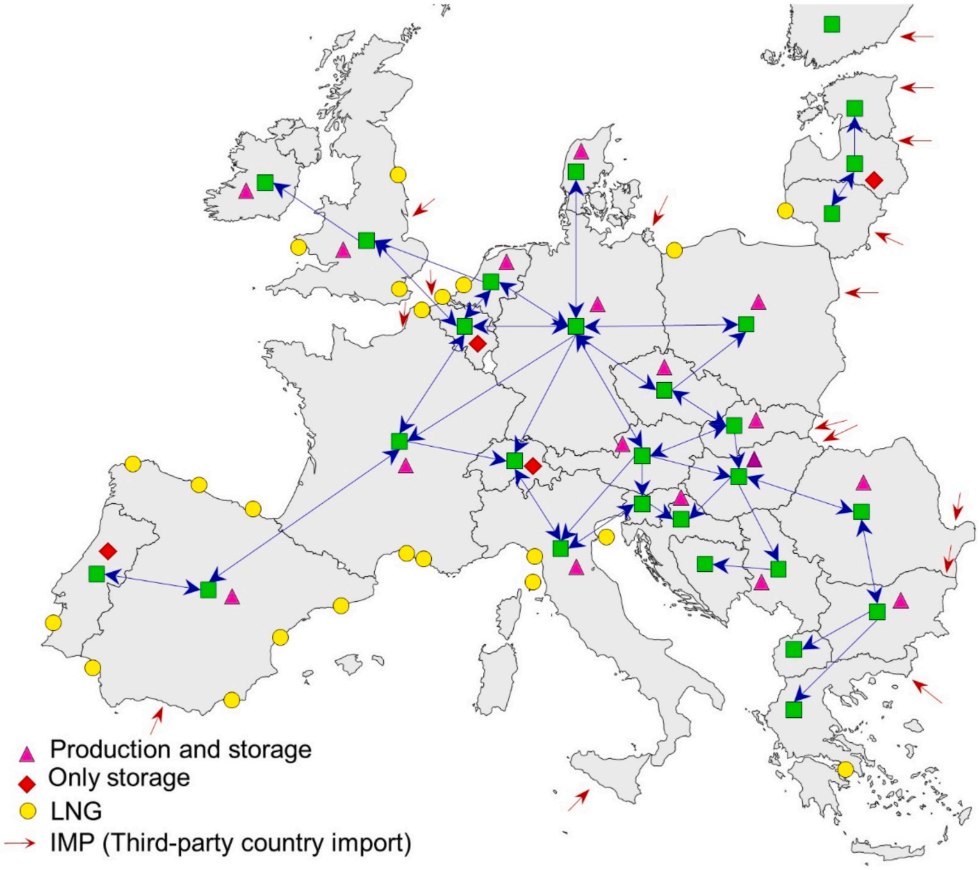

Fig. 1. Natural gas transmission system of the European Union in 2017.

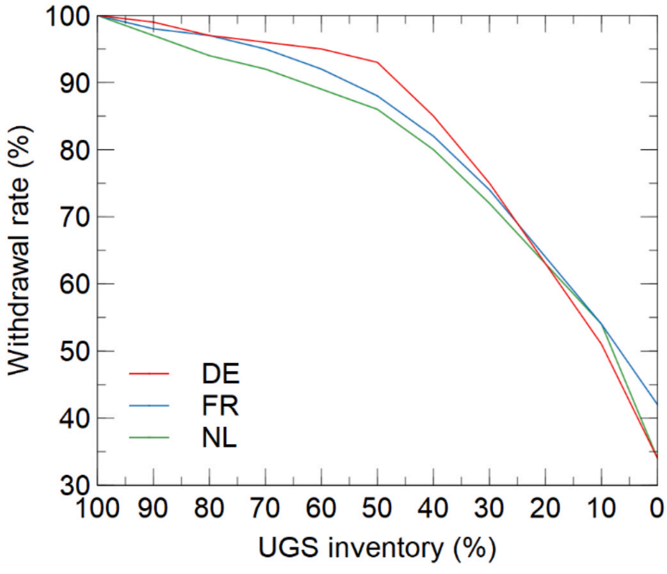

Fig. 2. Withdrawal capacity versus UGS inventory level of some EU countries [41].

4. Case studies

The sharp demand in gas that occurred during the European cold wave of January 2017 lasting several weeks was used as an application example to show the utility of the proposed model. The demand for gas shows a strong seasonal pattern in Europe, with a higher demand in winter. These variations are largely due to the temperature-related demand for heating in the residential and tertiary sectors.

As mentioned in Section 1, the two-week case study is a common design among simulation studies on the security of natural gas supply in Europe. Other studies analyse system capacities in the very short term, on the day of peak gas demand [32], and in the very long term, assuming supply crisis from one to three months [33]. However, the most interesting case is that of two weeks because this period makes it possible to assess the effect of a cold wave [13].

Almost 90% of the natural gas consumption in the EU derives from third countries [8]. If, in addition to a high demand for natural gas in several countries, additional constraints are imposed on natural gas imports, the system may enter into severe stress. This extreme situation may be exacerbated if the underground gas storage is low, which usually occurs in late winter. Therefore, to demonstrate the applicability of the mathematical model for optimal management presented in Section 3, the consumption data recorded from the 14th to the 27th of January of 2017 was used here together with the scenarios of total or partial disruption of gas imports to the EU.

The average demand during the fourteen-day peak demand period from the 14th to January 27, 2017, was 24,000 GWh/d. The peak gas demand in the EU was reached on the January 18, 2017, which was 25,521 GWh/d [34]. Interestingly, the peak electricity demand in the EU, that is, 581,276 MW, was also reached on the same day [35]. The interaction between the gas system and the electric power system must be considered because combined-cycle gas-fired power stations play a key role in maintaining the electricity supply as a backup for renewables during dark doldrums, a cold period such as a two-week cold wave with very low renewable electricity generation.

Another reason for selecting the cold wave of the 2017 Winter is that the storage inventory level in January and February 2017 was at historic lows, reducing the contribution from underground gas storage (UGS) to safeguarding the supply in the event of additional unforeseen

Table 3
Parameters a_i and b_i of eq. (9), modelling UGS inventory lower than 50% for each country.

Country *i*	a_i	b_i
Austria	0.01953	535.52
Belgium	0.06297	40.68
Bosnia	0.00000	0.00
Bulgaria	0.01584	13.03
Croatia	0.03593	8.48
Czechia	0.04585	253.18
Denmark	0.04425	58.32
Estonia	0.00000	0.00
Finland	0.00000	0.00
France	0.03427	1052.52
Germany	0.06491	2433.92
Greece	0.00000	0.00
Hungary	0.02246	435.46
Ireland	0.00000	0.00
Italy	0.03483	1069.20
Latvia	0.02716	113.40
Lithuania	0.00000	0.00
Macedonia	0.00000	0.00
Netherlands	0.03850	948.89
Poland	0.03666	223.91
Portugal	0.05280	30.84
Romania	0.02335	124.76
Serbia	0.02768	20.52
Slovakia	0.02929	172.57
Slovenia	0.00000	0.00
Spain	0.00651	77.22
Switzerland	0.00000	0.00
UK	0.06301	523.89

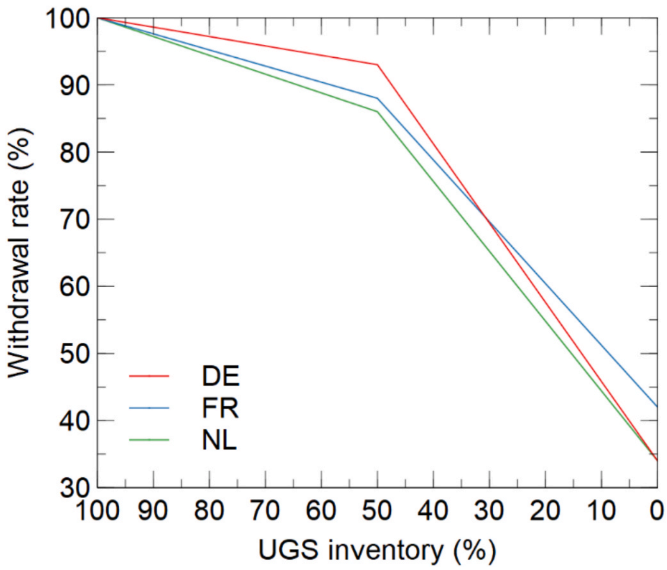

Fig. 3. Withdrawal capacity versus UGS inventory level of some EU countries upon linear approximation.

contingencies [34].

Data from the European natural gas system in January 2017 are outlined in Tables 1 and 2. The gas demand values were retrieved from Ref. [36], while the values of natural gas production, imports, LNG and cross-border capacity were gathered from Ref. [37]. The UGS data were collected from Ref. [38]. In the case study, EU countries and the following neighbouring countries were considered: Bosnia-Herzegovina, North Macedonia, Switzerland and Serbia.

The natural gas system represented in Fig. 1 includes 28 countries, which, in 2017, were connected by 35 cross-border interconnections, 18 of which were bi-directional. These infrastructures have been expanded in recent years to improve the European security of natural gas supply.

A few EU countries, such as Italy, France, Germany and the Netherlands, have the highest underground gas storage capacity. For geological reasons, Eastern and South-Eastern European countries have only a small gas storage capacity [39]. Therefore, properly using interconnection capacities between countries by optimally managing cross-border gas pipelines for trading gas from underground storage can improve the ability of EU and other neighbouring countries to meet the gas demand.

In this study, a model of underground gas storage is applied, assessing the UGS inventory effect on the withdrawal rate using deliverability curves. The amount of gas that can be withdrawn from a storage facility decreases with the decrease in stored gas [40]. Fig. 2 shows the curves of three EU countries built using the data provided by the Gas Storage Europe [41]. These curves represent a weighted average of the facilities in each country (salt caverns, aquifers or depleted gas reservoirs).

Fig. 2 shows an inflexion point in the curves when storage is higher than 50% inventory level, and the relation between the withdrawal rate and the stored gas is approximately linear when this level continues to decrease. For this reason, in the mathematical model of Section 3, a linear equation was proposed to relate the withdrawal rate to the UGS inventory between 0% and 50% of the UGS stock, as shown in eq. (9). The parameters of the equations for each country, calculated in Table 3, were determined by linear approximation in two sections of the data provided in Ref. [41] for UGS lower than 50% inventory level. The representation of eq. (9) in Fig. 3, for the same countries of Fig. 2, shows the goodness-of-fit of the linear approximation.

The mathematical optimisation tool developed in this research identified the best daily solution for gas resources (especially the use of UGS and cross-border capacities between countries) to meet as much as possible the natural gas demand for two weeks, not by maximising the demand met each day but by maximising the demand over the entire fourteen-day period. That is, a global solution to the problem was offered, instead of providing daily solutions that may not be optimal in the medium term. In addition, the solution ensures the best cooperation between the EU countries with the common goal of supplying natural gas to their end consumers, thereby meeting the demand.

Case studies were defined to assess the impact of various scenarios of gas supply disruption coupled with a low initial storage level during very high demand events:

- **Case 1.** Demand from the 14th to the 27th of January of 2017 and 50% initial storage
- **Case 2.** Russian pipeline gas supply disruption and 50% initial storage
- **Case 3.** LNG supply disruption and 50% initial storage
- **Case 4.** Demand from the 14th to the 27th of January of 2017 and 20% initial storage.
- **Case 5.** Russian pipeline gas supply disruption and 20% initial storage.
- **Case 6.** LNG supply disruption and 20% initial storage.

Case 1 analyses the capacity of the gas system to cope with a situation of high demand and half empty gas storage, that is, 50% inventory level. This was the real scenario in January of 2017 because an unusually cold winter quickly emptied UGS facilities, which only had 50% working gas stored at the beginning of the second half of January [34].

Cases 2 and 3, in addition to the situation of high gas demand,

Table 4
Breakdown of the main results by country in Case 1.

	Demand satisfied		Production used		LNG imports used		Pipeline imports used		UGS ST 100%	UGS ST 50%	UGS SWR 50%	UGS ST final	
	GWh	%	GWh	%	GWh	%	GWh	%	GWh	GWh	GWh/d	GWh	%
Austria	7274	100%	616	100%	0		0		47,315	23,657	998	19,760	42%
Belgium	13,066	100%	0		3143	100%	6832	100%	4092	2046	170	1610	39%
Bosnia	145	100%	0		0		0		0	0	0	0	
Bulgaria	1997	100%	42	100%	0		2499	23%	2926	1463	36	1312	45%
Croatia	2103	100%	518	100%	0		0		2765	1383	58	1056	38%
Czechia	7181	100%	70	100%	0		0		18,715	9358	682	7979	43%
Denmark	1904	100%	2031	85%	0		0		6150	3075	194	2920	47%
Estonia	291	100%	0		0		291	43%	0	0	0	0	
Finland	1415	100%	0		0		1415	41%	0	0	0	0	
France	41,684	100%	0		8610	100%	7980	100%	67,275	33,638	2205	24,408	36%
Germany	61,138	100%	2646	100%	0		45,926	100%	130,144	65,072	6657	30,986	24%
Greece	3028	100%	0		1050	100%	680	100%	0	0	0	0	
Hungary	8411	100%	952	100%	0		7730	91%	33,563	16,781	812	15,957	48%
Ireland	2539	100%	1680	100%	0		0		0	0	0	0	
Italy	54,010	100%	2394	100%	3801	100%	23,730	100%	93,787	46,894	2703	35,303	38%
Latvia	873	100%	0		0		873	35%	12,760	6380	287	6380	50%
Lithuania	1256	100%	0		854	100%	402	9%	0	0	0	0	
Macedonia	212	100%	0		0		0		0	0	0	0	
Netherlands	27,560	100%	27,104	100%	1217	40%	0		75,399	37,700	2400	30,630	41%
Poland	10,474	100%	1036	100%	1106	100%	9701	52%	16,601	8300	528	7113	43%
Portugal	3121	100%	0		2492	100%	0		1785	893	78	623	35%
Romania	8781	100%	4396	100%	0		4385	85%	16,329	8165	315	7714	47%
Serbia	1160	100%	211	100%	0		0		2265	1133	52	962	42%
Slovakia	3769	100%	0		0		6398	22%	18,003	9002	436	7799	43%
Slovenia	635	100%	0		0		0		0	0	0	0	
Spain	19,864	100%	42	100%	13,377	100%	7281	71%	15,810	7905	129	7388	47%
Switzerland	2896	100%	0		0		0		0	0	0	0	
UK	50,796	100%	28,098	100%	11,515	100%	12,483	59%	25,406	12,703	1324	11,031	43%
TOTAL	337,583	100%	71,836	100%	47,165	96%	138,606	69%	591,090	295,548	20,064	220,931	37%

included a hypothetical disruption of either gas imports from Russia to Central Europe by pipeline (Case 2) or LNG supply by sea (Case 3) during the fourteen-day study period. These situations are unlikely, but not impossible as similar events have already been recorded on different occasions in the past, particularly disruption of gas supply from Russia [42]. Any problem related to gas supply from Russia greatly impacts the downstream EU countries because Russia is the main supplier, with a 40% import quota for pipeline gas and 17% for LNG [43]. Russian natural gas is exported to the European market through five main pipelines, of which the two most important transit the Ukraine. Tense relations between Russia and Ukraine result in a high-risk scenario [44].

On the other hand, a global LNG supply crisis is possible, as recent events in January 2021 demonstrated when LNG shipments were diverted from Europe to Asia for commercial reasons in an unprecedented event during a severe cold snap. Europe had to increase the gas extraction from its storage reserves and use the import capacity of pipeline gas to overcome the lack of LNG supply. As a result, current gas storage levels in Europe decreased to a minimum after winter and inventory levels required for next winter were at risk.

To illustrate the behaviour of the mathematical model proposed for the European natural gas infrastructure, the previous cases were repeated in the scenario with the lowest level of gas storage (20%), that is, Cases 4, 5 and 6. These scenarios are not that unlikely because, for example, UGS stock levels reached 18.4% by the end of the 2018 winter [45].

5. Simulation results

This section presents the results of the six case studies defined above to illustrate how the tool proposed in this research can facilitate strategies for the best use of resources and infrastructures in the event of a two-week gas supply crisis. In each case, the formulation of the linear optimisation problem defined by eqs. (1)–(10) was applied to data from the European gas system outlined in Table 1 and to the 2017 capacities of the unidirectional and bidirectional gas pipelines of the interconnections of Fig. 1 and Table 2.

- **Case 1 (demand from the 14th to the 27th of January of 2017 and 50% initial storage)**

Table 4 outlines the results of the base case, defined with the gas demand data recorded from the 14th to the 27th of January of 2017. During this period, the storage inventory level in European countries was approximately 50%, that is, 294,000 GWh. The results indicate that the best solution to cooperatively meet the demand for gas during those two weeks, under the assumptions explained in Section 3, would consist of using 100% of the available gas production resources of countries from the system (mainly the Netherlands and the United Kingdom), 96% of the resources contributed by LNG terminals and 69% of the capacity of pipeline gas imports. Underground gas reservoirs would be emptied to 37% storage level.

The use rate of cross-border interconnections would average 37% of the available capacity in unidirectional and bidirectional gas pipelines (see Table 9); that is, to meet the average daily demand of 24,000 GWh/d during the two-week study period, 8700 GWh/d would have to be exchanged between the countries of the system, highlighting the importance of gas transit for ensuring the availability of each country to the other members of the system.

Underground gas storage also plays a key role in the optimal strategy to meet the demand. The results from using UGS outlined in Table 5 showed that withdrawal would increase in the first five days but would decrease in the following days. These findings are consistent because the

Table 5
Optimal UGS management in Case 1.

- **Case 2 (demand from the 14th to the 27th of January of 2017, 50% initial storage and Russian pipeline gas supply disruption)**

	Withdrawal rate - SWR (GWh/d)													
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
Austria	143	238	252	269	328	294	303	317	329	341	352	362	369	240
Belgium	25	25	26	28	31	31	33	35	36	38	40	43	45	57
Bosnia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulgaria	13	11	11	11	12	11	11	11	12	12	12	12	12	13
Croatia	26	25	25	25	29	25	25	25	25	25	25	25	25	26
Czechia	13	57	71	89	110	105	108	114	122	132	143	154	163	201
Denmark	12	11	11	11	12	12	12	12	12	12	12	12	13	12
Estonia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0	0
France	467	591	629	632	820	662	692	708	748	790	817	833	839	898
Germany	3493	3200	3064	2944	3110	2696	2579	2469	2349	2232	2109	1975	1865	1537
Greece	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hungary	53	64	64	64	74	64	64	64	64	63	63	63	62	55
Ireland	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Italy	732	766	798	814	1053	874	901	926	936	941	946	953	951	985
Latvia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lithuania	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Macedonia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	344	448	468	490	590	529	545	561	574	585	615	646	673	732
Poland	18	44	65	74	91	87	92	99	106	115	123	132	140	155
Portugal	19	17	17	18	22	20	21	21	22	22	23	23	24	27
Romania	32	34	34	34	40	34	34	34	35	35	35	35	35	33
Serbia	13	12	12	12	14	13	13	13	13	14	14	14	15	17
Slovakia	21	56	61	73	97	90	95	101	108	116	123	129	133	145
Slovenia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spain	30	31	32	35	44	39	41	42	43	44	45	45	46	47
Switzerland	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UK	46	84	88	104	165	141	147	151	154	154	150	147	141	183
TOTAL	5500	5714	5728	5727	6642	5727	5716	5703	5688	5671	5647	5603	5551	5363

	UGS level - ST (GWh)													
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Day 14
Austria	23,657	23,514	23,277	23,024	22,755	22,427	22,133	21,829	21,513	21,184	20,843	20,491	20,129	19,760
Belgium	2046	2021	1996	1970	1943	1911	1880	1847	1813	1777	1738	1698	1655	1610
Bosnia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulgaria	1463	1450	1439	1428	1416	1405	1393	1382	1371	1359	1347	1336	1324	1312
Croatia	1383	1357	1332	1308	1283	1254	1229	1204	1179	1155	1130	1105	1081	1056
Czechia	9358	9344	9288	9217	9128	9019	8914	8806	8692	8570	8439	8296	8142	7979
Denmark	3075	3063	3052	3041	3029	3017	3005	2993	2981	2969	2957	2945	2932	2920
Estonia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Finland	0	0	0	0	0	0	0	0	0	0	0	0	0	0
France	33,638	33,170	32,579	31,950	31,318	30,498	29,836	29,144	28,435	27,687	26,897	26,080	25,247	24,408
Germany	65,072	61,579	58,379	55,315	52,371	49,262	46,566	43,987	41,518	39,168	36,936	34,827	32,851	30,986
Greece	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hungary	16,781	16,729	16,665	16,601	16,537	16,463	16,399	16,336	16,272	16,208	16,145	16,082	16,019	15,957
Ireland	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Italy	46,894	46,162	45,396	44,598	43,783	42,730	41,856	40,955	40,029	39,093	38,152	37,207	36,254	35,303
Latvia	6380	6380	6380	6380	6380	6380	6380	6380	6380	6380	6380	6380	6380	6380
Lithuania	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Macedonia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	37,700	37,355	36,907	36,439	35,949	35,359	34,830	34,285	33,724	33,150	32,565	31,950	31,304	30,630

(*continued on next page*)

Table 5 (*continued*)

Poland	8300	8282	8238	8172	8098	8007	7920	7828	7729	7622	7508	7385	7253	7113
Portugal	893	873	857	839	821	799	779	758	737	716	693	671	647	623
Romania	8165	8133	8099	8065	8031	7991	7956	7922	7887	7853	7818	7784	7749	7714
Serbia	1133	1120	1108	1096	1084	1070	1058	1045	1032	1019	1005	991	977	962
Slovakia	9002	8981	8925	8864	8791	8694	8604	8509	8407	8299	8183	8061	7932	7799
Slovenia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spain	7905	7874	7843	7812	7776	7733	7693	7653	7611	7568	7524	7479	7434	7388
Switzerland	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UK	12,703	12,657	12,573	12,485	12,381	12,216	12,075	11,928	11,777	11,623	11,470	11,319	11,172	11,031
TOTAL	295,548	290,044	284,333	278,604	272,874	266,235	260,506	254,791	249,087	243,400	237,730	232,087	226,482	220,931

gas demand of the European system peaked on the 18th of January. In the breakdown of the data by country outlined in Table 4, the extensive use of UGS in Germany stands out. As a result, its storage stock would reach 24% at the end of the study period, a very low value that could compromise supply in the remaining weeks of winter. Germany is a country with a large storage capacity and a strategic position in Central Europe, with many gas pipelines interconnecting with neighbouring countries. For these reasons, Germany represents 45% of total deliverability from natural gas storage in the EU during the two-week period.

Table 6 outlines the results of Case 2, considering a total disruption of the pipeline gas supply to Central Europe from Russia. The main conclusion of this hypothetical case study is that, even with the best possible strategy for gas supply, it would not be possible to meet the demand in five countries, and South-Eastern European countries would be the most affected (see Fig. 4). This supply crisis would occur despite increasing the use of all available resources: 100% own production, 97% LNG regasification capacity and 86% available capacity to import pipeline gas (mainly from Norway and Algeria because importing gas from Russia would not be available in this case). Underground gas storage use would also increase, leaving the available UGS working gas reserves at 29% by the end of the fourteen-day study period.

These results are in line with the forecasting studies conducted by operators of the European networks at the beginning of the 2016/2017 winter [46]. Those studies predicted a possible gas supply drop in South-Eastern European countries if the Russian gas transit through Ukraine was disrupted. In our case study, the situation is even more critical because supply through Belarus is also disrupted.

- Case 3 (demand from the 14th to the 27th of January of 2017, 50% initial storage and LNG supply disruption).

This case illustrates a scenario of prolonged disruption of LNG shipping, which could occur for commercial or meteorological reasons. The results outlined in Table 7 show that Spain, Portugal and Greece would not meet their demand for natural gas. In other words, the LNG shortage would affect only the three countries located in the corners of the continent as they are more dependent on LNG and have weak gas pipeline interconnections with their European neighbours. The analysis of the results from Spain in more detail shows that, surprisingly, only 20% storage is used because gas withdrawal is limited by a low daily deliverability due to the type of underground storage existing in the country [41].

- Cases 4, 5 and 6 (20% instead of 50% initial storage).

As indicated in the description of the case studies, the calculations made in three new scenarios are repeated assuming that the UGS inventory status is 20% instead of 50% at the beginning of the fourteen-day study period.

The mathematical tool provides the best possible solution to meet the demand, optimising the management of all capacities of the European natural gas system. As expected, the results clearly showed an increased use of available resources (see Table 8) and cross-border capacities between the countries of the system (see Table 9). In particular, UGS would be intensively used, leaving the inventory levels of working gas of the storage facilities at minimum values, lower than 8%. Nevertheless, only 10 of the 28 countries would be able to meet the national demand for natural gas, while five countries would not be able to meet 80% of the demand. Bulgaria and Bosnia would be the most affected countries, meeting only 50% of consumer needs during the two-week study period (see Fig. 5). In order to graphically present some of the findings, Fig. 6 shows the main comparative results of the case studies.

The analysis of Cases 2 and 5 shows some relevant differences in the use of cross-border interconnections from the other cases. The disruption of the Russian pipeline gas supply forces the internal gas pipelines in the EU system to reconfigure, reducing the use of unidirectional pipelines and increasing the use of bidirectional pipelines (see Table 9). This shift occurs because some unidirectional pipelines of the EU system are designed for gas transit from Russia to other European countries. However, in Cases 2 and 5, bidirectional pipelines gain prominence by

Table 6
Breakdown of the main results by country in Case 2.

	Demand satisfied		Production used		LNG imports used		Pipeline imports used		UGS ST 100%	UGS ST 50%	UGS SWR 50%	UGS ST final	
	GWh	%	GWh	%	GWh	%	GWh	%	GWh	GWh	GWh/d	GWh	%
Austria	7274	100%	616	100%	0		0		47,315	23,657	998	17,434	37%
Belgium	13,066	100%	0		3143	100%	6832	100%	4092	2046	170	1475	36%
Bosnia	145	100%	0		0		0		0	0	0	0	
Bulgaria	1304	65%	42	100%	0		0		2926	1463	36	1035	35%
Croatia	2103	100%	518	100%	0		0		2765	1383	58	1011	37%
Czechia	7181	100%	70	100%	0		0		18,715	9358	682	6174	33%
Denmark	1904	100%	2028	85%	0		0		6150	3075	194	2914	47%
Estonia	291	100%	0		0		0		0	0	0	0	
Finland	1415	100%	0		0		1415	41%	0	0	0	0	
France	41,684	100%	0		8610	100%	7980	100%	67,275	33,638	2205	20,964	31%
Germany	61,138	100%	2646	100%	0		23,943	100%	130,144	65,072	6657	20,661	16%
Greece	2510	83%	0		1050	100%	680	100%	0	0	0	0	
Hungary	8411	100%	952	100%	0		0		33,563	16,781	812	10,078	30%
Ireland	2539	100%	1680	100%	0		0		0	0	0	0	
Italy	54,010	100%	2394	100%	3801	100%	23,730	100%	93,787	46,894	2703	30,566	33%
Latvia	873	100%	0		0		0		12,760	6380	287	4925	39%
Lithuania	1256	100%	0		854	100%	0		0	0	0	0	
Macedonia	130	61%	0		0		0		0	0	0	0	
Netherlands	27,560	100%	27,104	100%	1387	45%	0		75,399	37,700	2400	24,247	32%
Poland	10,324	99%	1036	100%	1106	100%	0		16,601	8300	528	3179	19%
Portugal	3121	100%	0		2492	100%	0		1785	893	78	606	34%
Romania	7207	82%	4396	100%	0		0		16,329	8165	315	4593	28%
Serbia	1160	100%	211	100%	0		0		2265	1133	52	877	39%
Slovakia	3769	100%	0		0		0		18,003	9002	436	6748	37%
Slovenia	635	100%	0		0		0		0	0	0	0	
Spain	19,864	100%	42	100%	13,377	100%	7368	72%	15,810	7905	129	7293	46%
Switzerland	2896	100%	0		0		0		0	0	0	0	
UK	50,796	100%	28,098	100%	11,515	100%	12,550	60%	25,406	12,703	1324	8958	35%
TOTAL	334,566	99%	71,833	100%	47,335	97%	84,498	86%	591,090	295,548	20,064	173,738	29%

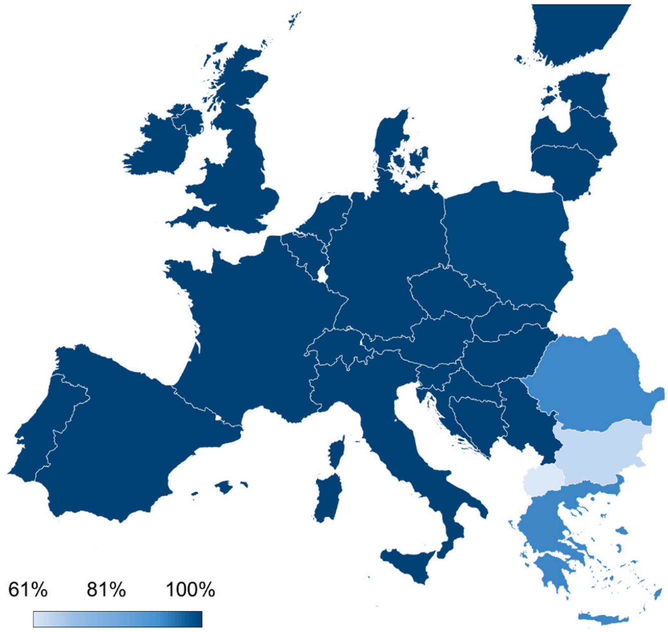

Fig. 4. Demand met by country in Case 2 study.

compensating for the loss of the Russian supply and by rebalancing internal gas flows in the EU system with the increase in the use of UGS and other sources of natural gas supply.

6. Conclusions

This article proposed a mathematical tool to maximise the coverage of global demand for natural gas during a fourteen-day supply crisis in the European natural gas system. The tool offers collaborative solutions to crises spurred by political events or natural phenomena, facilitating strategies for the optimal use of available resources and facilities, such as liquefied natural gas, underground storage and cross-border interconnections. The tool makes it possible to quickly update the decision-making process in the event of a supply crisis because its computation only requires seconds, while other techniques take hours or days to reach solutions as those based on simulation methods.

Six case studies were applied evaluate the impact of various gas supply disruption scenarios considering two different levels of initial storage during high-demand events. The findings demonstrated the applicability of the proposal, identifying optimal solutions throughout the entire interconnected gas infrastructure.

The mathematical model developed here can be applied to any interconnected gas system but is particularly relevant for the EU. Gas shortages can have significant economic and social effects in the EU, as it is highly dependent on external supplies. Therefore, the proposed tool offers means to meet the challenging objectives of Regulation (EU) 2017/1938, i.e. to provide a more cooperative approach, reduce the impact of gas supply disruptions and address the potential vulnerabilities in some member states revealed in this research for a two-week supply crisis. As observed in the case studies, South Eastern European countries are highly vulnerable to gas disruptions from Russia, while the Iberian Peninsula and Greece are more exposed to LNG shortages. These findings are quite similar to those already obtained in other studies developed by the European Network of Transmission System Operators for Gas (ENTSO-G) [47].

Table 7
Breakdown of the main results by country in Case 3.

	Demand satisfied		Production used		LNG imports used		Pipeline imports used		UGS ST 100%	UGS ST 50%	UGS SWR 50%	UGS ST final	
	GWh	%	GWh	%	GWh	%	GWh	%	GWh	GWh	GWh/d	GWh	%
Austria	7274	100%	616	100%	0	0%	0		47,315	23,657	998	19,212	41%
Belgium	13,066	100%	0		0	0%	6832	100%	4092	2046	170	1538	38%
Bosnia	145	100%	0		0	0%	0		0	0	0	0	
Bulgaria	1997	100%	42	100%	0	0%	2580	24%	2926	1463	36	1293	44%
Croatia	2103	100%	518	100%	0	0%	0		2765	1383	58	1035	37%
Czechia	7181	100%	70	100%	0	0%	0		18,715	9358	682	7059	38%
Denmark	1904	100%	2029	85%	0	0%	0		6150	3075	194	2921	47%
Estonia	291	100%	0		0	0%	291	43%	0	0	0	0	
Finland	1415	100%	0		0	0%	1415	41%	0	0	0	0	
France	41,684	100%	0		0	0%	7980	100%	67,275	33,638	2205	15,976	24%
Germany	61,138	100%	2646	100%	0	0%	45,926	100%	130,144	65,072	6657	30,127	23%
Greece	2210	73%	0		0	0%	680	100%	0	0	0	0	
Hungary	8411	100%	952	100%	0	0%	7702	91%	33,563	16,781	812	15,831	47%
Ireland	2539	100%	1680	100%	0	0%	0		0	0	0	0	
Italy	54,010	100%	2394	100%	0	0%	23,730	100%	93,787	46,894	2703	32,592	35%
Latvia	873	100%	0		0	0%	873	35%	12,760	6380	287	6380	50%
Lithuania	1256	100%	0		0	0%	1256	28%	0	0	0	0	
Macedonia	212	100%	0		0	0%	0		0	0	0	0	
Netherlands	27,560	100%	27,104	100%	0	0%	0		75,399	37,700	2400	28,145	37%
Poland	10,474	100%	1036	100%	0	0%	11,658	62%	16,601	8300	528	6561	40%
Portugal	1274	41%	0		0	0%	0		1785	893	78	145	8%
Romania	8781	100%	4396	100%	0	0%	4385	85%	16,329	8165	315	7642	47%
Serbia	1160	100%	211	100%	0	0%	0		2265	1133	52	955	42%
Slovakia	3769	100%	0		0	0%	8236	28%	18,003	9002	436	7375	41%
Slovenia	635	100%	0		0	0%	0		0	0	0	0	
Spain	13,840	70%	42	100%	0	0%	10,248	100%	15,810	7905	129	6295	40%
Switzerland	2896	100%	0		0	0%	0		0	0	0	0	
UK	50,796	100%	28,098	100%	0	0%	20,987	100%	25,406	12,703	1324	9233	36%
TOTAL	328,894	97%	71,834	100%	0	0%	154,779	77%	591,090	295,548	20,064	200,315	34%

Table 8
Main results of the case studies.

		Demand satisfied		Production used		LNG imports used		Pipeline imports used		UGS final	
		GWh	%	GWh	%	GWh	%	GWh	%	GWh	%
Case 1	Base case, UGS level at 50%	337,583	100%	71,836	100%	47,165	96%	138,606	69%	220,931	37%
Case 2	Disruption from Russia, UGS level at 50%	334,566	99%	71,833	100%	47,335	97%	84,498	86%	173,738	29%
Case 3	LNG disruption, UGS level at 20%	328,894	97%	71,834	100%	0	0%	154,779	77%	200,315	34%
Case 4	Base case, UGS level at 20%	337,583	100%	71,830	100%	47,329	97%	143,463	72%	47,926	8%
Case 5	Disruption from Russia, UGS level at 20%	327,797	97%	71,929	100%	49,000	100%	191,689	96%	9053	2%
Case 6	LNG disruption, UGS level at 20%	326,759	97%	71,835	100%	0	0%	166,150	83%	35,268	6%

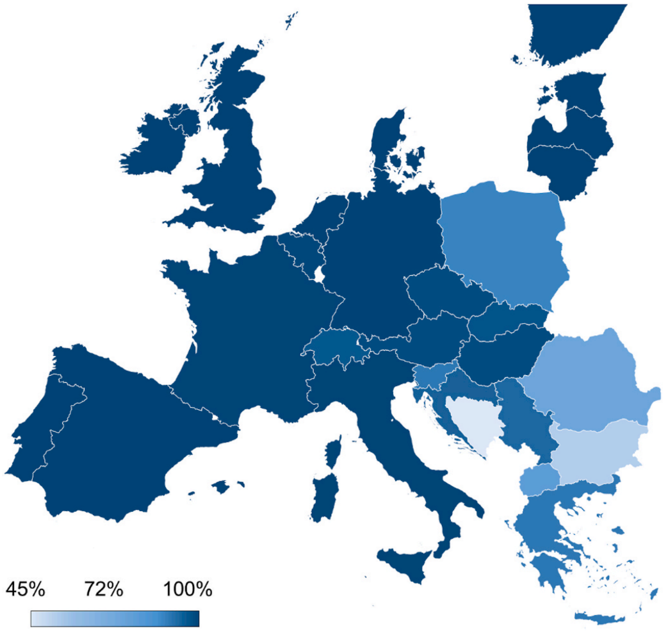

Fig. 5. Demand met by country in Case Study 5.

Given the dynamic nature of demand, production, storage and network flows, it is challenging to establish contingency plans in advance for all possible scenarios during a supply crisis. In fact, it may be necessary to continuously update the actions to be taken on the infrastructure, even if the crisis continues for an extended period. The cooperative solution resulting from the proposed mathematical model would enable rapid recovery of transnational gas infrastructures after a

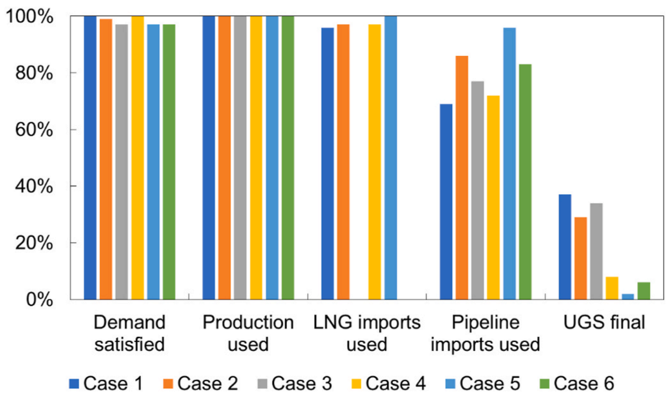

Fig. 6. Comparative results of the case studies.

Table 9
Average daily use of cross-border capacities.

	Unidirectional		Bidirectional		Average
	GWh/d	%	GWh/d	%	%
Capacity max	11,558		4674		
Capacity min			−7453		
Case 1	6193	54%	1661	36%	37%
			−897	12%	
Case 2	5603	48%	2709	58%	36%
			−233	3%	
Case 3	6418	56%	1342	29%	39%
			−1517	20%	
Case 4	6283	54%	1588	34%	38%
			−1060	14%	
Case 5	5251	45%	2975	64%	36%
			−284	4%	
Case 6	6539	57%	928	20%	40%
			−2067	28%	

partial or total outage caused by intentional threats, technical failures or natural disasters. In this way, the proposal could be helpful for transmission system operators, public authorities, utilities and other stakeholders. Moreover, measures taken for the security and resilience of gas systems could also benefit electrical infrastructure and minimise cascading effects across the energy sector as natural gas and power systems become increasingly interconnected.

Credit author statement

Jose M. Yusta: Conceptualization, Methodology, Software, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Funding acquisition. **Jesus Beyza:** Methodology, Software, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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