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Assessment of the Robustness of the European Gas System to Massive Gas Outages and Evaluation of the Effect of Increased Energy Efficiency on the Security of Gas Coverage in Different Countries

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Abstract: The aim of this paper is to simulate the European natural gas system in extreme situations and to determine its weaknesses in terms of demand coverage. An assessment has also been made of the targets set for existing energy efficiency regulations and their effects on the coverage of future natural gas demand. This document assesses the potential for energy efficiency improvements associated with European countries and the effect of such improvements on the lessening of the natural gas demand. Once the efficiency improvement potential has been identified, the results of demand coverage in various scenarios of natural gas supply cut-off via pipelines were studied. The expected result reflects the study of the effect of the presumed demand reduction, due to the improvement of energy efficiency, on the self-sufficiency of the natural gas network and the improvement of energy coverage for EU countries. To carry out this study, an evaluation of the current infrastructures was developed, the existing resources were optimized, and the independence of the system was quantified in relation to the current situation of natural gas consumption at the European level. The proposed model has resulted in improvements in the coverage of the demand of certain countries and has detected those with systems that are not robust enough to face extreme crisis situations. The main conclusions are that the natural gas system has improved considerably from 2009 to the present, and that, in the event of massive gas cuts, there is a real risk of being unable to cover the natural gas demand of several countries with a very high dependence on gas from Russia.

Keywords: gas supply; renewable energy sources; non-renewable energy sources; energy consumption; demand; energy efficiency; European Union

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1. Introduction

The evolution of non-renewable relative energy consumption in the world has followed different paths in every region, according to recent statistics from the BP annual review [1] and the World Bank [2]. In general terms, the overall non-renewable energy consumption in the world increased by about 60% in the period of 1990–2020, while the world population soared by almost 2.5 times and the GDP increased by 1.5 times in this period. This trend shows a decoupling of energy consumption versus GDP and population growth worldwide. However, the objective of keeping fossil fuel consumption flat has not been met. Indeed, the non-RES energy consumption per currency unit of GDP has increased since 2002 in percentual terms, as has the per-capita consumption since 2002, until the COVID-19 pandemic in 2020 (see Figure 1).

The situation in Europe shows better figures, with a non-RES energy consumption decrease of 16% (COVID−19 slump excluded). The GDP grew in Europe by 75%, while the population went up by 5% during that period. Therefore, there was a clear improvement in terms of per-capita and per-currency-unit non-RES energy consumption across the continent that provided room for an absolute decrease in energy consumption despite the GDP and population growth in that period (see Figure 2).

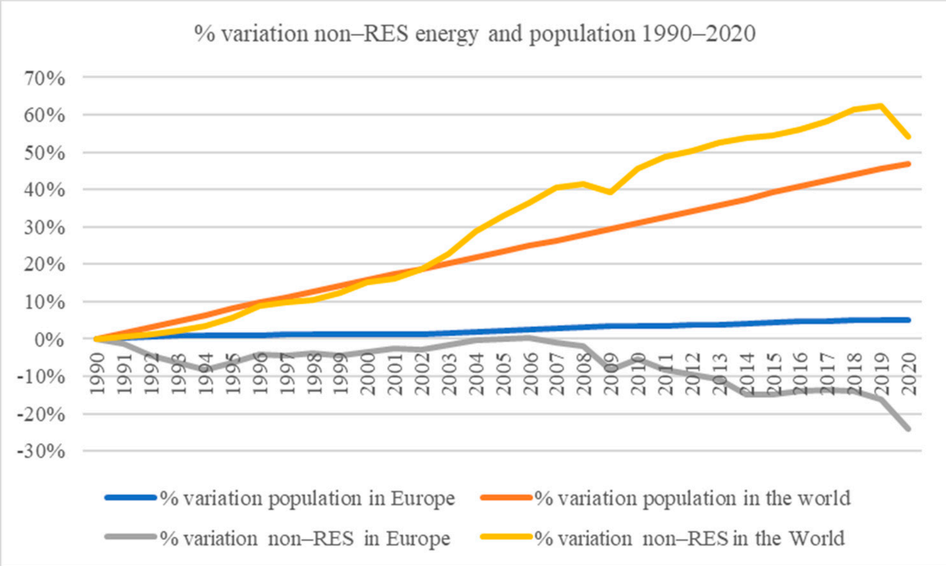

Figure 1. Variation in non-RES energy and population from 1990 to 2020.

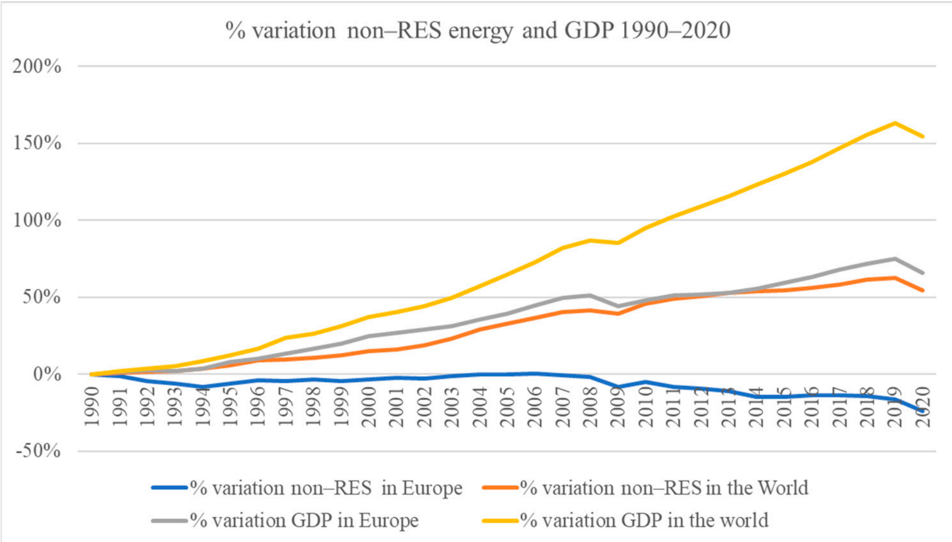

Figure 2. Variation in non-RES energy vs. GDP from 1990 to 2020.

The better performance of the European region with respect to other regions of the world can be explained by three factors. First, the already high quality of living standards and the low vegetative growth do not exert much pressure on the absolute energy consumption increase; second, the transition from an industrial production economy to a service-based economy is helping to drive down the energy consumption per currency unit; third, the ambitious decarbonization targets set by the European Commission with the 20/20/20 objectives for 2020 have led to a push for country-level strategies to reduce energy consumption and increase the generation from renewable sources. Figure 3 shows the evolution of RES versus the total primary energy consumption in this period. Europe leads the statistics; it reached a 10% contribution by 2019, although this was still far below the 20% target.

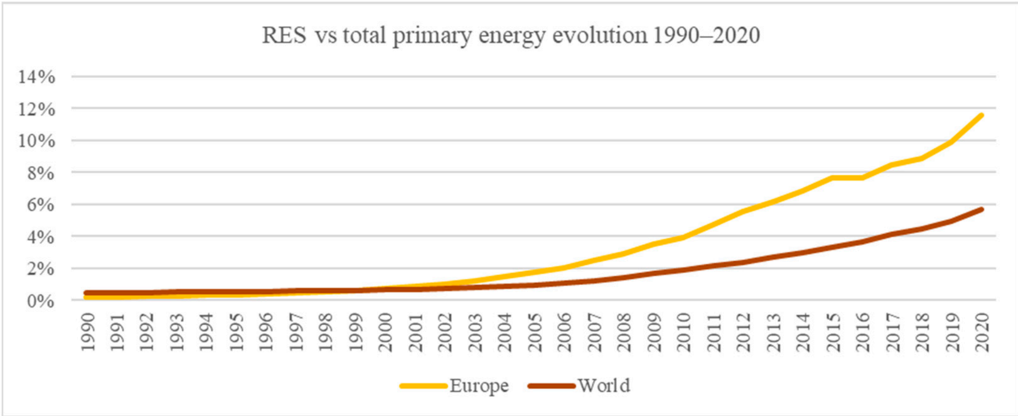

Figure 3. RES and total primary energy evolution from 1990 to 2020.

Highly industrialized countries trigger significant carbon emissions [3]. Restrictive regulation places an important emphasis on companies' environmental decision making [4]. The European Union has recently defined the Fit for 55 target within the European Green Deal [5].

Beyond the objective of increasing RES, the demand in Europe for energy used for climatization and heating systems for both residential and industrial purposes is covered mainly by natural gas and LNG.

At present, there is currently great uncertainty in Europe as to how to cover the energy demand in the winter months, especially in those countries with energy dependence on developing countries. The current situation exposes an evident and growing uncertainty due to the political and commercial situation in which Ukraine and Russia find themselves, which directly affects the European Union in terms of natural gas supply for energy use.

As can be seen in Figure 4, the EU demand decreased by 20% between 2009 and 2015, at which point it began to remain constant, with minimal fluctuations that are currently maintained. The trend of GN production has been declining since 2000 as well, in concordance with the previously reported analysis that demonstrated a reduction in the use of non-renewable resources in this region. On the other hand, net imports have been increasing since 2000, and it is expected that between 2019 and 2030, they will increase by approximately 15%.

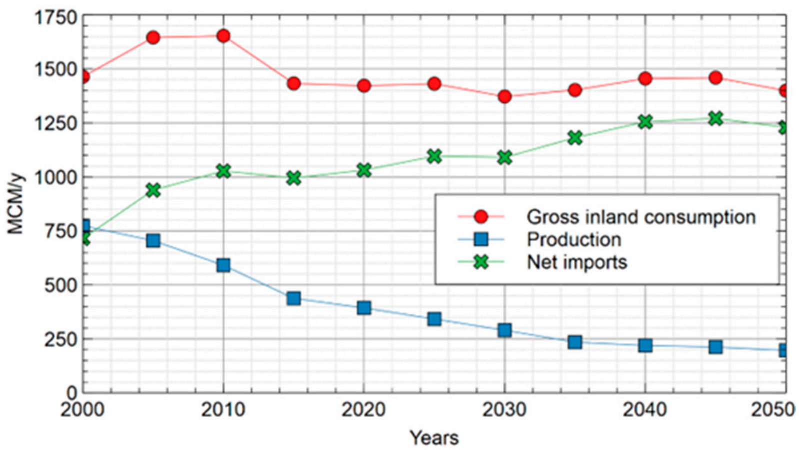

Figure 4. European Union forecast demand.

In 2021, the European Union imported around 140 billion m^3 (bcm) of natural gas (1 bcm of natural gas, with a calorific value of 43,128 MJ/m^3, is equivalent to 11,980 GWh) from Russia throughout the year. In addition, some 15 bcm was received in the form of liquefied natural gas (LNG), adding up to a total of 155 bcm of imported natural gas. This number represented 45% of the European Union's gas imports and 40% of its total gas consumption [6].

The second gas supplier was Norway. During 2021, this country exported 113 bcm via pipeline to Europe, covering 23% of the total demand. Despite the fact that Norway is a well-positioned country without commercial problems, it is unfeasible to increase their role in gas supply to Europe because they are constrained to 8% [7].

This conflict adds on to the confrontation between Algeria and Morocco in 2021, where the supply of 13.5 bcm[1] of gas from Algeria was lost due to the closure of the Algeria–Morocco–Europe gas pipeline. After this event, in 2022, the situation worsened when Algeria interrupted the supply from the only gas pipeline that remained available, with which 8 bcm of gas was provided through the Megdaz pipeline linking Algeria and Europe. This has especially harmed Southern Europe, with Spain being the main affected country, since 45% of its gas energy demand was supplied through this channel [8].

In this context, the European gas system has been steadily reinforced from 2009 to the present, driven by legislative and economic initiatives by European nations. Within this framework, countries have a range of solutions to meet NG demand, influenced by factors like resources, geographic location, and relations with external gas producers.

A nation's technical capacities for managing NG demand depend on its infrastructure, available resources, and management strategy. These capacities encompass NG production, gas storage, liquefied natural gas (LNG) imports, NG imports from developing countries, and cross-border gas pipelines.

The vulnerability of NG networks correlates directly with the number of existing infrastructures and the diversification of demand. For instance, access to LNG terminals and storage facilities can mitigate the impact of supply disruptions.

Even in cases where LNG facilities are inaccessible due to landlocked geography, various strategies are employed to enhance their interconnections with neighboring nations, thereby facilitating access to LNG infrastructure. Understanding these intricacies is crucial, in the broader assessment of the system's resilience, to coping with varying changes in gas demand and availability.

The main objective of this work is to develop a study on the robustness of the European gas system to possible changes derived from direct actions that imply an interruption of the gas supply to the European Union by modeling different scenarios, as well as to evaluate the position and resilience of each Union Member State in light of these changes.

2. Bibliographical Review

The introduction delves into an analysis of various factors, including GDP, renewable integration, citizen behavior in relation to energy consumption, and their collective influence on the prospective demand for natural gas. Within this section, we explore three distinct perspectives aimed at fortifying network robustness: considerations of demand security, principles of solidarity and cooperation, and the examination of existing models designed for simulating networks.

2.1. Security of Energy Supply

According to Directive 2009/73/EC of the European Parliament and of the Council [9], security of energy supply constitutes an essential component of public security and is, therefore, intrinsically linked to the efficient functioning of the internal gas market and the integration of the isolated gas markets of the member states. Gas can only reach the citizens of the Union through the network.

One of the resources proposed for regulation purposes is the adaptability of the system for the supply of other energy carriers that collaborate in this energy security strategy. This can also be guaranteed through storage systems and a plan for preventive measures based on the results obtained via different crisis management models.

2.2. Solidarity and Cooperation

The concept of solidarity is directly linked to the need to guarantee basic service coverage to vulnerable consumers in the first place, i.e., residential households and small businesses, and the role of the member states is to ensure this coverage as a public service. In this way, these vulnerable customers should be able to benefit from security of supply and reasonable prices [10]. This social view is considered by green investors in their investment choices [11].

The solidarity mechanism is used as a mechanism of last resort once all emergency measures have been exhausted. Within the European Union, the member state requiring solidarity will have the possibility to opt for the most advantageous offer in case there is more than one option among the offering member states. From this, the concept of customers protected under the solidarity mechanism is created [12].

For its part, the cooperative action is defined to address cross-border situations with the regulatory authority of the concerned member states. In the case of infrastructure to or from a third country, the regulatory authority of the member state in which the first point of interconnection with the network of the member states is located may cooperate with the competent authorities of the third country after consulting the regulatory authorities of the other concerned member states [12]. A clear example of this cooperation and solidarity raised during 2022 in view of the current situation is that countries that do not have storage capacity can have a gas reserve in a neighboring country in a regulated and safe way.

Cooperation can also be regional and include the concept of emergency supply corridors in the simulations offered by crisis management models. With these results, risk groups are defined and preventive action plans and emergency plans are drawn up.

The interconnected system is a way to make up for supply outages or crises due to various reasons such as shortages of the resource, damage to the supply network, or political and commercial conflicts between countries. The latter is one of the most critical scenarios for supply coverage and is addressed in this paper.

2.3. Management Crisis Models

The following is a list, including details, of crisis management models that have been developed in recent years and have contributed to the definition of the model developed in this paper (See Table 1).

Table 1. Description of management crisis models [13–20].

Model	Date of Model	Agency	Minimum Study Period	Software Version	Results
Gasmod	2009	DIW Berlin (German Institute of Economic Research)	Monthly	No	Economic optimization of a gas system; numerical resolution of the problem with maximization of global profit and by each country according to the strategy.
Gemflow	2011	JRC Commission, JRC Institute for Energy, Energy Security Unit (Kwabena)	Daily	No	Infrastructure analysis and bottleneck detection; probability of meeting demand in crisis situations generated.
Columbus	2012	EWI	Monthly	No	Trade flow projections; infrastructure utilization; investment demand; price developments.
EUgas	2014	JRC Commission, Institute for Energy, Energy Security Unit	Daily	No	Physical evaluation of critical infrastructures; satisfied demand broken down into domestic, industrial, and for electricity production.
MYNTS-Gas	2016	Fraunhofer Institut	Daily	Yes	European gas network modeling.
NEMO tool	2016	ENSTOG	Daily	Yes	Lineal optimization and hydraulic modeling of national infrastructure to model the European infrastructure with the most relevant accuracy.

Table 1. *Cont.*

Model	Date of Model	Agency	Minimum Study Period	Software Version	Results
SAInt	2017	JRC Commission, Institute for Energy, Energy Security Unit (Kwabena)	Daily	Yes	Development of parameters to quantify the impact of interruptions on security of supply; implementation in the innovative SAInt simulation tool to evaluate security of supply; detailed information on the weather and propagation of contingencies.
GAMAMOD	2019	Technische Universität Dresden (EE2)	Daily	No	Optimal European supply structure; use of natural gas infrastructures; minimization of system costs.
GGM (Global Gas Model)	2019	Franziska Holz (DIW Berlin)	Monthly	Yes	Analysis of gas pipelines, liquefaction, regasification, storage, and utilization extensions; production, consumption, trade, and seasonal prices.
Simple Optimization Model	2020	Universidad de Zaragoza	Daily	Yes	Optimal management of gas infrastructures to improve the response of the system in situations of energy crisis.
System Development Map	2021	ENSTOG	Daily/Monthly	No	Gas infrastructure and capacity information; historical gas demand, supply, and storage; deliverability achieved.

3. Methodology

This section describes the simulation model selected to solve the gas demand issue in different proposed scenarios. The countries have been analyzed with the methodology described in the paper "Assessing the Impact of Investments in Cross-Border Pipelines on the Security of Gas Supply in the EU" [21]. To summarize, the countries within the European natural gas system are considered as nodes with technical and capacity information on the country itself. The information for each of these countries includes:

C_i: Satisfied daily demand of natural gas in country *i*;
P_i: Daily gas production in country *i*;
S_i: Daily quantity of gas extracted from underground storage in country *i*;
IMP_i: Daily quantity of natural gas entering the system through pipelines from third countries;
LNG_i: Daily quantity of liquefied natural gas injected into the pipelines of country *i*;
X_{ij}, X_{ji}: Daily quantity of gas exchanged via pipelines between countries *i* and *j*.

To solve the system, the proposed methodology establishes a linear optimization with the technical and capacity information of each of the countries considered as nodes. The interaction between neighboring countries within the general natural gas system occurs through existing pipelines. These interactions are intended to carry out punctual cooperation and to transfer natural gas from those countries with surpluses to countries that are vulnerable due to gas cuts from countries outside the system. The interaction capacity is measured according to the gas flow and the amount of energy that these countries are able to send and receive from neighboring countries. Natural gas can be exchanged through existing pipelines, as shown in Figure 5.

The model considers each country as a node composed of links that represent the connection with other members through cross-border pipelines, which can be unidirectional or bidirectional. Similarly, natural gas supply resources from developing countries are considered, either by pipelines or maritime routes. The production and storage capacities of each country are also considered in this study.

The exchange of natural gas takes place in two phases.

In the first phase, each country (i) must try to cover the maximum percentage of its domestic demand with its own resources. In this phase, countries that can cover their entire domestic demand and are able to deliver natural gas to neighboring countries through pipelines will be detected. Also, countries that cannot cover 100% of their demand and need cooperation from neighboring countries to avoid energy shortages will be detected.

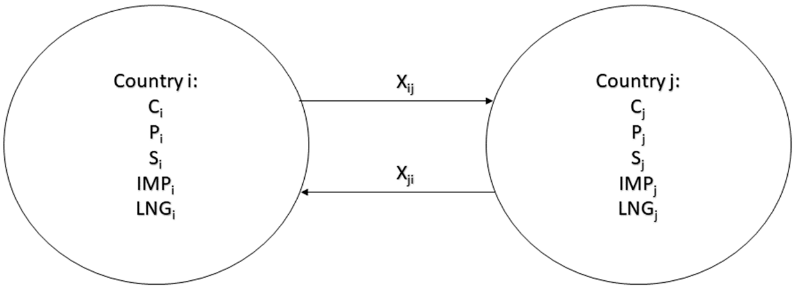

Figure 5. Natural gas exchange model.

Countries with a deficit to cover their internal demand:

$$P_i + S_i + IMP_i + LNG_i - C_i \leq 0 \tag{1}$$

$$0 \leq S_i \leq S_i^{max} \tag{2}$$

Constraint 1. *Natural gas IMP_i that is imported through pipelines from external countries can enter and transit within the integrated network under study. IMP_i^{max} is the maximum import capacity. If no regasification infrastructure exists, the IMP_i^{max} is equal to 0.*

$$0 \leq IMP_i \leq IMP_i^{max} \tag{3}$$

Constraint 2. *Some countries do not have LNG regasification plants. Therefore, the amount of gas injected into the grid is limited by its maximum capacity LNG_i^{max}.*

$$0 \leq LNG_i \leq LNG_i^{max} \tag{4}$$

Constraint 3. *The amount of natural gas exchanged between countries allows us to solve possible national deficits through solidarity. Therefore, a limited amount of natural gas can be delivered and received via cross-border pipelines.*

$$-X_{ji}^{max} \leq X_{ij} \leq X_{ij}^{max} \tag{5}$$

Constraint 4. *In the same cross-border pipeline, the natural gas transmission capacity in the $i \rightarrow j$ direction may be different to the $j \rightarrow i$ direction. Therefore, the limits X_{ij}^{max} and X_{ji}^{max} may have different values. The balance equations between countries i and j are represented in (6) and (7).*

$$Node\ i: \rightarrow\ P_i + S_i + IMP_i + LNG_i - \sum X_{ij} - C_i = 0 \tag{6}$$

$$Node\ j: \rightarrow\ P_j + S_j + IMP_j + LNG_j + \sum X_{ij} - C_j = 0 \tag{7}$$

Constraint 5. *The demand to be satisfied, C_i, ranges from 0 to C_i^{max}.*

$$0 \leq C_i \leq C_i^{max} \tag{8}$$

Once the objective function and the constraints of the mathematical problem have been formulated, it can be concluded that the problem is of linear type, because all the variables of the problem are continuous and the equations are linear. The optimization problem was programmed in MATLAB® software, version R2018a.

3.1. Proposed Scenarios

The mathematical model was applied to the EU-28 natural gas system and some neighboring countries (i.e., Switzerland, Serbia, North Macedonia, and Bosnia–Herzegovina) in order to provide possible solutions to collaboratively satisfy the domestic demand of all countries in crisis situations and massive gas cut-offs by the main suppliers. The studied scenarios are listed below:

1. Case 1. Base scenario.
2. Case 2. Massive gas cut-off scenario.
3. Case 3. Extreme scenario with achievement of energy efficiency targets for 2030.

3.1.1. Case 1. Base Scenario

The year 2019 will be used as the base for the analysis of the system's robustness against massive gas cut-offs. Table 2 shows the technical data for each member of the European gas system for this year.

Table 2. Base scenario. Technical data of countries based on existing infrastructure of 2019 (GWh/day) [22–24].

Node	Country	C_{max}	P_{max}	P_{max} (Forecast)	S_{max}	IMP_{max}	IMP_{max} (Extreme Condition)	LNG_{max}	X_{ij} max	X_{ji} max
		2019	2019	2030	2019	2019	2019	2019	2019	2019
1	PT	255	0.00	40.8	85.68	0.00	0	200	80.00	144.00
2	ES	1496	1.53	239.36	200.48	732.00	0	1911.00	368	245.00
3	FR	2832	1.35	453.12	2416.56	590	590	809	693	1783
4	IT	3699	173.77	591.84	2898.27	1558	0	601	670	2103
5	CH	181	0.00	28.96	0.00	0.00	0	0.00	904	1051
6	DE	4888	206.87	782.08	6442.45	4213	1240	0.00	5536	5191
7	BE	912	0.00	145.92	169.50	488.00	0	477	2492	2679
8	NL	1649	1351.61	263.84	2942.38	0.00	488	418	3337	1145
9	DK	96	128.60	15.36	180.9	0.00	963	0.00	4	124
10	AT	469	30	75.04	1057.7	0.00	0	0.00	2052	2114
11	CZ	465	5	74.4	529.4	0.00	0	0.00	2505	2706
12	PL	739	135.01	118.24	543.06	1336	0	158.00	932	262
13	LT	79	0.00	12.64	0.00	325.00	0	122	182	65
14	LV	42	0.00	6.72	246	63	0	0.00	170	68
15	EE	16	0.00	2.56	0.00	27	0	0.00	40	10
16	SK	266	13.52	42.56	491.56	2028.00	0	0.00	2381	1721
17	HU	618	50.34	98.88	839.71	517	0	0.00	347	381
18	SI	45	0.00	7.2	0.00	0.00	0	0.00	76	149
19	HR	142	27	22.72	60.57	0.00	0	0.00	57	131
20	BH	11	0.00	1.76	0.00	0.00	0	0.00	0.00	15.00
21	RS	126	14.27	20.16	56.50	0.00	0	0.00	21	316
22	RO	596	335.13	95.36	491.56	1114	0	0.00	872	225
23	BG	132	3	21.12	36.20	577	0	0.00	939	892
24	MK	13	0.00	2.08	0.00	0.00	0	0.00	0.00	20
25	EL	252	0.00	40.32	0.00	399	0	205	356	118
26	IE	217	112.25	34.72	27.00	0.00	0	0.00	0.00	385
27	UK	3972	1454.12	635.52	892.33	1499.00	1499	1597	1205	1297
28	FI	93	0.00	14.88	0.00	220	0	0.00	10	0

The gas demand to be covered which was selected for the model, C^{max}, was the real consumption on 21 January 2020, which was the day of the highest natural gas consumption at the European level.

In maps of the European gas system, an improvement in the infrastructure was detected with respect to the 2009 configuration. The proposed simulations will evaluate whether this has been sufficient to eliminate the existing bottlenecks.

3.1.2. Case 2. Massive Gas Cut-Off Scenario

The main suppliers of natural gas via pipelines to European countries are Russia, Norway, Algeria, and Libya, with maximum system injection capacities of 9180, 4780, 1870, and 4200 GWh per day, respectively. Considering the interruptions and crisis events that have been occurring since 2009, the model will simulate the European gas system against a massive cut-off of natural gas injected by external countries. Only gas from Norway will be left in the model because there has been no crisis nor geopolitical or commercial events until now. Table 2 shows that the proposed massive cut-off represents 69.5% of the gas from developing countries.

3.1.3. Case 3. Extreme Scenario with Achievement of Energy Efficiency Targets for 2030

Once the current gas system in an extreme situation was simulated, the European gas system was studied for the energy efficiency improvement forecast proposed for 2030 if the infrastructure is maintained. Table 3 shows the expected future demand in the event of achieving the energy efficiency objectives. However, the simulation of this case is based on a hypothetical reduction in the European natural gas demand of 60% with respect to 2019, considering:

1. The increase in biogas that will replace the thermal demand covered by natural gas to date [25].
2. Improved energy efficiency, which will affect 32.5% of energy consumption [26].
3. Exploitation of natural gas infrastructures to inject H2 and carry out a blending of NG and H2 of between 5% and 20% [27].
4. Increase in RES up to 40%, avoiding the use of NG for electricity production [28].

Table 3. Results of percentage coverage of real demand in the system based on existing infrastructure on 2019 (GWh/day).

Country	Case 1	Case 1 % Demand Coverage	Case 2	Case 2 % Demand Coverage	Case 3	Case 3 % Demand Coverage
	C real		C real		C real	
PT	255	100%	255	100%	102	100%
ES	1496	100%	1496	100%	598	100%
FR	2832	100%	2832	100%	1133	100%
IT	3699	100%	3699	100%	1480	100%
CH	181	100%	181	100%	72	100%
DE	4888	100%	4888	100%	1955	100%
BE	912	100%	912	100%	365	100%
NL	1649	100%	1649	100%	660	100%
DK	96	100%	96	100%	38	100%
AT	469	100%	469	100%	188	100%
CZ	465	100%	465	100%	186	100%
PL	739	100%	739	100%	296	100%
LT	79	100%	79	100%	32	100%
LV	42	100%	42	100%	17	100%
EE	16	100%	16	100%	6	100%
SK	266	100%	266	100%	106	100%
HU	618	100%	618	100%	247	100%
SI	45	100%	45	100%	18	100%
HR	142	100%	142	100%	57	100%
BH	11	100%	11	100%	4	100%
RS	126	100%	126	100%	50	100%
RO	596	100%	596	100%	238	100%
BG	132	100%	89	67.50%	53	100%
MK	13	100%	6	47.70%	5	100%
EL	252	100%	226	89.60%	101	100%
IE	217	100%	217	100%	87	100%
UK	3972	100%	3972	100%	1589	100%
FI	93	100%	0	0%	0	0.00%

4. Results

This section shows the simulation results of the different proposed scenarios, as well as a brief analysis from the point of view of demand coverage and pipeline congestion.

4.1. Analysis of Demand Response

Table 3 shows the results obtained in the base scenario and the scenarios proposed with respect to the percentage coverage of the system's real demand. See Table 3.

It can be observed that the optimization model proposed to solve the system cooperatively was able to avoid cut-offs in most of the countries in all scenarios. However, four countries were detected that were unable to cover their demand partially or fully in extreme situations. Bulgaria, North Macedonia, and Greece did not manage to cover 100% of the demand, with 67.5, 47.7, and 89.6%, respectively. On the other hand, Finland would cover 0% of its gas demand in the event of a massive outage.

Once the consequences of a massive gas outage were analyzed, the effect of achieving energy efficiency targets and whether they are able to de-stress the system was assessed. The results show that a 60% reduction in demand compared to 2019 would avoid partial outages, and only Finland would be unable to cover its demand due to the isolation of the gas system.

4.2. Regarding Interconnections

The interconnections between the countries of the European system suffer significant modifications in order to compensate for the elimination of injected gas from developing countries. In the base case, the average saturation of interconnections is 25%, so there are no major bottlenecks for exchanging surplus gas. In the case of a massive gas cut-off, the system cooperates by increasing the percentage of network saturation to 33.4%. The third scenario shows a relaxation in infrastructure congestion, reducing the percentage to 17.7%, lower than the base scenario (see Table 4).

Table 4. Optimal management of the European pipeline network (GWh/day).

Country i	Country j	Capacity max	Capacity min	Case 1	Case 1 % Pipeline Saturation	Case 2	Case 2 % Pipeline Saturation	Case 3	Case 3 % Pipeline Saturation
Germany	France	609	0	102.83	16.90%	74.74	12.30%	100.84	16.60%
Bulgaria	Macedonia	20	0	13	65.00%	6.21	31.00%	5.2	26.00%
Serbia	Bosnia	18	0	11	61.10%	11	61.10%	4.4	24.40%
Czech	Poland	28	0	19.13	68.30%	20.28	72.40%	19.95	71.30%
UK	Ireland	385	0	77.75	20.20%	77.75	20.20%	0	0.00%
Austria	Slovenia	113	0	65.76	58.20%	67.15	59.40%	34.31	30.40%
Austria	Hungary	153	0	60.59	39.60%	96.76	63.20%	24.82	16.20%
Latvia	Estonia	168	0	0	0.00%	16	9.50%	6.4	3.80%
Hungary	Serbia	142	0	66.23	46.60%	66.23	46.60%	4.4	3.10%
France	Switzerland	258	−100	122.15	47.30%	151.19	58.60%	95.89	37.20%
Belgium	Netherlands	393	−1437	−200.74	14.00%	25.68	6.50%	−47.32	3.30%
Germany	Switzerland	349	−164	4.85	1.40%	−9.14	5.60%	−45.69	27.90%
Netherlands	UK	494	−168	−34.22	20.40%	−62.56	37.20%	17.17	3.50%
Slovenia	Croatia	54	−8	19.28	35.70%	25.89	47.90%	7.32	13.60%
Austria	Italy	1150	−194	52.52	4.60%	68.64	6.00%	13.22	1.10%
Hungary	Croatia	77	−49	35.15	45.60%	28.54	37.10%	−7.32	14.90%
Romania	Bulgaria	806	−148	−4.02	2.70%	77	9.60%	15.22	1.90%
Bulgaria	Greece	118	−65	−9.05	13.90%	20.88	17.70%	−3.58	5.50%
Germany	Czech	2306	−1231	169.71	7.40%	391.67	17.00%	200.07	8.70%
Slovakia	Hungary	129	−51	25.9	20.10%	75.01	58.10%	−15.98	31.30%
France	Belgium	270	−850	17.58	6.50%	96.73	35.80%	49.28	18.30%
Italy	Switzerland	444	−640	54	12.20%	38.94	8.80%	22.2	5.00%
Spain	France	224	−165	36.91	16.50%	173.19	77.30%	28.71	12.80%
Spain	Portugal	144	−80	0	0.00%	0	0.00%	−11.79	14.70%
Belgium	Germany	397	−320	184.53	46.50%	191.37	48.20%	156.5	39.40%
Netherlands	Germany	1446	−593	−157.18	26.50%	179.9	12.40%	−46.91	7.90%
UK	Belgium	652	−803	−53.63	6.70%	385.82	59.20%	41.85	6.40%
Germany	Austria	350	−390	−93.88	24.10%	−63.82	16.40%	−123.74	31.70%
Czech	Slovakia	1246	−400	150.57	12.10%	371.39	29.80%	180.11	14.50%
Latvia	Lithuania	65	−68	0	0.00%	−16	23.50%	−6.4	9.40%
Austria	Slovakia	246	−1570	−272.75	17.40%	−296.38	18.90%	−196.09	12.50%

Table 4. *Cont.*

Country i	Country j	Capacity max	Capacity min	Case 1	Case 1 % Pipeline Saturation	Case 2	Case 2 % Pipeline Saturation	Case 3	Case 3 % Pipeline Saturation
Italy	Slovenia	28	−22	−1.48	6.70%	3.74	13.40%	−8.98	40.80%
Germany	Denmark	124	−4	−2.65	66.30%	−1.89	47.30%	−1.92	47.90%
Germany	Poland	234	−932	−153.51	16.50%	−20.28	2.20%	−19.95	2.10%
Hungary	Romania	77	−50	−14.88	29.80%	77	100.00%	11.77	15.30%
		Total			25.00%		33.40%		17.70%

5. Discussion

Considering the analysis of the demand response results, the initial observation suggests that currently, under severe conditions, there might be countries unable to meet 100% of their demand. This highlights that the infrastructures are not adequately prepared to supply sufficient natural gas to all member countries in the event of a total outage. However, in the hypothetical scenario where energy efficiency goals are achieved, this risk is eliminated with the existing infrastructure. This implies that no additional infrastructure investment will be required if the energy efficiency objectives set for 2030 are met.

Our analysis of the results obtained in the evaluation of gas pipeline congestion indicates that in Case 3, congestion was even lower than in the baseline case, which assumes the absence of a supply crisis. Similar to the analysis of demand coverage results, infrastructure congestion improved with energy efficiency without the need for investments in gas infrastructure.

6. Conclusions

In the case of a massive natural gas outage, the demand coverage at the European level would suffer direct effects such as partial outages in countries like Bulgaria, North Macedonia, and Greece. On the other hand, Finland would suffer a total supply cut. In other words, the dependence on imported gas by the EU gas system is very high, and there is no internal alternative except cooperation against outages. Although there have been improvements in gas infrastructure that have enhanced the robustness of the system, it is unfeasible to eliminate all risks of shortages.

The third scenario assumes that the robustness and independence of the natural gas system will be improved through the application of energy efficiency measures, and that the EU countries will be able to achieve the objectives set for 2030. In this scenario, the network will be able to cover the total demand of all EU countries, except for Finland. This is mainly due to Finland's physical isolation from the global gas system. The system's robustness improved considerably in the 2030 target scenario, even improving on the 2019 baseline scenario. In other words, the correct implementation of energy efficiency measures in these countries can improve the robustness of the current network.

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