Imperial College London

Department of Chemical Engineering

Strategic Gas Storage Coordination among EU Member States during Supply Crises: An Optimization Approach

by

Marzia Sesini

Submitted for the degree of Doctor of Philosophy

Copyright Declaration

I hereby declare that the work presented in this thesis is my own and that everything that is not my work has been appropriately referenced.

Abstract

Given the strong presence of natural gas in the European Union (EU) energy mix (25%), this work focuses on natural gas strategic storage reserves as a first non-market based solidarity measure to increase energy security among EU Member States in response to natural gas supply "high-impact, low-probability" events (HILP). It presents a two-stage stochastic LP optimization gas transport model minimizing costs to study the short-term resilience of the network to supply shocks when using strategic storage in a coordinated fashion and including a policy perspective (i.e., EU Regulation 2017/1938) to evaluate the impact of HILP on the level of demand curtailment, survival time, and the natural gas supply mix among MS in the EU.

The model is implemented to analyze three applications related to natural gas storage: (1) assess resilience and security in the EU gas system during a real case of shock in demand during an exceptionally cold weather; (2) test the role of coordination in case of short-term HILP events in the EU natural gas network; and (3) examine solidarity measures, such as strategic storage, among EU Regional Risk Groups during gas system disruptions due to HILP events.

Results highlight the value of gas infrastructure diversification and the role of storage in the gas market and its inherent value in the system. In particular, the cost efficiency found in the coordinated use of strategic storage during a short-term emergency emphasizes the importance of storage-based solidarity in mitigating the effects of HILP supply disruptions and securing resources to the grid. They indicate that geographical proximity alone, without solidarity interventions, is insufficient to provide system resilience and that solidarity interventions enhance survival time for Regional Risk Groups in the EU and reduce liquefied natural gas (LNG) and system costs, offering an additional insight on the interplay between storage and LNG.

Acknowledgements

I would first like to express my sincere gratitude to Snam: without their financial support my PhD degree would have not been possible.

My gratitude goes also to my supervisor, Dr. Adam Hawkes, for his assistance and support throughout the entire course of my PhD degree. His insightful feedback pushed me to sharpen my thinking and brought my work to a higher level. Here I would also like to extend my deepest appreciation to my two invaluable co-supervisors, Dr. Sara Giarola and Dr. Anouk Honoré, for their unwearing guidance, mentorship and enthusiasm. Your deep knowledge and expertise was truly instrumental in defining the path of my research from the research question formulation to the methodology and beyond. For this and your presence, I am extremely grateful. Finally, I would like to acknowledge Dr. Matteo Di Castelnuovo for inspiring my interest in pursuing a PhD degree at this academic institution and in the topic of energy and natural gas.

I would also like to acknowledge my colleagues from Snam for their wonderful collaboration. I want to thank them for their patient support and for all the opportunities I was given to further my research. I would particularly like to single out Andrea Stegher, Simona D’Angelosante, Giovanni Angius, Paola Occhio, Michela Lavelli, and Eric Beretta Vasco for their generosity in sharing their deep experience and knowledge of the natural gas market with me.

In addition, I would like to thank all my friends for their presence, care and sympathetic ear during this meaningful period of my life and in particular, Viola C., Barbara B.P., Andrea B. and Richard McM.. Finally, I would like to thank my pillars and grounding roots through and through: my father Massimo and my brother Maurizio. You are always there for me.

To my mother, who is watching over me.

Table of contents

List of figures

List of tables

List of publications

Journal publications

Sesini M, Giarola S, Hawkes AD. The impact of liquefied natural gas and storage on the EU natural gas infrastructure resilience. Energy 2020;209:118367.

Sesini M, Giarola S, Hawkes AD. Strategic natural gas storage coordination among EU member states in response to disruption in the trans Austria gas pipeline: A stochastic approach to solidarity. Energy 2021;235:121426.

Sesini M, Giarola S, Hawkes AD. Solidarity measures: Assessment of strategic gas storage on EU regional risk groups natural gas supply resilience. Applied Energy 2022;308:118356.

Chapter 1. Introduction

This chapter presents the context of the study. The key features of the EU natural gas market are explained in relation to decarbonization of the grid and energy security in Europe. These features cover different aspects such as energy balance, energy sources, and the role of both import/export through pipeline and via LNG and of storage. A thesis brief is presented in Section 1.2, and the structure of this thesis is outlined in Section 1.3. The research objectives are examined in Chapter 2 in more details, after the background for the thesis and the literature gaps are highlighted in the same chapter.

1.1 Natural gas context in Europe

In a European energy system that evolves towards full decarbonization, natural gas can play a pivotal role in leading the EU to reach its long-term aim of decarbonization as well as in reducing the external energy dependence of the Union. Over the past decade, the gas type mix has been progressively changing: not only LNG has become more abundant and other biofuels have been entering the gas network. Since 2016, biomethane has seen a 0.7% increase in production and trade within the EU grid, but also services related to consolidate usage of the commodity (i.e., gas storage) have been evolving to grant a liquid and integrated market [1]. Furthermore, current consumption of natural gas, which accounts for 25% of the energy mix, is expected to increase, mainly driven by coal-to-gas substitution in the power sector, reaching an average of approximately 500 bcm gas demand by mid-century in Europe [2–4].

The seasonal demand for natural gas requires supply flexibility, which has largely been provided in Europe by indigenous production. Declining reserves will increase the dependency on imports both from remote sources (e.g., Russia and Algeria) and of LNG which are less flexible sources. Both the two main European natural gas producers, Norway and the Netherlands, are declining production. Due to increasing seismic activities the Dutch government has decided to cap production of Groningen field, the largest European natural gas field from a 86 bcm (winter 2013/2014) to a 11.8 bcm (winter 2019/2020) annual cap [4].

As far as diversification of supply is concerned, despite recent geopolitical conflicts, the EU remains the main destination for Russian gas, in particular Eastern European countries, which are not able to supply their consumers with gas from alternative sources. With the extension of Nord Stream 1 and 2 and the creation of Turk Stream to bypass Ukraine finished in 2019, anticipated imports from Russia are significant, with a steady 180 bcm delivery by 2024 [2,5]. On the other hand, LNG could be a significant measure to improve diversification in Europe natural gas supply with additional regasification capacity being created and oversupply of LNG in Europe from US and Australia. In addition, although it has not always proved to be a reliable source during supply crises (i.e., in 2013 and 2017), LNG can also help balancing seasonality and managing shorter-term natural gas (and electricity) demand variations [6,7].

In this context, gas storage can become a strategic resource for the EU natural gas market where diversification of sources is limited and constant over time. It remains particularly important in managing the risk of supply disruptions; in providing the flexibility to smooth the seasonal and within-day volatility of gas demand; in ensuring market liquidity to give robust price signals; in optimizing the efficiency of the network (storage plants are closer to consumption areas than production/import areas); as well as in granting the flexible back-up capacity needed in a system with a growing share of variable renewable energy sources. Hence, it contributes to the efficient functioning of the overall energy market as well as effectively responding to security of supply (SoS) needs.

1.2 Research Description

The concept of energy security in the EU has evolved over time. In the 90s, the focus was on the completion of the internal gas market and on the creation of internal competition (First Gas Directive) [8]. The EU focused on infrastructure and regulation in the 2000s to maintaining supply security and establishing a self-standing and competitive internal market (Second Gas Directive [9] and Third Energy Package [10–12]). Finally, in the 2010s there has been a shift in perspective towards a more "converging energy security supra-national society": regional cooperation, coordination, solidarity have been the driving principles of the Gas Regulation 994/2010, the 2016 Security Package and Regulation 1938/2017 [13–18]. In addition, the European Network of Transmission System Operators for Gas (ENTSO-G) 2014 Stress Tests results highlight how coordinated non-market based measures work best in responding to emergencies crisis levels as defined by Regulation 94/2010 [14].

As Boersma [19] emphasizes, although governance and infrastructures have been given little attention in the energy security literature, without a strong institutional framework, gas systems cannot function correctly. Governments need to manage the non-quantifiable risks of energy security [105] and more specifically, as Stern [20] and Kopp [21] suggest, potential "high-impact, low-probability" events (HILP). Political threats (such as political unrest, terrorism and civil war), climate emergencies (such as landslides, floods, earthquakes and storms), technological risks (such as fires, leakages, cyber-attacks and equipment malfunction), social risks (such as strikes and vandalism), are all events that are going to increase gas prices and restrict its availability, affecting availability for final consumers.

The concept of energy security is polysemic in nature, contextual and dynamic. Hence, it cannot be unequivocally defined. It has had various definitions, none of which simultaneously covered three aspects that are fundamental when looking at the concept from a policy perspective in an emergency crisis: continuity, HILP, and availability/accessibility (economics/policy).

Framing energy security through energy insecurity with a bi-dimensional perspective, policy and economic, has been one of the two main streams in which literature has addressed the issue of defining energy security. Energy insecurity has been perceived as a tradeoff, distributing the risk between various energy options. Since it is difficult to measure simultaneously all of the occurring risks, the choice of boundaries and limiting the scope of the concept with severity filters is paramount [22]. To this end, Stern [20] suggests that risks could be linked to the source and transit of gas supply as well as the facilities through which gas is delivered. Hence, resilience could be achieved in the short-term by having adequate and functioning supply infrastructures. As Kopp [21] states, it is then the government that has to insure against non-quantifiable risks, thus again increasing resilience. To account for resilience, Winzer [22] adds the scope of the impact to the definition of energy security, which includes the continuity of the supply of the commodity as well as of the services.

Physical interconnections, infrastructure crossing different markets, regimes, and jurisdictions are a few of the challenges MS are facing with regard to gas markets, which makes the discussion of governance essential. As Sovacool [23] concludes in his study on energy security performance, promoting energy security requires international trade coalitions as well as supranationally coordinated state strategies. Recent debates at the EU level, after the Energy Security Package, have also emphasized the need for legislation on the Governance of the EU gas market. In relation to the concept of solidarity in emergency situations included in the EU 2015 Review of the Security of Supply Regulations, the Package calls for the urgent development of a comprehensive integrated plan in which political and economic rationales are intertwined with cooperative and coordinated responses to supply failures [24].

As Tagliapietra and Zachmann [25] highlight, the EU has a high margin of flexibility, with many unused options in its gas infrastructure system. Their study shows how the EU, on aggregate, could survive a disruption from its largest gas supplier on the peak day or over the course of the year, whereas at the Member State (MS) level some regions are more exposed to the risk than are others. The main issue, according to the authors, is flexibility of the unused options, rather than import diversifications [25].

Until today, strategic gas storage has mostly been developed at the country level, either as a storage obligation or as strategic storage, and a shared and integrated management of gas storage in light of energy security in the European gas market has not been considered. A coordinated management of gas storage might provide a more integrated approach to the topic by analyzing not just the potential and practicality of gas demand and supply aggregation, as Buchan and Keay [26] propose, but also mapping energy security elements into it. In the 2016 EU Security Package and subsequent Regulation 1938/2017, gas storage has been suggested as a potential non-market based solution to support supply security [17,18]. Three factors strengthen the role of gas storage in the EU gas market: a high reliance on imports, a lack of source diversification, and the impact of falling domestic production on market seasonality and flexibility. Hence gas storage is an important insurance tool to give flexibility in the liberalized gas market, as well as a quick emergency response mechanism as discussed in Section 2.1 of this work.

Although the problem of optimizing natural gas network supply has been addressed by many authors, as Flouri et al. [27] and Chyong et al. [28] suggested, only a few of them have looked the effects of natural gas supply disruption on energy security in the EU market under Cournot oligopoly minimum cost model dealing with strategic gas supply concerns [27–29].

In addition, the literature review suggests that the vast majority of gas market models have been mostly focusing on supply flows rather than on securing energy services, which instead would stress that security can be achieved through different means [30]. They either investigated the adequacy and robustness of the natural gas system in response to disruptions of imports [31] or to a limited number of external disturbance events [29], such as unusually low temperatures for an extended period of time in several MS, a drop in demand; or internal disturbances [32], such as component failures happening at the cross-border points or connections. Another component that has mostly been neglected is the integration of "international" and "policy challenges" as defined by Vivoda et al. [33]. As Giuli [34] points out, integrating in the model considerations on whether a Member State is dedicated to cross-border cooperation on energy related problems (e.g. solidarity) is a particularly important feature, because the external supply option remains under the jurisdiction of the Member State. At the time of writing most EU natural gas network models are either mixed complementary programming (MCP) models focusing on price-driven competition suitable to analyze market power (as in Yang et al. [35] and in Baltensperger et al. [36] among others), or two-stage stochastic scenario based optimization models assuming perfect competition to design resilient distribution networks suitable to investigate policy-related issues and long-term security of supply (as in Smeers [37] and in Hosseini et al. [38] among others).

To the best of our knowledge none of the previous literature has proposed a detailed infrastructure model analyzing the short term resilience of the whole European natural gas infrastructure as well as coordinate interregional responses when confronted with a non-hypothetical demand shock, adequately modeling supply-demand crises of natural gas systems, and analyzing the relative resilience and adaptive capacity of the network over short-term periods, which would prevent the system from collapsing.

This work formulates and applies such a model. It presents a modeling framework that, through a policy perspective, highlighted by the EU Regulation 2017/1938 [18], looks at a coordinated use of strategic gas storage (i.e., a gas stock that is set aside from the market to smooth out disruption in supply) among EU Member States.

The proposed two-stage stochastic linear programming (LP) model explores an EU-wide optimized coordinated first response to security of supply issues after market-based measures have failed, starting with a first non-market measure (i.e., a measure which does not influence actors' behavior by changing their economic incentive structure, but works through the imposition of certain obligations or by enacting non-monetary incentives [39]) such as shared and integrated management of strategic storage (i.e., a gas stock that is set aside from the market to smooth out disruption in supply) in case of an HILP over short-term periods. It minimizes the expected system cost of gas supply in a multi-country region (i.e., the EU gas network).

Three main applications were developed:

- **Cold spell**. The study seeks to implement a deterministic equivalent of the HILP cost minimization model without strategic storage to reflect current gas flow trends during a real case of exceptionally cold weather in Europe. The procedure implies that the gas volumes are set to flow along the main gas directions. The model assesses the impact of LNG and storage on the EU natural gas infrastructure resilience
- **Modeling HILP scenario with supply disruption**. The two-stage stochastic HILP cost minimization model is applied to test competition between production and coordinated strategic storage utilization in Europe. A scenario-based approach is used to model uncertainty in the gas supply in the EU gas network using the criteria of volume delivered, and temporal and spatial availability. The model assesses the role of strategic storage

coordination as a first non-market based measure in case of short-term supply disruption or unexpected demand shocks in the region.

- **HILP model with Regional Risk Groups**. The two-stage stochastic HILP cost minimization model is applied to study EU solidarity mechanism which includes specific Regional/Risk Groups (EU Commission in the 2016 EU Security Package and EU Regulation 1938/2017 [15,18]). Based on results from the previous application of the model, a quantitative analysis is carried out to assess the effectiveness of solidarity measures with the current configuration of the gas network with regards to responding to emergencies.

The deterministic version of the model, in the first application, assesses the resilience and security in the EU natural gas system, highlighting the value of gas infrastructure diversification and hinting at the critical role storage may play in adapting to the consequences of climate change, which effects, together with political turmoil and technical material failures, are posing a threat to infrastructures more and more [1,40]. The two-stage stochastic cost minimization version of the model, in the second application further unpacks the value of storage in the system under abrupt and unexpected supply outages and demand spikes. In examining the use of strategic storage in response to HILP events, it emphasizes the cost-effectiveness achieved with a non-market-based solidarity measure in securing energy to the EU natural gas network in gas supply emergency. Finally, in line with the 2019 EU energy security agenda, which has led to the concept of solidarity among MS in responding to HILP events jeopardizing the EU energy supply, the stochastic optimization version of the model in the third application, assesses solidarity among Member Stated in mitigating the ripple effect of natural gas disruptions. In analyzing the coordinated use of strategic storage, it highlights its value in balancing the natural gas network during emergencies and provides further evidence supporting the EU legislative path towards an Energy Union.

Medium and long-term projections on the use of natural gas in a carbon-constrained world project uncertain level of penetration of this fuel. Despite most of the projections see its use reduced compared to nowadays consumption, natural gas is still a key enabler of the decarbonization of the energy system [41].

In a first instance, it will progressively replace more carbon-intensive fuels, such as coal and it will provide an essential back-up for renewables generation until energy storage will not become available at a lower cost. The scale-up of the Carbon Capture and Storage (CCS) will then make power generation from natural gas sources more environmentally sustainable [42].

Other applications for natural gas will be in industry, where it is expected to play a major role as a feedstock, for example to hydrogen or ammonia. In transport, maritime transportation and heavy-duty vehicles will see an increase use of natural gas, before hydrogen will become more available [43].

In the long term, gas infrastructures could be converted for the transport of hydrogen and biomethane [43]. To this end, although with a focus on strategic storage, this work, presenting a LP optimization modeling the full natural gas supply chain so as to increase its reliability, can be extended to the re-purpose of the infrastructure by looking at cost reduction and efficiency of the infrastructure with the integration of renewable resources.

1.3 Thesis Structure

After an introduction, **Chapter 1**, setting out the challenges and the methodologies of the approach, the thesis is organized as follows:

Chapter 2 sets out the general background on energy security and resilience of the European natural gas network. It also provides a literature review on existing analytical approaches to assess resilience in the natural gas supply chain in Europe identify optimization as the appropriate methodology to study the issue. First, the chapter analyzes gas storage ad its use in different Member States, then it delves into the concept of energy security. To frame the boundaries of the study two perspectives on the concept have been taken into account: a policy and a natural gas supply chain one. This chapter concludes highlighting the importance of designing a resilient network when it comes to securing energy to the whole EU system.
In addition, a review on modeling gas supply disruption in the EU natural gas network has been compiled. The focus of the review has been on models that deal with gas network and supply chain resilience, including uncertainty design of the network; their strengths and weaknesses are identified. This chapter concludes with the general objectives of this thesis and with the specific objectives for each of the three main applications related to energy security in the natural gas supply chain studied in this thesis, which will be then delved into in Chapter 4, Chapter 5 and Chapter 6.

Chapter 3 explains the materials and methods adopted in this work. First a HILP model mathematical framework is presented, with the assumptions made and the input parameters and constraints. Following, specific case studies are presented with a detailed description of input data, assumptions and scenarios for the three specific applications related to supply/demand shocks in the EU natural gas network using the HILP model.

Chapter 4 presents a deterministic equivalent of the HILP model and discusses the results for the study on the impact of LNG and storage on the EU gas network resilience under demand shocks.

Chapter 5 shows the obtained results on how strategic storage can be utilized in coordination among EU Member States as a first non-market based response measure in the interconnected regional European gas system and examines results for a number of scenarios representing the uncertainty in the gas supply volumes at different severity level. A two-stage stochastic cost minimization formulation of the HILP model is implemented at this stage.

Chapter 6 shows results from the application of solidarity mechanism among EU regional risk groups during a supply/demand shock and discusses network configurations with respect to EU Regulation 2017/1938.

Chapter 7 summarizes the main findings and contribution of this thesis, with key insights from the applications in Chapter 4, Chapter 5 and Chapter 6. It provides the limitations of this work and directions for future research.

Chapter 2. Background

This chapter explains the background of the study providing a literature review focusing on modeling energy security in the EU natural gas market. Section 2.1 starts out with a view on natural gas storage in the EU as a market and non-market tool: what its main physical characteristics are and how specifically it is being used by different Member States. Following, the concept of energy security is deeply investigated. Two different perspectives on its definition are taken: a policy and a natural gas supply chain one. The first one, in Section 2.2, reviews the evolution of EU policies related to energy security and configuration of the natural gas network. Whereas the second one, in Section 2.3, focuses on defining the concept of energy security with respect to the natural gas supply chain. In Section 2.4 starts a review on existing optimization models that have examined the topic with a perspective on natural gas supply chain looking at the two main approaches adopted by the vast majority of authors: minimum cost models and competitive market models. The discussion is both on analytical methods and conclusions. The review then moves onto modeling uncertainty in the supply gas network as availability and accessibility of gas and the ability to respond to disruptions become paramount in the network during energy emergency. The review and the subsequent identification of literature gaps help set out the research objectives, which are described in detail in Section 2.5. Both the general objectives on the development of the modeling method, and the specific objectives on the applications to which the HILP model will be applied are described.

2.1 Gas storage in the EU

For a definite picture of the exposure of EU countries to supply disruptions, it is essential to have a clear understanding of the role of storage in the internal gas market (commercial storage), as well as the use of storage as an emergency response measure, and where across different EU Member States a mandatory strategic storage reserve (strategic storage) is already in place.

2.1.1 Gas storage technical features

Storage comprises three activities: injection, storing, and delivering. Most gas storage facilities are underground (UGS) and are high operating pressure, as opposed to above ground facilities which are low pressure and have minor strategic significance [44]. Over 50% of the total storage capacity in the EU belongs to three countries: France, Germany, and Italy, which together hold 54% of the total number of facilities in the EU [45]. Countries with a Third Party Access (TPA), or negotiated access regime (nTPA) to storage, have the largest capacity, with the exception of Italy, which opted for a regulated access regime (rTPA), but still has the second highest capacity in gigawatt hours (GWh) of European nations (see Table 2-1).

Table 2-1 Storage reserves in EU [46]

Member State	N. of facilities	Commercial (GWh)	Non-Commercial (GWh)	Total (GWh)
Germany (N)	61	220.000	39.000	260.000
Italy (R)	13	177.000	18.000	195.000
Netherlands (N)	5	130.000	0	130.000
France (N)	21	130.000	0	130.000
Austria (N)	10	90.000	2.000	92.000
Hungary* (R)	5	67.000	0	67.000
Czech Republic (N)	9	40.000	0	40.000
Poland (R)	9	24.000	12.000	36.000
Slovakia (N)	2	35.000	0	35.000
Romania (R)	7	33.000	0	33.000
Spain (R)	4	32.000	0	32.000

Latvia (R)	1	24.000	0	24.000
United Kingdom (N)	9	16.000	0	16.000
Denmark (N)	3	10.000	0	10.000
Belgium (R)	1	9.000	0	9.000
Bulgaria (R)	1	4.000	2.000	6.000
Croatia (R)	1	5.250	750	6.000
Portugal (R)	1	3.000	0	3.000
Sweden (N)	1	100	0	100

(N) nTPA; (R) rTPA; * Although GSE classifies all Hungarian capacity as commercial, the member state has some non-commercial capacity as well.

There are two key characteristics of gas storage (see Table 2-2):

- Working capacity of the cavity, in Gigawatt hours (GWh) or Million Cubic Meters (Mcm): volume of gas that can be stored in a reservoir, and
- Deliverability and injection rate, in GWh or Mcm per hour/per day (GWh /hr; GWh/d; Mcm/hr; Mcm/d): the amount of gas that can be injected and withdrawn from the facility on an hourly or daily basis.

The working gas capacity and the injection and deliverability rate are complementary and can vary, as can the working capacity, temporarily or permanently. The injection rate varies inversely with the storage total working capacity: it is at its lowest when the storage is nearest capacity and grows as the gas is taken out. Conversely, the withdrawal rate is highest when the storage is nearest capacity and lessens as working gas is withdrawn [47]. Depending on the type of UGS (i.e., aquifer, depleted field, or salt cavern) the average speed (Withdrawal Potential/Working Gas Ratio) can vary considerably. Salt cavities have the highest injection and withdrawal rates, and are concentrated mostly in France, Germany, the Netherlands, Poland, Portugal and the UK [45].

Additional technical features that describe gas storage functioning are (see Table 2-2):

- Cycle, or turnover, rate of a storage facility: a flexibility measure that defines the number of times in a year that a reservoir can be loaded and depleted, and
- Cushion gas: differs from working gas, in that it is an amount of gas needed for the facility to function. It is also referred to as base gas as it remains permanently in the storage cavity. It provides the minimum storage pressure necessary for optimal gas injection and withdrawal and, in salt caverns, ensures stability. By keeping the pressure inside the reservoir, the natural gas maintains the physical characteristics of the facility. It is part of the initial capital cost of the storage, consisting of one third to a half of the maximum storage volume, but can be recovered at the phasing out of the storage facility.

Table 2-2 Key storage characteristics in Europe [44,46]

Factor	**Salt cavern**	**Depleted field**	**Aquifer**
Working capacity [GWh]	250.000	835.000	171.000
N. of storage	51	74	22
Main usage	Multi cycle.	Limited multi cycle. Seasonal. Strategic.	Seasonal. Strategic.
Advantages	High injection rates. Low cushion gas. Phased development.	Existing and understood. Relatively low cost. Large capacity.	Large capacity.
Disadvantages	Small volume in individual caverns. Brine disposal. Subject to convergence. Higher operating cost.	High cushion requirement. Slow injection and withdrawal rates.	High cost. Extended development time. Potential environmental objections.

Deliverability* (GWh/d)	85	26	2
Cushiom gas requirements (% of total capacity)	20%	45%	55%
Cycle rates	6,9	2,1	1,6

* Assuming a working capacity of 1.773 GWh.

2.1.2 Gas storage market and non-market measures

Volume flexibility is a crucial component in the balancing of the gas markets. Demand swings are driven by multiple factors, such as weather temperature, level of economic activity, electricity demand, and intermittency of renewables. Since the vast majority of gas users are captive in the short and medium term, their gas demand becomes relatively price inelastic and they put a high premium on a supply that is reliable and constant [44].

Flexibility has been defined as the ability of the energy system to balance itself to handle external changing physical and commercial signals and still being reliable in providing services within the system. It does not only apply to the gas market itself, but as the interplay between electricity market and gas market becomes more significant in a decarbonized Europe, with smart meters, smart appliances, and renewable energy resources being integrated into the system, flexibility becomes a crucial asset of the whole energy networks to help balance energy flows and redirect energy supply and demand, integrating different resources accordingly [48,49].

As far as the gas network is concerned, different measures help achieve a physical balance in the gas network. It can be achieved thought variations in the gas transported through the pipelines from outside the system to regulate inflows-outflows imbalance, while still having available line-pack to secure the network working pressure. Beside pipeline swing (e.g., diversification of supply routes and line-pack flexibility), supply flexibility (e.g., creating a variation in supply through LNG terminals or production sites (production swings)), and additional commercial flexibility measures help the system operators balance the system: liquidity in the spot market, network services (e.g., transmission system models, balancing regimes and interconnections to country with exporting capacity), and forms of demand side response (e.g. interruptible customers) [50].

Although competition among these sources has been increasing as a part of the shift towards a liberalized gas market, it has not significantly decreased the role of storage in fulfilling demand swings; in fact, storage capacity utilization from 2010 has not been contracting (e.g. 90-95% full at the beginning of winter from 2011), signaling gas storage insurance value [45] (See Figure 2-1). Aside being a physical flexibility tool to balance the inflows and outflows of the whole gas network (physical balance) to keep the right operating pressure in the grid, commercial storage also represents a valuable tool to improve market flexibility to cope with demand shifts allowing trade among gas agents in the market (commercial balance). By ensuring physical availability of volumes, commercial storage ensures volumes are physically delivered, avoiding price spikes and discontinuity of gas supply [51] (see Figure 2-2).

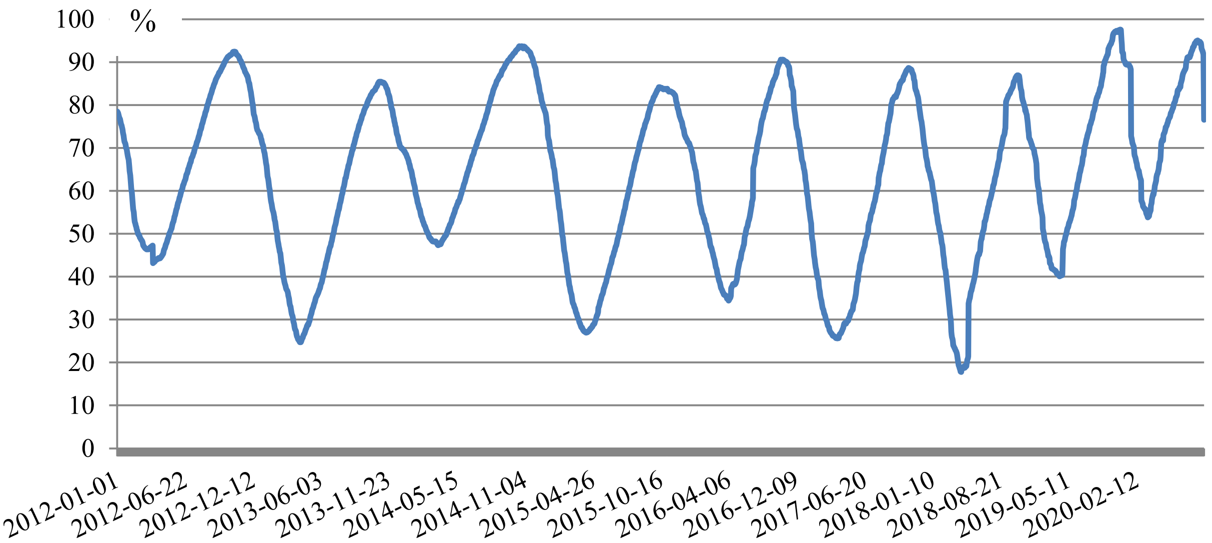


Figure 2-1 EU-28 underground gas storage use (%) (Source: Elaboration of the author based on [52])

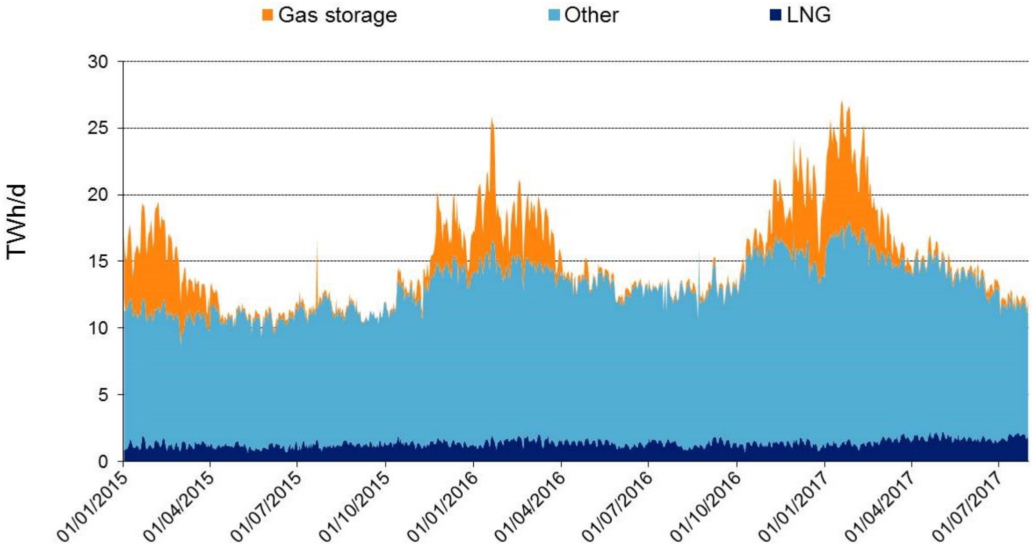
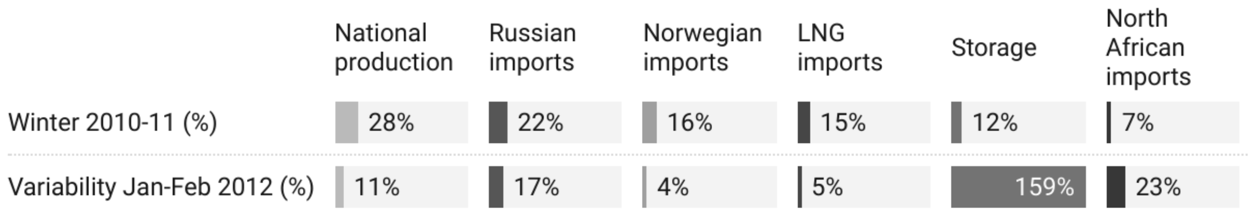


Figure 2-2 European Gas Flows 2015-17 (Source: [53])

Moreover, additional factors may increase the importance of commercial storage as a tool to provide flexibility, such as increased dependence on imports from more distant sources, reduced reliability of producers (geopolitical and commercial aspects), increased volatility of demand for power generation, and the need for "fast-flexibility". To this end, each flexibility measure has a specific reaction time and spatial dimension, so that if an unexpected peak in demand occurs, some of these measures, even though cheaper, might not be suitable. That is the case with storage favored over other flexibility measures to deliver additional volumes when a need for a quicker response measure arises [45].

Responses to peak demand will vary depending on the system that needs to respond and can change through time depending on boundary conditions, such as a change in the energy mix. Hence, a flexible reaction is influenced by different factors, such as the existence and amount of indigenous production, the presence and volumes of commercial gas storage, the source and type (e.g., pipelines or LNG) of supply, how demand is constructed, and its degree of interruptibility.

As Le Fevre [44] stresses, the importance of commercial storage lies also in allowing for a flexible reaction during moments of heavy demand. In particular, even though storage had a lower impact in total terms as a percentage of total European supply sources (12%) in winter 2010-2011, it was critical during the extreme cold winter (January-February) of 2012, and subsequent disruption from Russian supplies, where it was accounted as the joint highest source of supply to Europe (159%) (see Figure 2-3).



	National production	Russian imports	Norwegian imports	LNG imports	Storage	North African imports
Winter 2010-11 (%)	28%	22%	16%	15%	12%	7%
Variability Jan-Feb 2012 (%)	11%	17%	4%	5%	159%	23%

Figure 2-3 European supply source breakdown and flexibility (Source: Elaboration of the author based on [44])

Market players have a number of incentives to keep gas in storage, making it a cost effective solution to flexibility issues. On the other hand, some MS already have stock obligations they need to fulfill, even though legal requirements differ from state to state. Only three out of the eleven countries, representing 80% of the total EU storage working gas capacity, do not have storage obligations: the UK, Germany and Austria (Figure 2-4). The amount of stockholding in each of these countries varies from 3% of national consumption in the Czech Republic to 25% in France [45].

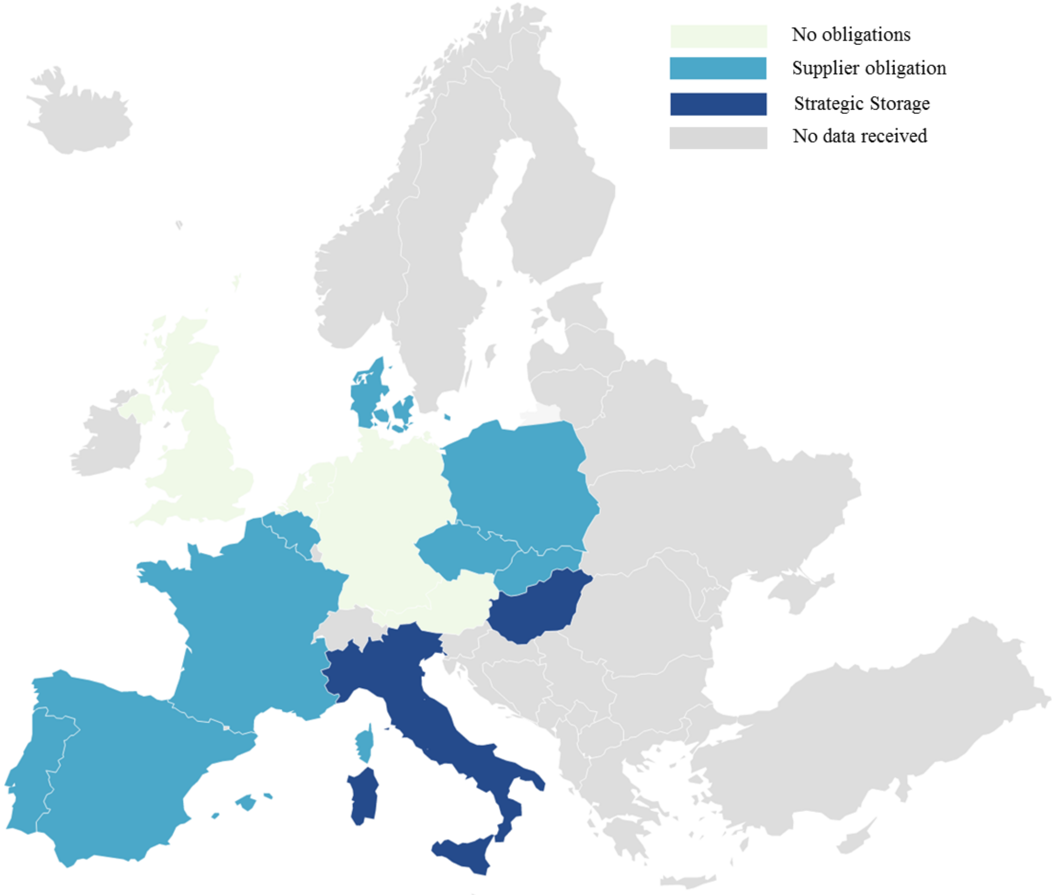


Figure 2-4 Mandatory storage security of supply interventions in the EU by type (Source: CEER, 2014) N.B. Hungary has both storage obligations and strategic storage.

Bulgaria, the Czech Republic, Denmark, France, Hungary, Italy, Poland, and Spain all have storage obligations that see either gas suppliers, storage users (in Denmark), or the consumers directly connected to the transmission grid (in Spain), being accountable for them. This means that these Member States are required to have a given amount of gas stock ready to use when needed. Moreover, not only do gas suppliers in France need to store gas, but they also have an obligation on the minimum withdrawal capacity to hold as well (see Table 2-3).

Table 2-3 Overview of mandatory storage Security of Supply intervention in selected EU Member States (Elaboration of the author based on [25,45])

Member State	**Storage obligation (SO) and Strategic storage (SS), where available**
Austria	N/A
Bulgaria	SO The main supplier (Bulgargaz) is obligated to store the gas amount needed to protect suppliers and to cover seasonal shortages. Criteria to establish those quantities are not disclosed. Capacity is 887 GWh in 2016.
Czech Republic	SO Market parties, namely suppliers, are in charge of fulfilling at least 20% of the supply standards using underground storage facilities. Capacity is 798 GWh in 2016.
Denmark	SO Obligations are fulfilled via market-based tools. TSO (Energinet) pays storage users to keep volumes stored during winter, which can only be used in emergencies. Criteria to determine such amounts are not disclosed. Storage capacity is 762 GWh.
Germany	N/A
France	SO Market parties (suppliers) are obliged to store starting from at least 80% of the estimated seasonal storage rights by November 1st, which are

	based on the consumers’ climate zone and metering frequency.
Hungary	SO + SS Both measures are in place, accounting for 24% of annual domestic gas consumption. As part of the SO, all suppliers are required to store 10% of total gas sales irrespective of their aggregated consumption or source portfolio, whereas distribution system operators (DSO) and TSO have to store less than 1% of total consumption, divided as follows: 20% of their network losses gas within a gas year for DSO, and 20% of their network losses plus compressor fuel gas within a gas year. A dedicated storage facility, Szöreg, is partially reserved as strategic storage.
Italy	SS Storage companies take shared storage capacity off the market and commit it to strategic reserve. All costs of the storage gas reserve are bared by domestic producers and importers. The Ministry determines the quantities, which have averaged around 16.312 GWh over the past five years.
Poland	SO Importers are required to maintain a stock of stored gas equivalent to at least 30 days of the average daily imports. The entire amount of mandatory gas has to be able to be injected into the grid within a period of no more than 40 days.
Spain	SO Gas suppliers and direct consumers have to keep storage reserves equivalent to 20 days of their firm sale/consumption as estimated from the sales of the previous natural year (16.950 GWh in 2016). Moreover, the Spanish Government requires them both to keep operative reserves as follows: 1. Volumes equivalent to 2 days of firm sales, computed as the average daily sales from April 1st to March 31st, which can be held in regasification facilities as well.

	2. Volumes equivalent to 8 days of firm sales, computed as the average daily sales in October from year n.
UK	N/A

Depending on the country, storage that accounts as a security reserve can be located within national boundaries or abroad. If the supplier guarantees the transmission capacity, some Member States, such as Poland and Czech Republic, allow the reserve to be located outside the nation. In Poland, in particular, the volumes must be able to be delivered to the national distribution network in no more than 40 days. On the other hand, some Member States, such as Spain, require that reserves which are considered strategic are located inside national boundaries unless those reserves are subject to a bilateral agreement.

The volumes to be put aside are set every year, whereas the criteria to determine how much gas should be stored last longer. Although some Member States (i.e., Bulgaria and Denmark, have not disclosed them), the known criteria vary from member state to member state and generally share the following common characteristics:

1. Demand of protect customers in winter. In France, this translates into storage obligations being proportional to “storage rights” attributed to protected customers. Gas suppliers need to stock 80% of the estimated seasonal “storage rights” by the start of the heating season.
2. Assure a certain quantity of gas, either imported or past firm sales based, in a given period. This happens in Poland, where gas suppliers have to keep in storage gas volumes to cover 30 days of the average daily imports, and in Spain, where gas suppliers need to keep in stock 20 days of their firm sale /consumption.
3. Stock a percentage of total consumption. In Hungary, it accounts for 10% of yearly consumption.
4. Meet supply standards with gas stock. In the Czech Republic, underground storage needs to account for at least 20% of the supply standards.

Unlike storage obligations, where an obligation is placed on market participants to have an amount of gas stored, forecasting the need to balance tensions between supply and demand, and hence helping mitigate possible market failures, strategic storage is a pre-fixed volume of gas taken out of the market (Figure 2-5). Across the EU, only Hungary and Italy have special strategic storage reserves. Further, Hungary is the only member state that requires both a strategic storage site and storage obligations on suppliers, as a consequence of its high dependence on natural gas, mostly imported from Russia, and the 2006 and 2009 Ukrainian crises. Hungarian and Italian storage serves as a buffer in the event of a market failure or an emergency, or to safeguard the transmission system's integrity in extreme circumstances, and it can only be utilized to meet the requirements of protected consumers.

In Hungary, obligations and strategic storage represent 24% of the annual domestic consumption, with 4.255 GWh of volume stored as a strategic stockpile, which can be used only to supply households and communal consumers in emergencies. This volume is calculated based on 45 days of protected consumer consumption. The EC estimates that Hungarian strategic storage costs 85 million euros/year, whereas the cost of Italian strategic storage, with a working gas size of around 16.312 GWh, is 60 million euro/year [45]. The higher costs of the Hungarian strategic storage, as opposed to the Italian one, might be due to the geological nature of the Szoreg facility, an oil field with a gas cap, which is the only Hungarian dwell allocated to hold the strategic reserve in the country.

1. Strategic Storage: a certain level of non-market gas volumes
(e.g., 4.255 GWh in Hungary)

2. Storage Obligations: a share of the expected consumption
(e.g., 20% of supply standard in Czech Republic)

Figure 2-5 Strategic Storage vs Storage Obligations (Source: Elaboration of the author based on [54])

In Italy, the amount of gas to be kept in strategic storage is set yearly by the Ministry (16.383 GWh in 2017), which is the only one that can authorize its utilization. In any case, reserves cannot be lower than: "a) volume necessary to enable the supply of up to 100% of the largest imports from the most widely used import infrastructure for at least 30 continuous days throughout the seasonal peak season; b) volume needed for modulation in the case of hard winter, calculated for the hardest winter in the last 20 years." (Legislative Decree 164/2000 art.12.11-ter and subsequent Legislative Decree 93/2011 art.27 11-ter) [55,56]. Italian reserves have been tapped in 2004/2005 and 2005/2006, contributing to the total consumption by 15% and 24% respectively. In both Hungary and Italy, the volumes are taken out of the market. In the latter, strategic stockpiles are charged to domestic gas producers and importers (Legislative Decree 93/2011 art.27. 11-bis) [56]. Whereas, storage capacity costs are charged to storage companies (SSO), which offer this service under a regulated regime. SSO are compensated for the stored capacity through a fee paid by all importers and domestic producers, which bear all the costs of the strategic gas reserve. In particular, SSOs are allowed to receive a regulatory rate of return on the value on the capital they invested in strategic storage volumes [45].

Both mandatory storage interventions (storage obligations and strategic storage) have been introduced in most of these countries in the 2000s, beginning with Spain in 1998, to the Czech Republic, which instituted them only recently, in 2013. These obligations have evolved over time, both with regards to strategic capacity that needs to be stores and the entity responsible for holding it. Italian strategic storage saw a 10% decrease from its initial levels (from 19.468 GWh to 15.886 GWh in 2012). In France, obligations on suppliers went down to 80% from 85% of "storage rights". On the other hand, in Spain, the responsibility of keeping the gas in storage shifted from the TSOs to the suppliers, and the obligations on reserves grew from 10 days of firm sales to 20.

The natural gas market liberalization offers storage both challenges and opportunities. A major challenge, as seen above, comes from the unbundling of activities that can force storage to compete with other sources of flexibility, which in turn can lower the underlying asset value of storage, especially in the case of an initial over-investment. Another challenge arises from the tendency of shippers to resolve imbalances not through physical flexibility, but by trading at liquid hubs. As Le Fevre [44] points out, under-booking storage in favor of trading to balance the system might result in lower storage capacity, resulting in a system that is less able to deal with high-impact, low-probability events. On the other hand, exploiting trading opportunities is a mechanism to extract value by utilizing a storage asset, taking advantage of both seasonal spread (i.e., buying and injecting gas in summer when the prices are low and withdrawing it in winter when prices are high), and flex spread (i.e., in times of high volatility capitalizing on the difference between spot and future prices).

As highlighted, multiple functions such as seasonal flexibility needs, short-term flexibility needs, price volatility or price spread, insurance value against supply disruptions or price spikes, production needs, balancing needs, and mandatory security of supply measures, can incentivize market players to book storage capacity. Two types of flexibility offer the opportunity to overcome two different demand peaks: capacity (power) and energy (quantity). The first is short-term and relates to how fast the gas can be withdrawn to cope with demand needs, whereas the second is more seasonal and relates to volumes needed to meet demand spikes. Hence, drivers to storage use and development can be summarized as follows: winter/summer spread (fundamental price signals of the value of flexibility), hub price volatility that might originate trading opportunities, availability and costs of alternative flexibility measures competing with storage, yearly swing consumption variations due to a number of factors (e.g., changes in the demand mix, different weather conditions, etc.), and SoS measures [45].

Finally, looking at the gas supply disruptions that invest Europe over the past 20 year, Skea et al. [40] investigates the advantages of investing in gas infrastructures in the UK market, finding that strategic investment in gas storage may possibly considerably alleviate supply shock in the nation. As a result, factors other than price incentives can contribute to gas storage becoming a significant insurance instrument for providing flexibility, such as the insurance value of storage against unexpected events and the lack of seasonal alternatives (e.g. LNG), mandatory strategic storage, share of storage capacity already allocated long-term, and reputation loss in the event of supply disruptions.

When dealing with supply shocks or unexpected demand spikes, framing the concept of energy security becomes paramount. This will be investigated in more detail from three complementary perspectives: policy, natural gas supply chain, and modeling - respectively in Sections 2.2, 2.3 and 2.4 - setting out the background for the three main applications related to energy security in the natural gas supply chain studied in this research.

2.2 The concept of gas energy security from a policy perspective

Since most EU MS are relying heavily on natural gas, and the volumes of imported natural gas is expected to increase up until 2030 with little diversification, potential disruption in the natural gas supply threatens European economic growth, development, sustainability, and survival for both fuel importers and suppliers [2,5]. Security of supply, protection of the environment, and economic efficiency are the three main dimensions of the EU energy policy [57]. Recent events in the geopolitical arena (e.g. the 2014 Ukraine – Russia conflict), coupled with the carbon constrained policy roadmap of the EU, have called into question the first two of these energy policy dimensions. This has forced the political agenda of the EU to focus on the issues surrounding the uncertainties of gas markets and energy security, and in particular the security of supply in the context of gas markets, as some of the most pressing to be deal with in its energy mix.

Since 1980, the EU has been trying to shape the institutional framework of its gas system, but so far without reaching a clear end to this process (see Table 2-4). Back in 1980, the concept of privatization and liberalization of the European gas market raised the political agenda. Elements then missing from the market were, among others: competition (i.e., unbundling), cross-border integration, and harmonization [58].

As Boersma [59] identifies in his analysis of the status quo in the EU energy policy, the objective of the EU reforms for two decades, starting in the early 1990s, has been to focus on the market with a twofold approach: completing the internal market and creating a competitive natural gas market. This has been followed by attention to the impact of other compelling aspects of the energy system, such as infrastructure and regulation, to ensure security of supply and create a self-standing and competitive internal market [19]. The struggle between MS' national powers and European Commission (EC) supra-national powers, when it comes to energy policy, has been such that it is hard to identify who is actually driving the process of integration in the EU market. Pushing and pulling to find compromises, this dichotomy is slowing down the completion of an internal energy system process.

Looking at the last decade of European energy directives and regulations, there are a few milestones that have marked the path of reforming the EU energy scenario, starting with the First Gas Directive on gas market (98/30/EC), to the latest Regulation 1938/2017 in early 2017, incorporating environmental and security aspects into the discourse.

The First Gas Directive went into effect on August 10, 1998. As Kopp [21] observes, the Directive was a timid attempt to set common rules for the transmission, distribution, supply and storage of an internal natural gas market. To begin with, MS still had different views on the advantages of liberalization of the market over the established monopoly system. Moreover, several aspects, although introduced and touched upon, were not completely resolved by the Directive: TPA, whether MS could choose between regulated or negotiated TPA; gradual market opening within MS; and diminished market power of main integrated players to prevent cross-subsidization and foster competition. The Directive was just partially laying down the basis for the separation between transmission and supply, but at this stage the separation was only based on companies' accounts of gas and non-gas activities.

In light of the substantial flaws of the First Directive, in 2003 the EC introduced the Second Gas Directive (2003/55/EC), taking first and foremost a clearer position on integrated energy companies' unbundling to correct market distortions and increase transparency. In addition, the EC emphasized the importance of consumers in a well-functioning market, who were allowed to freely substitute gas suppliers, and who benefitted from the creation of a mechanism to prompt transparent contract conditions and to settle disputes [9].

The Directive also called on Member States to select systems operators to invigilate safety, reliability, and interconnection facilities, as well as independent regulators to monitor transparency, discrimination, levels of competition and tariffs. This ultimately led to the creation of the Agency for the Cooperation of Energy Regulators (ACER) in 2009.

Once again, the EC identified significant shortcomings in the structure and (partial) implementation of the new legislation, resulting in the 2009 development of the so-called Third Energy Package, which became effective in March 2011. It was comprised of two directives and three regulations, with the objective of providing a cohesive framework to complete an internal market. The Package tried to intervene on elements that were still not functioning, such as infrastructure congestion and effective unbundling of companies across the EU. Specifically, the objective of Directive 73/2009 and Regulations 713 and 715/2009 was to increase consumer rights as well as to stress the importance of common rules for an internal natural gas market. They looked into facilitate cross-border trade, spur infrastructure investments and improve coordination at the EU level. The end goal was the harmonization of the natural gas market, with price signals, dependent on supply and demand, determining the flows of the commodity [10–12].

In particular, Art. 9 of Directive 73/2009 dealt with the pressing issue of unbundling, giving the option of Independent System Operator (ISO) or Independent Transmission Operator (ITO) aside from the full ownership unbundling. The main difference, as Boersma [19] points out, lays in the "unchanged balance sheet of integrated companies", leaving companies with strong financial pressure.

To improve the liquidity of the gas market, the Package included several provisions, among others: on separating transmission assets from production and supply activities; on contract path establishing tariffs; on entry-exit networks access model for shippers to book capacity independently at entry and exit points; on certification procedures for TSO in line with unbundling obligations; and on technical rules for network operators, with guidelines on transparency, capacity allocation, gas balancing and trading, network security, reliability and connection, TPA, and interoperability (i.e., twelve Network Codes, only five of which were finalized by 2016) [21].

To this end, a Gas Target Model (GMT) has been developed "not only to [guide] the coherent implementation of the Network Codes, but also to [specify] the steps required to realize liquid and dynamic gas markets thereby enabling all European consumers to benefit from secure gas supplies and effective retail competition" [60]. Since 2012 the model has been undergoing reviews, the latest of which was in 2015 by ACER. With this review, ACER took into account the above mentioned drastic changes the gas market has been going through in recent years, starting from an uncertain demand picture (i.e., the American shale gas revolution, cheaper coal, and low emission allowance price); to a decreasing supply (i.e., declining European production and slow rising of unconventional gas supply); and finally to security of supply concerns [60].

On the other hand, Regulations 113 and 115/2009 focused more on infrastructure and specific regulation aspects dealing with TPA and transparency obligations. In addition, they established both ACER, a European institution, and the European Network of Transmission System Operators, both for the electricity (ENTSO-E) and gas market (ENTSO-G) [11,12]. ACER was created to improve the current regulatory framework, the latter two to spur cooperation with transmission companies. ENTSO-G was asked with developing codes to address cross-border investment and interoperability, which, although not substituting for national codes, are now giving the EC a wider supra-national perspective on developing a pan-European transmission system, looking both at the technical and financial evolution of infrastructures.

Organizations such as ACER, the European Regulators Group for Electricity and Gas (ERGEG), the Center of European Energy Regulators (CEER), ENTOS-E and ENTOS-G, have been establishing since 2000 by the EU, either voluntarily or by law, with the intent for them to offer recommendations and cooperate with the Commission to complete the internal energy system. However, even with the support of such organizations, it is hard to reach a consensus on the need for infrastructure at the EU level. Infrastructure considerations have been included in the EC strategy of ensuring energy security since 1996 with Decision 96/391/EC [61], but the lack of agreement between MS on how to approach the issue has made it difficult to reach consensus on projects of common interest in the cross-border infrastructure network and on their priority, under the so-called TEN-E (Trans-European energy network) Guidelines, which identify nine priority corridors.

The aim of these guidelines, recently included in Decision 1364/2006/EC, which was subsequently repealed by Regulation 347/2013, was that of contributing to effective interconnection and interoperability in the EU energy system, linking remote regions more effectively via enhanced territorial union. However, insufficient progress was made in this direction and many projects have been delayed or withdrawn.

Failure of investment to support these projects was ascribed by the EC to lack of a common regulatory framework to coordinate them. In addition, the lack of mechanisms to coordinate technical standards, the need to balance rules and gas quality, and the insufficient level of unbundling claimed by some MS, were posing a threat on the construction of a truly single EU market.

With this in mind, the European Parliament and Council decided to establish the European Energy Program for Recovery (EEPR), to financially sustain and foster the accomplishment of the EU energy and climate policy targets, but the results have been debatable. As Boersma [19] points out, in October 2014 MS agreed to allocate financial resources to six construction projects out of 248 projects of common interested listed in October 2013. Of these six projects, only three received funds for physical construction of infrastructure: an interconnector in Scotland, a gas transmission pipeline in Lithuania, and an interconnector between Poland and Lithuania for a total of approximately €356 million on a total estimated required budget of €200 billion. This highlights the significant degree of fragmentation of infrastructure companies at the EU level and of disagreement at the member state level in addressing the issue. Moreover, this underlines the necessity of creating a body, such as ENTSO-G, focused primarily on cross-border investments and interoperability to deal with lack of cooperation and common intents, providing a "more European" perspective on the issue [19].

According to Aalto and Temel [62], "[…] the EU's conception of energy security reveals a new agenda combining security of supply (SoS) (amount, time, location) and price, with wider environmental and social concerns", overlapping with the more market oriented principles established so far. In their analysis, the authors also point out how the concept of energy security in Europe has been evolving in a solidarity direction, moving from self-interest and mere coexistence of Member States to a cooperative union in the 90s, to what they define as a more "converging energy security society" with the Third Energy Package in 2009. This is true, at least internally more than in the external energy relation of the EU. As seen, the EU has in fact liberalized its internal gas market and called for coordination in SoS measures and external energy relations, as well as committed to fight climate change [62].

However, despite efforts by the EC, energy security is still an issue that remains framed mostly with a national perspective [62]. Since the early 2000s, from the Gas Security of Supply Directive 67/2004 to the Gas Regulation 994/2010, the EC has been trying to shift responsibility from the national to the EU level. However, even if policies and legislation have tried to shift the paradigm, their contribution to European energy security has been limited [13,63].

Both Directive 67/2004 (Art. 4) and Regulation 994/2010 (Art.8) dealt with requirements to cope with disruptions of natural gas supply to "ensure natural gas to the protected consumers" in three main circumstances: "a) extreme temperatures during a 7–day peak period occurring with a statistical probability of once in 20 years; b) any period of at least 30 days of exceptionally high gas demand, occurring with a statistical probability of once in 20 years; and c) for a period of at least 30 days in case of the disruption of the single largest gas infrastructure under average winter conditions- determined according to the so-called N-1 indicator" (see Regulation 994/2010, Annex I for calculation formula) [13,63].

In addition, the main objective of Regulation 994/2010 is to secure gas supply by exceptional measures when the market is unable to deliver the required volumes of gas. To this end, Art.10 of the Regulation introduces three crisis levels to help classify the intensity of the emergency: a) early warning (signal of possible disruption, but no real event); b) alert (interruption, but the market is still able to cope with it), c) emergency (market interventions are not sufficient for supply to meet demand). This last level can be categorized by HILP) events [13,20].

Regulation 994/2010 represents the "basic building block of gas supply security across the EU". It indeed mandates the provisions and supply standards each member state needs to have in place to analyze its readiness to cope with gas supply disruptions. These include the N-1 standard to measure threats to the EU gas supply; the permanent bi-directional capacity (i.e., reverse flow and obligations) or the Risk Assessment, the Preventive Action Plan, and the Emergency Plan [64].

Notwithstanding all the efforts to create standards and categories to classify emergencies, as Zeniewski et al. [65] observe, there are three main aspects on which MS interpret Regulation 994/ differently: procedures and criteria to define crisis levels, who assesses whether there is a crisis or not; when and how to issue non-market measures. For instance, where the Regulation mandates three crisis levels, France has only one, versus four in Poland and five in Ireland. With respect to who is declaring the crisis status, depending on the State, it could be a crisis manager, as in the case of Ireland, a TSO, as in Belgium, or a regulator, as in Germany. Finally, when it comes to non-market based measures, in Austria they can be put in place only when crisis level three has been reached and all other measures have failed, while in France the government can manage the emergency at any time.

The main takeaway from the Zenewski et al. [65] report, which Boersma [19] highlights, is that "…in most cases…emergency plans treat supply disruptions as exogenous and focus on domestic response options. Few national policy makers have thought of increasing imports of natural gas from neighbors as a viable strategy… and there was little emphasis in the preventive action plans on building resilient networks that take a regional approach." [19]. Not only do Member States emphasize domestic security responses, ignoring in most cases cooperation among nations, but there have been cases, such as in Slovakia, where transnational actions were banned.

Nonetheless, from 2014 ENTOS-G Energy Stress Tests (EST) emerged that SoS can be substantially enhanced by the coordination of the measures adopted by Member States in emergencies. The tests assessed the impact on the EU energy system in case of complete interruption in supplies from Russia or a disruption in supply through Ukraine, for either 1 month or for 6 months in winter, with a "non-cooperative" and a "cooperative" scenario. Results showed a strong impact on Eastern Member States, and other states in the Energy Community suffered a 60% reduction in gas needed. Following the outcome of the tests, the Commission concluded that in a functioning market, market-based measures to cope with disruptions should be the guiding principles, but non-market measures in a cooperative scenario, one with equal (relative) burden sharing, are paramount in emergencies when the market fails. Hence, government intervention should be planned on a regional-basis and only utilized in those emergencies when the market fails. The model regarded commercial storage as a key measure to secure supply, but pointed out that long-lasting crises could empty storage reserves quickly; hence the need to employ other SoS measures to safeguard consumers [14,66].

Although trying to construct a single standard that could work for all Member States might have been unrealistic, since perceptions of security and level of import dependence (to name just a couple of factors) differ from Member State to member state, the final step contributing to the development of an Energy Union has been the so-called 2016 Energy Security Package, which aimed to provide a common guidance to Member States on how to implement internal, but mostly external policy objectives to foster a tangible integration among states .

As seen so far, the focus in the development of the EU Energy Security related policies up until the second half of the 2010s has been "internal objectives". As the EU is very much dependent on external imports, it reacted by bringing forward internally-oriented SoS policies, focusing on internal sources of supply and on security of transit inside the EU, to cut dependency on external imports. Thus far, the measures promoted by the EU on energy security have been moving in the direction of enhancing domestic production, diversifying energy sources (RES Directive), completing the internal energy market (Third Energy Package and Network codes), improving internal lacking infrastructures to smooth transits within Europe (Infrastructure Package and PCIs), and, on the internal demand side, further developing energy efficiency (Energy Efficiency Directive).

With the Energy Security Package in 2016, then Regulation (EU) 2017/1938, the EU moved a step forward in tackling the external dimension of energy security, which deals with external sources of supply and their transit beyond the borders of the EU (e.g., Morocco, Algeria, Turkey, Ukraine or Belarus). The Package comprises both legislative texts, such as the proposal for repealing Regulation 994/2010 on Security of Gas Supply and the Decision on Inter-Governmental Agreements, and non-legislative texts, such as the EC Communications on LNG and Storage Strategy and the Heating and Cooling Strategy. To ensure that national choices on security of supply do not have a negative impact on other neighboring Member States, the new regulation tries to mend the dichotomy between Member States' powers and those of the EU, introducing a solidarity principle and mandatory regional prevention and emergency plans to strengthen regional cooperation [14–18].

To this end, Member States will have to ensure better coordination in assessing common risks, possible simultaneous crisis, and available resources through the mandatory writing of Risk Assessments, Preventive Action Plans and Emergency Plans, already introduced by Regulation 994/2010. The writing of these documents is to be coordinated at the regional level using a common template, and their content needs to be updated every four years. The Emergency Plans will have to include the technical, legal and financial agreements, which can allow Member States to implement the solidarity principle in case a crisis is declared. In addition, Member States will have to collectively decide where to build reverse-flows at each cross-border interconnection point and to involve all Member States along each associated supply line in this decision.

As far as cooperation is concerned, EU Member States will be divided into regions based on their geographic proximity, common supply lines and interconnection of their energy systems. To improve interconnectedness among states and regions, infrastructure standards have also been addressed by the proposal, which would make it more difficult for Member States to be exempted on bidirectional capacity. The EU has been divided into seven regions [15] as follows:

- North West: United Kingdom and Ireland;
- North-South Western Europe: Belgium, France, Luxembourg, Spain, The Netherlands and Portugal;
- Southern Gas Corridor: Bulgaria, Greece and Romania;
- Central-East: Czech Republic, Germany, Poland and Slovakia;
- South East: Austria, Croatia, Hungary, Italy and Slovenia;
- Baltic Energy Market I (BEMIP I): Estonia, Finland, Latvia and Lithuania;
- Baltic Energy Market II (BEMIP II): Denmark and Sweden;
- Cyprus;
- Malta, when connected to another Member State, will be considered as part of the region of that Member State.

Various criteria have been adopted to divide MS into these four geographical regions, which can be linked to market or network adequacy. Under the latter indicators such as current and planned interconnections or interconnection capacity can be found, whereas criteria such as supply patterns and market maturity fall under the former. However, regional cooperation structure with geographical proximity criterion remains the predominant criteria adopted [24].

As Aoun and Rutten [64] points out, geographical proximity does not determine the energy flexibility of a country and its ability to absorb supply shocks. However, for MS to promptly respond to disruptions, key components to take in to account to properly aggregate them are: country-specific security of supply needs; its energy profile; and the relative importance of gas in its energy mix. And according to the authors, the current proposed regions do not take into account “the reality on the ground” and do not consider the “heterogeneity of Member States’ energy mixes” [64].

Some concerns relate to the fact that North and South-West markets have been put together based on the assumption that all of them are mature markets. This leaves Spain and Portugal isolated. Further, the groups have been created based on a one-sided picture of SoS, where the premises where of Russian gas restrictions, but ignoring the likelihood of other types of supply disruptions. Again, the fact that different types of supply risks require different responses by MS has been ignored, especially in the case of supply shocks originating at the local level. Indeed, a disruption of gas supplied by Russia calls for different cooperation than that of an LNG disruption. In the first case, France and Germany would have to cooperate, whereas in the second one, cooperation among The Netherlands, France, Belgium and Germany might be needed [64].

Finally, although in its opinion the European Economic and Social Committee welcomes the idea that the Commission should coordinate action when necessary and of a three-layer approach between gas undertakings, MS and the EU when it comes to the security of gas supplies, it stressed the importance of some MS belonging to more than one region simultaneously. It also noted that the stress test conducted in 2014 [67] showed how a major disruption of gas supplies from the east MS would still have a severe impact throughout the whole EU [68].

Critiques have led to a revised regional division in Regulation 2017/1938, which resulted from negotiations on the Security Package proposal. In Annex I, four regional risk groups based on the major transnational risks to the security of gas supply and on the main gas supply sources and routes in the Union were formulated [18]:

1. Eastern gas supply risk groups:

(a) Ukraine: Bulgaria, Czech Republic, Germany, Greece, Croatia, Italy, Luxembourg, Hungary, Austria, Poland, Romania, Slovenia, Slovakia;

(b) Belarus: Belgium, Czech Republic, Germany, Estonia, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Slovakia;

(c) Baltic Sea: Belgium, Czech Republic, Denmark, Germany, France, Luxembourg, Netherlands, Austria, Slovakia, Sweden;

(d) North-Eastern: Estonia, Latvia, Lithuania, Finland;

(e) Trans-Balkan: Bulgaria, Greece, Romania.

2. North Sea gas supply risk groups:

(a) Norway: Belgium, Denmark, Germany, Ireland, Spain, France, Italy, Luxembourg, Netherlands, Portugal, Sweden, United Kingdom;

(b) Low-calorific gas: Belgium, Germany, France, Netherlands;

(c) Denmark: Denmark, Germany, Luxembourg, Netherlands, Sweden;

(d) United Kingdom: Belgium, Germany, Ireland, Luxembourg, Netherlands, United Kingdom.

3. North African gas supply risk groups:

(a) Algeria: Greece, Spain, France, Croatia, Italy, Malta, Austria, Portugal, Slovenia;

(b) Libya: Croatia, Italy, Malta, Austria, Slovenia.

4. South-East gas supply risk groups:

(a) Southern Gas Corridor — Caspian: Bulgaria, Greece, Croatia, Italy, Hungary, Malta, Austria, Romania, Slovenia, Slovakia;

(b) Eastern Mediterranean: Greece, Italy, Cyprus, Malta.

From the Security Package, Regulation 2017/1938 is moving towards more Europeanization and regional approaches and away from national ones, in line with Part 3, Title XXI, Art. 194 1. (a), (b) and (d) of the Treaty on the Functioning of the European Union (TFEU) of 2007, which states [69]: "1. In the context of the establishment and functioning of the internal market and with regard for the need to preserve and improve the environment, Union policy on energy shall aim, in a spirit of solidarity between Member States, to: (a) ensure the functioning of the energy market; (b) ensure security of energy supply in the Union; (c) promote energy efficiency and energy saving and the development of new and renewable forms of energy; and (d) promote the interconnection of energy networks." [69].

As Giuli [34] highlights in his commentary on the Energy Security Package, there are two main issues when trying to implement a solidarity principle among MS on the path to an Energy Union: MS' heterogeneous views on the concept of energy security, and the weak position of the EU on MS' jurisdiction when it comes to external supply choice. In fact, according to the TFEU Part 3, Title XXI, Art. 194: "2. Without prejudice to the application of other provisions of the Treaties, the European Parliament and the Council, acting in accordance with the ordinary legislative procedure, shall establish the measures necessary to achieve the objectives in paragraph 1. […] Such measures shall not affect the right of a Member State to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply…" [69] . External supply choice remains a national prerogative, which could put the nearby MS' gas security at risk considering they will have to take collective security obligation in case of major disruptions [34].

Although it has to be acknowledged that the 2017 Regulation favors market mechanisms as security measures over compulsory solidarity ones, until a full implementation of a liquid internal gas market is in place, developing an EU market for what Tagliapietra et al. [25] calls a “gas security margin” could be a more effective measure. The authors argue that there is a need for a systemic approach in dealing with supply disruptions, moving away from supply diversification and reduction of dependence on imported gas towards protecting and maintaining less used alternatives, such as natural gas storage, so that when disruption occurs, those can be utilized to safeguard supply security. Their focus is on both unused available options and on the need to reduce the European fragmentation when it comes to security of supply measures from a policy and technology standpoint. They propose to create an EU market for a gas security margin that will extend to all MS the mandatory gas storage obligations currently enforced in some of them, including all gas systems flexibility options. According to Tagliapietra et al. [25], the design of such a gas security margin would operationalize the supply standard, as in Art.8 of Regulation 994/2010/EU, “prevent[ing] double counting and reduc[ing] the cost of the standard itself and shield the internal market” [13].

In the 2016 Security Package and subsequent Regulation 2017/1938, gas storage has indeed been identified as a possible supply-side non-market based measure to support SoS [14–18]. The European Parliament underlines the importance both of cross-border accessibility of gas storage to implement solidarity during supply emergency, as well as of finding ways of strategically and effectively using such an asset at the EU and regional level. Furthermore, it highlights how a regional concept of storage can only be achieved by eliminating existing regulatory barriers [17]. However, before moving forward to analyze the potential of coordinated strategic gas storage security measures at the EU level, the concept of energy security and the topic of metrics and models to frame energy security within the gas market require further investigation to help frame the boundaries of the problem and will be discussed in the following Section 2.3 and subsequently in Section 2.4.

Table 2-4 Evolution of the concept of energy security in the EU policies over the last 30 years

Year	**The 90s**	**The 2000s**	**The 2010s**
Policy	**First Gas Directive** 98/30/EC [8]	**Second Gas Directive** 2003/55/EC [9] **Third Energy Package** (Directive 73/2009; Regulations 713 and 715/2009) [10–12]	**Gas Regulation** 994/2010 [13] **Energy Security Package** 2016 [34–37] **Regulation** 2017/1938 [18]

Evolution of energy security	Completion of the **internal gas market** and creation of an **internal competition**	**Infrastructure and regulation** to ensuring security of supply and creating a self-standing and competitive **internal market**	Towards a more **“converging energy security supra-national society”:** cooperation, coordination, **solidarity**
Implications	- Gradual market opening within MS - Regulated or negotiated Third Party Access - Separation process between transmission and supply	- Energy company unbundling - Central role of consumers - Operators and regulators (e.g., ACER) to monitor transparency, discrimination, levels of competition and tariffs	- Common rules, harmonization and liquidity of the internal natural gas market - Regulations dealing with infrastructures and Third Party Access and transparency obligation - Creation of European Network of Transmission System Operators (electricity (E) and natural gas (G)) - Requirements to collectively cope with disruptions of natural gas supply both internally and externally

2.3 Definition of energy security in the natural gas supply chain

The initial (1990-2010) focus of the EC on the market component rather than on the other vital components of the energy system, such as infrastructure and regulation, reflects the bulk of academic contributions to the debate on energy security. Only in recent years has the literature been diversifying and introducing broader analyses of the EU energy systems. It is important to note that infrastructure investments and the design of regulatory regimes are a national matter and the shift to bring them to a supranational level has been irresolute, hence making it difficult to discuss it with a more inclusive perspective [19].

In addition, there is a consensus among authors in the field that, although the broader concept of energy security has increased in popularity over the years, there is a lack of methodological development to evaluate as well as unequivocally define the concept. Theoretical contributions to the concept are focusing on different aspects on two main fronts: definitions and metrics for energy security [30,70–72].

These contributions agree on the idea that energy security is polysemic in nature, contextual and dynamic, hence there is a "need for conceptual clarity to support rational policy analysis and international comparison" [73]. Moreover, further limitations to the concept of energy security are imposed by different and constantly changing interlinked factors that as a result frame its definition, such as: energy sources, "eyes of the beholder", energy market heterogeneity, geographical location, scientific background of researchers, temporal dimension, intended audience, and purpose/context of the analysis.

As Luft and Korin [74] point out with the phrase "eyes of the beholder", the coexistence of many different meanings for energy security can refer to stakeholders' different perceptions of the concept, depending on their interest and position in the value chain: countries, continents, regions, end-users, importers, exporters, shippers, traders, distributors, retailers and so on.

A distinction, for instance, can be made between consumers, or energy importers, and producers, or energy exporters [74]. The former seek security of supply and low prices, striving for diversity of energy supplies, to minimize by availability of alternatives the impact of a supply disruption. The latter look for security of demand, so that their production will be purchased consistently over time resulting in stable and predictable revenues. In addition, the concerns of both these stakeholders vary depending on their geographical location. A consumer in the US will have different energy security priorities than will a consumer in the EU, and the same can apply to EU MS consumers' priorities.

Another contrasting energy security perception is that of international organizations and transit states. On one hand, international organizations should be facilitating international cooperation among countries on energy security issues; hence, their perception on energy security issues should be the more neutral one.

On the other hand, the role of transit states is becoming more and more significant in the geopolitical arenas and economic scenario. Two examples are Turkey and Ukraine, which are providing energy resources from Eastern to Western markets. With a strategic geographical location, both these countries are becoming increasingly critical to the security of the EU energy supply, as well as to the security of Russian demand. They can both supply a significant quantity of natural gas to Europe, increasing its source diversification, but also challenge the role of Russia as an energy bridge to Europe [74].

Furthermore, traders and government have very different perceptions on what energy security is. Traders oppose a market-centric view to the institutionalize paradigm that see the market being both a political construct and only one of the institutions of capitalism with less significant role than that of the state and politics [75]. Buyers and sellers let the market needs rule, whereas government sees energy security as an unquantifiable threat with which it needs to deal.

To traders, a properly developed and flexible market, with the right price and signals, the right level of information and transparency, which is allowed by minimal regulations to self-equilibrate, will not experience energy security issues. This view lies on quite a few assumptions that might be incompatible with economic reality: no transaction costs, perfect information, and economic equilibrium [76].

On the other hand, the utmost interest of governments is in maintaining or improving citizens' safety, hence, depending on their jurisdiction, governments will use different methods, policy and regulations to face current energy security problems. They have to cope with Stern's HILP events, such as climate emergency or facilities failures [20]. These type of events could either cause (for instance) unavailability of volumes or price spikes, thus, as Yergin [77] states, "the objective of energy security is to assure adequate, reliable supplies of energy at reasonable prices and in ways that so do not jeopardize major national values and objectives".

Another aspect that needs to be taken into account in the definition of energy security relates to the heterogeneity of the markets. There are considerable differences between the oil, natural gas, nuclear and electricity energy markets, e.g. the structure (regional vs global), the infrastructures (ease of disruption, level of rigidity), and the storage methods (mature or not). The IEA study on gas supply [78] observes these singularities across energy markets, suggesting defining energy security independently between energy markets for the sake of conceptual unity. Hence, different energy sources can be a factor affecting the definition of energy security.

Finally, energy security is dynamic as it depends on the time horizon, which could be short- or long-term [70]. The latter values stability over cost-effectiveness, favoring strategic security over operational security of the market. In the natural gas industry, it means dealing with potentially fatal collapses of supply sources or facilities versus daily and seasonal stresses of severe supply emergencies, brought about by political conflicts, extreme weather events, accidents, and sabotage, to name a few. Hence, energy security might mean having adequate and functioning supply infrastructures as opposed to supply availability and reliability, depending on the time dimension considered [20].

These perspectives influencing energy security conceptualization have led to two separate literature streams. On one hand, there is what is becoming a systemic research effort, which attempts to define energy security within a multi-dimensional framework, find the need for a more cohesive approach in developing an integrated understanding of the concept, and broaden the economic market-centric view. Questions to be answered according to this approach are overarching ones, such as: "How do we make our energy systems more secure without merely trading our [existing] vulnerability for another one?" [72].

On the other hand, some authors see the "impracticality of seeking a common definition of energy security" [70] and have decided to frame it through its opposite: energy insecurity, which is what policies usually frame. Others limit the scope of the concept to security of supply (SoS) (e.g. Winzer [22]), looking at it through a bi-dimensional perspective: political and economic view. Energy security is perceived as a tradeoff between security and efficiency; hence, according to Stirling in [79], achieving security means distributing risk between various energy options, thus increasing resilience. It is then the government that has to provide insurance on non-quantifiable uncertain risks [21]. This approach explores more specific questions, such as: "What are the risks/threats and the energy use, energy mix, and reliance on local resources or imports?"

Moving away from Chester [76], who affirms that the multiplicity of approaches and meanings that can be attributed to energy security conceptualization suggests that there cannot be a universal and clear-cut solution either to the definition of energy security or to the way it is faced, because the factors affecting it are continually changing and evolving; Cherp and Jewell analysis [73] considers energy security as one single concept but with various expressions under different conditions, becoming highly contextual, hence only acquiring different forms, not becoming a different concept, each time it is defined.

The authors apply the logic of security to energy, as developed by Baldwin [80], concluding that "a valid concept of energy security should be based on a concept of security in general" [73]. In his work, Baldwin presents seven questions to which security should give an answer: security for whom? Security for which values? From what threats? How much security? By what means? At what costs? In what time period? [80].

Taking into account the first three questions Baldwin poses, Cherp and Jewell [72] try to combine them with the framework known as "4As", developed in 2007 by the Asia Pacific Energy Research Centre, which classifies elements related to SoS into four interconnected elements: physical (Availability), geopolitical (Accessibility), economical (Affordability), and environmental (Acceptability) [81]. With respect to previous works, the authors come up with a more holistic view of energy security based on how the concept has historically evolved and the academic discipline in which it has been rooted, based on what they define as a three perspective approach: sovereignty (political science), robustness (natural science, technology), and resilience (economics).

The first perspective, "sovereignty", concentrates on the external threats posed on a country by foreign actors, such as "unreliable exporters". The second one, "robustness", sees risks such as scarcity of resources as quantifiable elements. The last perspective, "resilience", sees threats to energy, markets, technologies and societies, which are non-linear, extremely complex and uncertain systems, as unpredictable an uncontrollable. This perspective includes regulatory changes, unpredictable economic crises and climate alterations.

In line with integration of the 4As framework into a three perspective approach of Cherp and Jewell, with his approach Winzer generalizes the 4As framework [22]. Although narrowing the definition of energy security by proposing to define it as energy supply continuity, to construct his framework he integrates in it three dimensions of risk. Introducing the risk dimension, or risk source, into his approach operationalizes the approach of Cherp and Jewell merging sovereignty and robustness into the human and the natural risk dimensions, but adding the technical risk (i.e., failure of infrastructure components), which has been mostly neglected in the previous literature [22]. To account for resilience, Winzer adds the scope of the impact, which determines how energy security is measured; this includes the continuity of supply seen as continuity of commodity, economic, and service supply. The last falls outside the 4As and introduces an impact measure that "[reveals] the structural connections between the [other two] impact measures" [22].

In addition to reducing the overlap between the three dimensions and between the trade-offs of different policy goals, as well as to measure energy security more precisely, the author then applies severity filters to the threats' impacts, such as speed, size, sustention, spread, singularity and sureness, all of which refer to a different aspect related to the risk, whether that be the time-scale, the magnitude of changes, the duration of the impact, the frequency of recurrence, and so on.

His approach originates from two aspects he noticed in his review of the concept of energy security in the literature. On one hand, he infers that in most cases authors refer to energy security as related to the safeguard from threats, whether that be the absence of, the protection from Krause & Nye [82] and Johansson [83] or, as in the case of IEA [78], the management of those risks. On the other hand, he observes that the choice of conceptual boundaries to define SoS has a large impact on results, and that it is difficult to measure simultaneously all of the occurring threats: how authors select these risks affects their analysis and results.

Hence, the need for authors to limit the scope of the concept, either with severity filters (as in his case), the scope of the measured impact or the source of risk. Introducing the concept of energy security continuity, in his view, would first reduce double counting of risks, would then bypass what Buzan et al. [84] calls the problem of securitization (i.e., transforming regular political issues into matter of "security"), and finally would frame the problem in a more integral way.

Combining the integrated definition of security by Winzer [22] with the suggestion of Stern [20] of considering security as a multi-dimensional matrix as well as with the number of definition deeming energy security under a bi-dimensional perspective, allows the formulation of the definition of security of gas supply.

The definition of Winzer [22] views energy security as "the continuity of energy supplies relative to demand", whereas the matrix of Stern [20] encompasses the "threats of supply and price disruptions arising from risks associated with the sources of gas supply, the transit of gas supplies and the facilities through which gas is delivered", and finally bi-dimensional definitions of energy security assess concepts such as availability, accessibility and price [20,22].

Hence, security of gas supply for the purpose of this study can be defined as "the continuity of availability and accessibility of gas supply relative to demand, and vice versa, when high-impact low-probability events occur in any part of the gas supply chain". Based on this definition, the importance of a resilient gas network and gas infrastructures is highlighted. Efficiently planning for a resilient network requires assessing the adequacy of infrastructure and market design; hence background knowledge of models dealing with energy infrastructures vulnerability and robustness to strain, technical performance, and changes in the system characteristics in the European natural gas network. This aspect will be investigated in the following sections of this research Section 2.4 and Section 2.5.

2.4 Modeling energy security in the literature

Although the weighting and aggregation of indicators in some cases might fail to quantify unpredictable risk, such as policies, technological and climate changes, indicators are indeed a necessary step in the formulation of energy security dimensions and its analysis. As Kopp [21] suggests "[…] indexes help track the evolution of energy systems and give a benchmark to compare case studies and policies options, both as a country self-assessment or cross-country assessment [...] Their aggregation allows the comparison of energy security risks and the identification of policy trade-offs and entails a thorough examination of energy concerns and resilience mechanisms." [21].

Mansson et al. [30] analyze different methods to evaluate energy security and security of supply. Mostly they have been applied according to the scientific discipline of origin, incorporating methods from the fields of economics, engineering, political science and natural science. Strengths and weaknesses have been underlined by the same authors for each methodology, from the partial inadequacy of economics methods to account for radical system changes, to the fact that the engineering methodology is based on actual observations and the knowledge of the distribution of threats is essential for it to perform well, which means the method can only be successfully applied to the study of recurring technical failures. In particular, economics-based methods have been used to optimize the security of supply alternatives or to identify cost effective solutions, whereas engineering-based methods have been adopted to study threats to the security of supply chains and to compare levels of security among various energy systems.

In some cases, Mansson et al. [30] propose to aggregate the data in complex systems that combine different methodologies. According to the authors this could help compare outcomes over time and/or space, overcome the fact that different methodologies might lead to contrasting solutions depending on the initial assumptions, and improve the analysis of energy security by unifying the various assumptions each methodology makes and the different scientific fields in which those assumptions are made.

Even if few exceptions exist (e.g. Sarica et al. [85]), where the most common combination of methodologies is that of economics and engineering, since such systems require a thorough analysis and description of the system features, they have so far not been applied to the analysis of energy systems that differ widely from one another or which have long timeframe changes [86].

In particular, cost-benefit analysis and impact-assessments have been used especially in macro-economics to evaluate economic vulnerability (i.e., welfare loss as a consequence of volatile prices), comparing and identifying cost efficient strategies to increase security [87,88]; whereas deterministic methodologies have been found to be more apt to analyze infrastructure resilience, vulnerability and robustness, optimizing technical and infrastructural reliability and evaluating how disruption directly impacts the overall system, with a focus on interdependencies between different parts of the system.

2.4.1 Optimizing supply disruptions in the EU natural gas network

Authors, reflecting the ever-changing and contextual nature of energy security definition, tend to construct ad hoc models that best address their specific research question. There are two main techniques to optimizing natural gas supply chains presented in the literature: minimal cost models and competitive market models [29]. On the one hand, there are models assuming perfect competition that are appropriate for investigating policy-related concerns and long-term supply security [37,89,90]. On the other hand, there exist models that assume imperfect competition in the EU gas market and are suited for addressing market power analysis concerns.

The majority of market models can be categorized either on the Bertrand price-driven competition (ideal markets), or on Cournot oligopoly (quantity driven competition [90]. The Bertrand competition tends towards the perfect market competition equilibrium where prices match marginal costs, whereas the latter primarily addresses with strategic gas supply problems. Unlike Bertrand, Cournot scenarios assume large players in the market to have the same “strategic weight” as smaller players, with prices higher than the marginal costs [91].

Hence, as Smeers [37] and Lochner [89] both argue, models based on imperfect competition in the EU gas market are more suited to addressing market power concerns (e.g. based on Bertrand perfect competition), whereas models that suppose perfect competition and focus on infrastructures (e.g. based on Cournot imperfect competition), are more suited to addressing policy-related issues, hence questions related to security of supply. In particular, focusing on Europe, Holz et al. [91] found that Cournot scenarios results render a more realistic picture of the European natural gas system, if compare to the perfect competition scenarios [37,89,91].

Flouri [27] and Chyong &Hobbs [28] suggest a few notable models can be named that have helped frame the consequences of natural gas supply outages on energy security, specifically in the EU. GASMOD by Holz et al. [91] is a two-stage oligopolies gas market model that, using Mixed

Complementary Programming (MCP), analyzes the role of Russian supply to the European markets and the effects of a Russian supply disruption on prices and consumption [91]. A nonlinear complementary (NCP) model from Egging et al. [92] contributes to the analysis of security of supplies to Europe by giving a detailed presentation of the market structure, including global LNG, and market power of exporters. Various scenarios are constructed by the authors to simulate disruptions in Europe of Russia supplies via Ukraine to analyze profit maximization of market players [92]. The dynamic GASTALE model, a computational game theoretic model representing TSO and SSO investment decisions developed by Lise et al. [93], expands earlier GASTALE model versions, to include multi-year dynamic investments to assess energy corridors in Europe, from 2005 to 2030 with a five years incremental timeframe, and to study the impact of demand uncertainty on security of gas supplies to Europe accounting for deferrals of investments in infrastructure capacities [93,94].

The research focus of the above-mentioned oligopolistic large-scale simulation models, in particular that of GASMOD and GASTALE, is on the market power of downstream suppliers in European markets and how they could react to potential long-term gas import delays from key suppliers (e.g., Ukraine, Algeria, Russia, etc.). Both of these models are two-stage game in European gas market, but while GASTALE does not include domestic production in the optimization, GASMOD assumes it to be an endogenous variable, accounting separately for upstream imports to Europe (first stage) and downstream trade within Europe (second stage). GASMOD does not discriminate between market segments and assumes just one participant per nation since it concentrates on strategic connections between producers in the first stage and traders in the second stage. Both GASMOD and GASTALE only deal with long-term costs, ignoring short-term operations and endogenously computed investment decisions, and, at least in their early incarnations, they do not simulate storage [91,93,94].

Egging et al. [92], although still focusing on market power analysis using an NCP approach and assuming imperfect competition, made progress towards a more detailed strategic European gas simulation. The market structure the authors consider is more comprehensive than in previous works and includes: market players, such as producers, traders, LNG liquefiers, LNG regasifiers, storage operators, and transmission operators; fifty-two countries representing the demand side; three consumption sectors (residential, industrial and power generator); and three seasons (low demand, high demand and peak demand). The results of their complementary model are long-term market equilibrium values, and return consumption and price levels for different alternatives, such as LNG and storage, in case of supply disruption.

These models assume imperfect competition in the EU gas market, which makes them more suitable to address issues related to competition and competitiveness, compared to those model that suppose perfect competition and focus on infrastructure, and are hence more apt to investigate questions of investments in relation to security of supply [37,89].

Where the Egging et al. [92] model does not account for short-term disruptions, Szikszai and Monforti [95] showed how when European peak load is affected by disruptions on the Ukrainian gas supply side the astounding majority are scenario with a unrecoverable imbalance during the first day. In addition, findings from their study confirm that albeit demand-side management responses where critical in maintaining the gas network system in the early stages of the crisis, they were insufficient.

MC-GENERCIS model by Monforti and Szikszai [96], and its later development into the GEMFLOW model, using a probabilistic Monte-Carlo approach assesses the implication for the transmission gas pipelines if crucial importers, such as Ukraine and Algeria, stop supplying gas to Europe [95,96]. Finally, TIGER model by Lochner and Bothe [97], a linear programming supply-demand transmission cost-minimization model, with a network flow design that optimizes the entire EU network system with regards to the cost for gas supply subject to multiple infrastructure constraints [89,97–99].

Both GEMFLOW model and TIGER model provide short-term considerations of the European gas network with higher temporal and spatial granularity details. In particular, GEMFLOW moves a step forward from its earlier version MC-GENERCIS by including, alike TIGER model, the temporal dimension (i.e., the time evolution of a crisis), which very few tools in the literature build in. In the GEMFLOW model, time is a key variable, which changes the results depending on the date and length of the crisis. To his end, one of the main results of the model is that it gives the operability time of the system, namely, it returns how many days before the system shuts down.

TIGER is a comprehensive static dispatch LP model that considers gas flows in pipeline, storage, and LNG terminals, using nodal pricing as the analytical framework. The model is built on perfect competition, with TSOs conducting gas swaps, and perfect foresight. Capital costs are not accounted for; only existing infrastructure or exogenous additions are used. It has been used to investigate European gas flows, cross-border market integration, and gas security supply in relation to infrastructure adequacy. Through linear optimization it looks at the gas transmission system - including detailed grid characteristics such as pipeline length, location and interconnections - for forty countries in Europe based on present and projected gas infrastructure constraints. The model's goal is to return detailed gas flow in Europe at the lowest possible cost over a 10-year period on a monthly or daily basis, limited by existing capacities. Each European country is identified by a node, implying that there are no bottlenecks within internal gas network of each country. Infrastructure asset utilization data, with the valuation of physical bottlenecks and transmission capacity between countries, as well as a locational marginal cost estimation of gas supply for each node and time period (measured in days) are some of the possible outputs from the model. The last is evaluated as the derivative of the shadow cost of the energy balance restrictions, or nodal prices, which are then used to calculate the optimal transmission and storage tariffs and ultimately derive congestion costs. This in turn implies the economic efficiency of capacity expansion on the routes the model takes into account. When the congestion cost indicator is greater than zero, it identifies a transmission infrastructure bottleneck [89,97,98].

What GEMFLOW proposes, instead, is a cooperative approach in light of the solidarity principle brought forward by the EU, which follows a regional level operation of the system. This mass-balance model uses the available domestic measures, prioritizing those within the system, to reach the longest system operability time. As Szikszai and Monforte [95] point out, although during the January 2009 gas peak crisis, which lasted about two weeks, market alternatives were used to bring gas promptly to the most impacted regions (i.e., Greece and Turkey), it was technically unfeasible in the first days of the crisis to bring the gas from where it was more abundant to those MS were customers were almost left with no gas. Hence, although demand-side management responses were put in place, this shows how HILP events affecting the EU gas network might pose a serious threat to the supply of gas to EU consumers. It also highlights how the lack of gas can spread throughout Europe with a domino effect, which is difficult to manage only implementing non-coordinated national emergency plan.

To this end, in the event of a crisis the GEMFLOW model looks at the gas network's adequacy and resilience, and "a solution" is found by listing all potential alternatives without ranking them. The model does not return the optimal solution, but just operational possibilities. It estimates demand-supply balances within Europe and then shows the results in terms of the imbalanced countries. In addition, the model does not include market laws, with the idea that in critical situations close to market failure, technical feasibility wins over market or strategic behaviors. Nor does it include cost analyses of the alternative solutions.

The model is based on an aggregated graph approach. Each member state is represented by a node (minus Cyprus and Malta, which are not connected to the gas transmission network via pipeline), plus an additional five countries outside the EU, namely Switzerland, Bosnia and Herzegovina, Croatia, FYROM, Serbia, and Turkey, for a total of 13 nodes. To simplify the system, each pair of countries is linked via one single virtual pipeline, which aggregates the maximum technical capacity of all actual gas flows. The model returns the workload of each pipeline involved in the simulation and helps identify potential bottlenecks in the pipelines. Moreover, to further simplify the model, the same logic is applied to all storage space and LNG capacities, which are also combined in only one virtual facility in each country. In this respect, the program univocally considers different types of storage facilities with different physical properties.

Since storage facilities are scattered around Europe and pipeline capacities differs from one country to another, the model allows the supply from storages to flow from bordering countries and, thanks to the Monte-Carlo approach, to randomize the consumption level to balance the whole gas system. This enables longer operability times of the model.

In addition, as the model implements a Monte-Carlo approach, the two-phase algorithm on which the model is based is repeated a large number of times. The first phase looks at domestic resources to balance all countries impacted by a disruption, whereas the second is solely concerned with those countries that are still unbalanced after the first run through; it searches for spare gas capacities in the network. It initially explores LNG reserves, and before reverting to domestic consumption and storage reserves, as the model is set to not use these to the maximum in the first phase. Then, if the system is still unbalanced, the model enters the second day of simulation [95,100].

Table 2-5 Summary of European gas models framing natural gas supply disruption

Model Name	**Purpose of the research**	**Optimization Objective**	**Model focus**	**Disruption**	**Foresight assumption**	**Solution Method**
GASMOD [92,101]	Examine the market power equilibrium in Europe	Economic behavior of market players	Market power of downstream suppliers	Long-term	Perfect foresight	MCP
GASTALE [93,94]	Analyze the impact of producers' strategic behavior on future gas	Investment decisions	Market power of downstream suppliers	Long-term	Imperfect foresight	NCP

	prices and investments in the gas network.					
TIGER [89,97,98]	Evaluates transport capacities, bottle necks and congestion costs in the European gas network infrastructure.	Supply-demand transmission cost-minimization	Infrastructure	Short-term	Perfect foresight	LP
GEMFLOW [95,96]	Analyze European gas system flow capabilities during supply disruption to inform decision-makers.	Demand-supply equilibrium	Infrastructure	Short-term	Perfect foresight	Monte-Carlo

From the review, the great bulk of the recent research on the EU gas market utilizes MCP (partial) equilibrium models to characterize market forces in the gas market [35,36,102–104]. However, a number of recent least costs models have increased the model’s geographical and temporal resolution to more accurately address the issue of European gas supply. To this end, in addition to addressing bottlenecks Deane et al. [105] accentuated the importance of modeling line packing (i.e., using a pipeline to store natural gas) to investigate the network's dynamic reaction to supply interruptions; while Eser at el. [29], besides including all physical system components, as well as hourly and end-user sectors resolution, tried to capture the behavior of the gas market (i.e., traders and gas system operator behavior) [29,105].

In particular, Deane et al. [105] examines the impact on power system operation and gas interruptions in the EU under low risk and high impact scenarios with an integrated electricity and gas modeling tool, with a focus on associated impacts for electricity prices and emissions. Using a mix integer linear programming (MILP) minimizing total system costs, the model analyze the impact of gas supply shortages on a large scale system and gauges the value of an integrated approach understanding the interplay between power and gas system. It proposes 5 scenarios with a yearly time steps to 2030 to evaluate the role of gas storage in the energy system. It renders the long-term ability of the predicted system to meet predicted demand.

Also Eser et al. [29] analyzes the anticipated decrease in gas demand by 2030 via LNG and pipeline sourcing options, as well as supply security scenarios. It investigates the predicted shortfall on EU gas demand by 2030 through 2 different strategies to cover it: via LNG increase import and via pipeline through Nord Stream 2. The authors present a novel model that captures gas trader and gas system operators’ behavior. A high spatial and temporal resolution to identify the technical, economic, and political risks associated with the European gas sourcing in 2030 is applied (i.e., spatial resolution for the gas transmission system with 500 network nodes, 52.000 km of high-pressure pipelines, 150 compressor stations, and 80 gas storage facilities). Gas demand is differentiated by end-user sector. Temporal resolution is hourly. The model extends the electric power system simulation framework of EnerPol to the gas network and combines a Monte Carlo approach with a cost minimization optimization approach. The output from the first one (i.e., an hourly cost-optimal import profile for gas traders) constitutes the boundary conditions for the second one.

Devine and Russo [106] investigates the impact of supply diversification in the UK-Irish market on consumers' energy bills and their sensitivity to market conditions by analyzing investments in LNG and storage infrastructures in the UK, whereas Skea et al. [40] describes the impact of hypothetical shocks on the UK energy system and qualitatively discusses the benefits of strategic investments and the policy implications of the results. On one hand, using a stochastic MCP problem, Devine and Russo [106] models the market on a daily basis, including reverse flow capacity. Where previous model neglected to reflect market uncertainty, this work allows for it with different demand curve and supply costs possibilities for 2025. In addition, unlike other MCP models that mostly consider large-scale natural gas markets on seasonal and monthly scale, here granularity is higher (i.e., daily steps and 2 interconnected markets). Considering the economic benefit for consumer of LNG and gas storage infrastructures in the context of the EU PCI helps the authors to investigate the effects of the new LNG capacity on gas prices as well as the LNG and storage investments complementarity to manage short-term peak loads and long-term seasonal loads on consumers' energy bills. On the other hand, Skea et al. [40] looks at commercially driven investments in the gas infrastructure in UK in LNG and storage up to 2025 to provide security of gas supply to the system and the associated cost on the energy system due to gas interruption on the largest piece of the largest gas infrastructure in the UK (i.e., loss of Bacton gas terminal). The study adopts the Combined Gas and Electricity Network modeling tool developed by Chaudry et al. [107] and identifies both shortfalls in the gas supply to customers and the cost to the energy system of mitigating actions (e.g. re-dispatching power stations). Subsequently, the impact of mitigating gas infrastructure improvements is analyzed, with incremental time steps of 5 years from 2005 to 2025. Two profiles on CO_2 reduction are constructed as input to the model: (i) Low Carbon - fall in primary and final energy demand - and (ii) Low Carbon Resilient - constraints on final energy demand.

Further, by simulating possible supply disruptions in Europe from key exporting nations, Richter and Holz [108], Flouri et al. [27] and Rodriguez-Gomez et al. [31] focus on EU supply security. While Flouri et al. [27] uses a Monte Carlo simulation to assess supply reliability of specific EU States and determine whether enough natural gas to meet demand arrives in each respective EU State, Rodriguez-Gomez et al. [31] and Richter and Holz [108] evaluate EU infrastructure improvements.

Starting from MC-GENERCIS theoretical background, Flouri et al. [27] looks at how supply interruption from North Africa (i.e., Algeria, third largest exporter to the EU) is to affect energy security of the EU, finding that reserve, namely storage, and supply diversification, as in LNG and production, but also as in natural gas quantities, are key in meeting demand. Whereas, with its global gas market equilibrium model, Richter and Holz [108] looks at market position, alternative suppliers, and development of current EU infrastructure to ensure supply while mitigating gas supply interruptions from Russia. It presents a mix-complementarity problem with a great focus on trade and infrastructure. It works on 5 years steps and cover 98% of the global gas market, using GGM (Global Gas Market) a partial equilibrium model. Using 3 hypothetical demand disruption scenarios, it investigates 3 aspects: market position, alternative suppliers, and expansion of existing infrastructure to secure supply and attenuate disruptions. Compare to earlier literature the model uses an updated and more refined set of data with a focus on EU infrastructure (i.e., high level of technical granularity on storage and transport infrastructure).

Conversely Rodriguez-Gomez et al. [31] by leveraging cooperation and solidarity measures across EU countries, employs a mass-balance model to analyze the effects and scale of the EU infrastructure improvements between 2009 and 2014 on security of supply. Building on from GEMFLOW, it implements a Monte Carlo approach to evaluate how the EU high-pressure network behaves under crisis scenarios following infrastructure improvements. The model developed by JRC simulates gas disruption of different duration, survival time, and non-served gas per country. It investigates security of supply by exploiting cooperation and solidarity mechanisms among EU countries, with no market or economic constraints on the gas flow. It includes thirty consumers countries and nine suppliers countries. Consumption is a constant. It does not look for the "optimal" strategy, but allows the system to evolve freely with a number of possible strategies to get a probabilistic picture of the resilience of the system. Four hypothetical scenarios are considered, based on the disruption of the main importers that provide gas to Europe via pipeline: Ukraine, Russia, Norway, and North Africa.

Finally, Bouwmeester and Oosterhaven [109] and Allevi et al. [110] chose a wider economic perspective on supply disruption. Economy-impacts are analyzed for selected EU regions in Bouwmeester and Oosterhaven [109], looking at pre- and post-disruption patterns in economic transactions, and Allevi et al. [110], evaluating whether the risk affects the import choices of Italian mid-streamers on both supply country gas mix type and payment methods (i.e., long-term contracts and hub pricing system). Bouwmeester and Oosterhaven [109] uses a non-linear programming to predict 4 different scenarios, minimizing the information gain between pre- and post-disruption patterns of economic transactions. It analyses economy-wide impacts for each selected region in the short and medium-term on trade balances, as well as on two welfare measures: value added generated in each regions (GDP aggregated), and total domestic consumption. On the other hand, Allevi et al. [110] uses a complementarity model to explore two different levels of flexibility for mid-streamers related to external supply of natural gas (i.e., long-term contract and spot-pricing). Instead of analyzing supply disruption through a possible set of scenarios, the authors directly integrate risk indicators into the model, to depict the economic impact of mid-streamers choices.

2.4.2 Modeling uncertainty in EU natural gas network

On the other hand, when referring to availability and accessibility of gas in the network during energy emergency, the concepts of uncertainty and disruption emerges, and the ability to respond to it becomes paramount to secure energy [73]. Hence resilience, in the definition of Ponomarov et al. [111] and Khalili et al. [112] is a topic that in the context of natural gas network needs attention.

Resilience has been deeply investigated in the field of supply chain management. To this end, as Mendez et al. [113] highlights, the generalization of short-term scheduling of batch operations to the modeling of complex networks significantly contributes to the area of minimum costs models. Whereas, as far as uncertainty is concerned, it can be addressed with two alternative supply planning approaches: stochastic linear programming (SLP) and robust optimization (RO). The two methods adopt a completely different philosophy in tackling uncertainty. The latter is well suited to generate solutions against all imaginable outcomes of the uncertain events, hence leading to more conservative, and possibly more expensive, solutions. Whereas the former includes the actual probability distribution of the events, which implies less conservative results since it gives small weights to less probable events. Unlikely SLP, RO evaluates the realization of the worst-case uncertainty without making any specific assumptions about the event's probability distribution. The uncertainty set is rather discretionary selected, thus the outcome is not fully independent of it. As a result RO has not been widely explored to portray uncertainty from supply chain disruptions. To this aim, Maggioni et al. [114] demonstrated that, in most of the cases, a two-stage stochastic programming enables higher cost saving than to robust optimization with the same supply planning problem involving demand uncertainty.

From industrial process applications, where process operations were optimized using models such as state-and-task network [115,116] and resource-task-network [117], optimal configurations of novel supply has been explored and new approaches introduced. In specific, collaboration, multiple sourcing strategies, multiple transportation channels, and back-up suppliers as key factors in preventing negative impact of disruption on the whole supply chain and for building resilient networks are critical elements in minimizing the negative effects of interruption on the whole supply chain and establishing resilient networks, according to the research from the area of supply chain (SCR) [118].

According to Hosseini et al. [38] systematic review of recent literature on quantitative methods for SCR, the most appropriate method to cope with unmet demand induced by supply interruption is to utilize two-stage stochastic scenario-based optimization models to build resilient distribution networks [38]. The goal is to improve SCR in two ways: by having redundant inventory (absorptive capacity) and by having backup suppliers (adaptive capacity). Namdar et al. [119] and Khalili et al. [112] focus on resilient sourcing strategies and risk mitigation. To establish the value of single and multiple source back-up and spot purchasing in a resilience plan, Namdar et al. [119] constructs a bi-objective two-stage stochastic model. In more detail, the authors look at standard industry resilient supply strategies as well as the effectiveness of risk mitigation strategies under supply disruption for both operational (i.e., Low-Impact-High-Frequency, such as equipment breakdowns) and long-term (i.e., High-Impact-Low-Frequency, such as natural hazards) risks from the perspective of a buyer. Their model investigates optimal level of investment of a buyer in resilient single and multiple suppliers sourcing strategies, and their effectiveness, due to disruption coming from uncertain events. Given a risk aversion level, the two-stage stochastic model mitigates disruptions by minimizing the maximum negative impact on a supply chain. Unlike previous models, it includes collaboration (i.e., supplier recovery rate) and visibility (i.e., warning against disruptions.) within the industry strategies it addresses. It performs a cost–benefit analysis of supply chain resiliency, rendering insights on managers' decision processes. Results show that to build a resilient system, when it comes to high-impact, low-frequency events and high risk aversion, diversification and backup are the favored strategies both for single and multiple sourcing.

Similarly, two stage stochastic supply model from Kalili et al. [112] study rerouting, surplus inventories and transportation capacity as risk mitigation strategies for a production-distribution planning problem in the event of supply cut. The study looks at capacity levels of production facilities, transportation links and distribution centers to evaluate their degree of vulnerability to operational and disruption risks concurrently. The model investigates the impact of extra capacities in the production facilities, backup routes for transportation links and pre-positioning of emergency inventory in distribution centers on the supply chain and how these strategies can contribute to the resilience of the system. The proposed two-stage scenario-based mixed stochastic-possibilistic programming model first minimizes total initial cost plus the expected cost, and then it optimizes the cost and resilience of the production–distribution chain under each disruption scenario. The aggregated model handles both operational and disruption risks at the same time, integrating proactive and reactive resilience (i.e., risk mitigation strategies and tactical decisions). Together they measure the resilience level through a novel indicator: restoration of disrupted capacities.

Adding on, Torabi et al. [86] focuses on suppliers selection, business continuity, looking at the back-up surplus and capacity of suppliers under natural and man-made operational and disruption risks and at strategies to enhance the supply side resilience level of the manufacturer. With a bi-objective mixed possibilistic, two-stage stochastic programming model the authors investigate a resilient supply base at the global supply chain level. Their work analyzes business continuity and the likelihood of disruptive events in the supply chain considering the trade-off between cost and resilience level of supply base. The model contributes with an insight on managerial decisions when it comes to allowing multiple supply sourcing, fortifying second group suppliers, back-up supplies to be use in case of emergency, recovery level and business continuity of suppliers, and inventory pre-positioning strategies in case of real-world case studies.

Finally, Turnquist et al. [120] focus on absorptive, adaptive, and restorative capacity of the system focusing on outage of a production node, or inoperability of distribution centers, and design, investment and recovery strategies trade-off in planning for the most resilient network in terms of costs and time to recover. The MILP problem looks at design infrastructure security and network resilience and examines distribution centers using a two-stage stochastic optimization model that simultaneously examines pre- and post-disruption design options while taking into account the extra capacity and restoration capacity of distribution centers, as well as additional connection of distribution centers with customers. The model jointly handles pre- and post-event investment decisions and post-event recovery strategies (i.e., increase capacity of distribution centers, reconfiguration of channels), as framework for resilience of infrastructure networks, such as manufacturing supply chain, food distribution, or water supply, examining a wide variety of potential damage scenarios.

As highlighted in this section, optimization model considering technical features of the infrastructure is the most apt methodology to study infrastructure resilience [30]. To this end, when it comes to the European gas network a group of studies focuses on market forces to address the European gas supply (e.g., [27,29,105–107]) and only few authors marry the issue of supply disruption and energy security (e.g., [92–95,97]). The other group of studies reviewed addresses the issue of uncertainty in the supply chain, which in the event of an HILP becomes paramount, but none has been transfer to the field of natural gas (e.g., [86,112,113,119,120]). In conclusion, LP has been applied to depict supply disruption in the natural gas network with a focus on infrastructure and assuming perfect competition, whereas stochastic programming method has been often used to assess uncertainty in the supply chain. These approaches have been employed in several gas and SCR model and the solution generally benefit the system and it is suitable to investigate policy-related issues, hence questions related to security of supply [37,89].

2.5 Research objectives

Based on the conducted background analysis and literature review (Sections 2.1 to 2.4), this section presents the general and the case-specific research objectives of the thesis. The following sections highlight the literature gaps of existing works and three main applications of the proposed HILP model in the European gas network. Understanding what is the optimized cost competitive solution as well as the most efficient allocation of gas flows and capacities across Europe in case a HILP event disrupting supply occurs, optimizing the existing capacities in strategic storage, is an issue that refers to energy security from a policy perspective. As a result, this thesis aims to make improvements in modeling methods to better address how sudden short-term shocks in natural gas supply and demand may affect the energy security in Europe. More specifically, the instances addressed by this thesis include the impact of LNG and storage on network resilience, strategic gas storage as a coordinated first non-market based measure, and network configuration through solidarity between MS.

2.5.1 General objectives: Development of the modeling method

While an exhaustive review of all academic contributions on energy security is outside the scope of this work, the summary outlined at the previous sections of this work shows that the definition of energy security within a systemic approach has not been addressed so far by the literature in a consistent way especially when it comes to HILP events, mega-disasters (i.e., infrastructure breakdown due to technological faults, natural disasters, or political instability) that are unlikely to occur, yet require policy intervention where the market is unable to meet demand. The analysis also confirms the necessity for a broad investigation of the EU energy system security, a contribution that this thesis seeks to make by concentrating on the gas sector and in particular strategic storage.

Given the lack of existing tools that (i) include short term resilience of the whole European natural gas infrastructure when invested by a HILP; (ii) link security of supply to storage as a measure to cope with short-term emergencies; and (iii) cover optimal configuration of a coordinated European market for strategic storage, this work investigates network resilience during supply/demand-shock events and, through whether the coordination of the strategic storage at the EU level, as a first non-market response measure to supply disruptions, could help the EU new agenda of combining security of supply objectives with solidarity and cooperation among Member States, it also investigates the most effective configuration of the EU gas network with regards to responding to emergencies.

Special strategies must be in place at national levels to ensure energy security, particularly in the face of HILP [20]. Most EU MS, for example, rely heavily on natural gas with little diversification of sources. This, together with heavy import dependence and the impact of the declining indigenous production on market seasonality and flexibility, could jeopardize the natural gas supply threatening Europe in case of HILP [2,3]. Coordination among Member States is necessary The call to a solidarity principle among Member States [15,18], using risk-pooling to both generate cost-effective alternatives and minimize negative spillovers from national supply-security policies, necessitates EU-wide coordination [15,18,121]. Among several unused alternative to face supply disruption situations, the role of gas storage could be a significant insurance instrument to ensure flexibility in the liberalized gas market as well as a rapid response emergency solution [44].

Three trends are consolidating the role of gas storage in the EU gas market: (i.) heavy import dependence, (ii.) little diversification of sources, and (iii.) the impact of declining indigenous production. In addition, there has been little research linking strategic storage to Security of Supply, HILP, and the securing of energy services, as well as including a policy perspective, solidarity and the 2016 EU Security Package/EU Regulation 1938/2017 [15,18] in the modeling framework that have been used to discuss supply disruption in the gas network. Finally, energy security for the purpose of this study has been defined as the continuity of availability and accessibility of gas supply relative to demand when HILP occur in any part of the gas supply chain.

From 1998 to 2011, there were 11 gas supply crises and mishaps in the EU gas grid, according to Skea et al. [40] historical assessment of gas supply disruptions

In the next six years, there were four more incidents, the bulk of which were caused by infrastructural flaws and harsh weather [1]. As the impacts of climate change become more evident, regions such as Europe will not only witness a rise in global average temperatures, but will also be increasingly vulnerable to extreme and unexpectedly cold weather events, where energy supplies will be difficult to mobilize to meet energy demands. It is critical to create ad hoc techniques for assessing energy security in Europe, as well as metrics for quantifying the resilience of the European natural gas network.

As highlighted, energy security, and in particular SOS, in the natural gas supply chain can be analyzed from different perspectives: supply of primary energy, upstream and market imports, domestic market and infrastructures, and economic vulnerability. Different approaches are adopted depending on which aspect has been evaluated. To this end, infrastructure resilience, vulnerability and robustness have been addressed with deterministic methodologies in particular optimization models considering the technical features in the infrastructure with a focus on the relationship and interaction between different parts of the system.

Hence, this thesis follows the existing approach based on the Linear Programming (LP) modeling to capture the policy-relate issue of security of supply in the European gas network optimizing the technical and infrastructural reliability of the system as well as the cost of competitive solutions in case of HILP disrupting the supply chain with a focus on existing capacities in strategic storage. The simulated result reflects the perfect market equilibrium and focuses on gas flow configuration.

To address the question, the present work:

- Develops a two-stage stochastic LP model discretized in to daily periods of emergency that minimizes the cost of gas delivery in a linked regional EU gas system in the event that a dramatic disruption occurs coincident with peak gas demand. The proposed model studies the SoS in the EU natural gas network to evaluate solidarity as a mean of cooperation to fight supply disruption in the natural gas network resilience during short-term supply shocks.
- Incorporates in the model all the natural gas supply nodes: natural gas extraction, LNG imports, commercial and strategic storage, pipelines, demand as well as event probability to account for uncertainty of HILP.
- Employs the model to examine three applications related to efficient allocation of gas flows and capacities across Europe in case a HILP event disrupting demand and supply dynamics to assess resilience and security in the EU gas system; to investigate the reliability and value of gas storage to reinforce energy security in Europe; and to explore optimal configurations of novel supply chains in order to inform national and international policies.

Since no work can be found on the EU new agenda of combining security of supply objectives with solidarity and cooperation among MS in relation to the natural gas supply network, the present thesis addresses the gap in the methodological development of techniques capable of both adequately representing a regional coordinated response to temporary supply-demand shocks in the EU natural gas networks, and examine adaptive capacity of the natural gas system through the network resilience. No study has extended the temporary shock approach of operational supply chain and SCR to the gas network and energy security modeling frameworks. A two-stage stochastic optimization-based model has been adopted to study SoS in the EU natural gas network to assess solidarity as a coordination mean to counter supply disruption in the natural gas network resilience over short-term shock in supply. Although it is applied to an EU case study, the model is generic and applicable to emergencies in the natural gas supply, helping discuss the gas infrastructure response to supply disruption beyond those investigated in this work.

It is clarified that mapping market dynamics and preventive measures is out of the scope of this thesis. In a wider perspective this work concerns the optimal use of strategic storage to secure natural gas delivery and in doing so how to account for solidarity among Member States. As discuss later the framework is intended to explore the flow configuration in the European network in the short-term with daily increment time steps during HILP, hence results do not provide insights on optimal ways of reaching SoS by different or alternative means.

2.5.2 Specific objectives

As presented in Chapter 1, the thesis will focus on three application related to resilience and SoS to which the HILP model will be applied. The specific research objectives for each of these applications are as follows:

Application 1: Cold spell

The objective of this study is to unfold the insurance value of storage in the European gas network during unexpected demand peak analyzing a real-world case. To do so, attention has been drawn to the adequacy of alternative ways as solely mean of supplying gas over short-term shock in supply and in particular to LNG because of the oversupply in LNG the EU has been experiencing at the time of writing (see Chapter 4).

Application 2: Modeling HILP scenario with supply disruption

Based on application 1 of this thesis, natural gas storage has been identified as a crucial component in network resilience during emergencies. Seeing the gap in the methodological development of techniques capable of both adequately represent a coordinated response to unexpected temporary supply-demand shocks in the natural gas network, and examine the adaptive capacity of the natural gas system through the network resilience, this application investigate strategic storage as a non-market based optimized coordinated first response to security of supply issues over short-term periods after market-based measures have failed to respond to the emergency. A hypothetical supply shock HILP scenario constructed on several real-world cases illustrates the applicability of the proposed model and allows studying uncertainty in the gas supply in the EU gas network (see Chapter 5).

Application 3: HILP model with Regional/Risk Groups

The objective of this section is to study the impact of a solidarity mechanism, such as the coordinated use of strategic storage among MS, on the configuration of the European gas network with regards to responding to emergencies. For this, a comparison of response to crisis due to outages in the supply during HILP events with different intensity level and event uncertainties among Regional/Risk Groups, as defined by Regulation 1938/2017 [18], is presented (see Chapter 6).

Chapter 3. Methods

This chapter describes the HILP model. The base model, in its deterministic version, is first presented. Then, a detailed formulation of the full model to account for uncertain demand scenarios is described. Finally, general input, data and assumptions are presented. The model then assesses three applications as indicated in Section 2.5.2, for which the specific applications are presented in detail in Chapter 4, Chapter 5 and Chapter 6.

3.1 General description of the model

The HILP model is formulated to simulate optimal natural gas flow configuration within the EU natural gas network minimizing costs. In its latest version, it takes a stochastic approach, analyzing the simultaneous unexpected demand and supply shocks to the grid, across all the natural gas supply chain stages. The mathematical framework hypothesize here is a minimum cost two-stage stochastic LP model over a defined time horizon discretized into daily periods of emergency. The supply chain is divided into four stages: extraction, storage, transmission, and end-user demand.

The proposed multi-echelon and multi-period model includes a spatially detailed description of the natural gas network based on an arc-node description, whit nodes corresponding to the region centers while arcs are the pipelines linking nodes. The modeled system consists of a set of regions/nodes i (alias j) linked by a set of arcs (i.e., pipelines, p). Natural gas can move from i to j if a pipeline (p) exists in a specific time (t). The defined time horizon discretized into daily emergency periods (i.e., 7 days). Nomenclature of parameters and variables in HILP is presented in Table 3-1 to Table 3-3.

The model takes into account forty supply/demand regions, each constituting a node, within Europe and neighboring countries: twenty-six EU Member States, plus the UK, Switzerland, Norway, and major importers and transit countries (i.e., Russia, Ukraine, Belarus, Algeria, North Africa, Tunisia, Serbia, Moldavia, Macedonia, and the Republic of San Marino), as listed in Table 3-4. Regions are characterized by input data, which include: pipelines capacities and length, regional demand, entry/exit commodity flows, production, LNG and storage volumes, and commodity prices.

The model is used to determine overall system costs within a simulation period of seven days. Starting from the initial time period t1 (the base period), the model uses a two-stage stochastic LP approach to minimize transport costs between regions in the EU, with fixed maximum capacities of flows between modes, and known characteristics of supply and demand. After “here-and now” decisions are taken at the beginning of the time horizon (t=1), "wait-and-see" decisions are taken after a number of random events e may realize ($t \geq 2$). Next, the complete simulation process runs for the following time periods, until the final period in the model time horizon (t7). Figure 3-1 and Figure 3-2 show the basic and illustrative model structure respectively.

Table 3-1 Model sets

Symbol	**Description**
i (alias j)	countries in the network (region/node)
p	pipeline
s	storage
sns	Storage, including commercial (sn) and strategic (ss)
t	time period
T1	first time period
Tlast	last time period
$e_{1,2,3}$	event

Table 3-2 Model parameters

Symbol	**Description**
$C_{e,p,i,j,t}$/ $tc_{e,i}$	transport cost [M*€/MWh*]
$cstor_s$	price of commodity in commercial storage [*€/MWh*]
$dmd_{i,t}$	demand in region *i* at time *t* [*MWh/day*]
$F_{i,t}$	maximum extraction capacity in region *i* at time *t* [*MWh/day*]
g_i	commodity price [*M€/MWh*]
$wgv_{j,s}$	working gas volume in storage [*MWh/day*]
$LNGup_{i,t}$	the maximum LNG input flow in region *i* at time *t* [*MWh/day*]
M_i	maximum output flow at node *i* [*MWh*]
$n_{,i}$	LNG commodity price [M*€/MWh*]
$pcap_{t,i,j,p}$	pipeline capacity [*MWh/day*]
prob (e)	probability of event e [*%*]
eff (i)	LNG regasification plant efficiency [*%*]

Table 3-3 Model decision variables

Symbol	**Description**
$x_{p,i,j,t}$	shipment quantities [*MWh/day*]
$extr_{i,t}$	gas extracted [*MWh/day*]
$LNG_{i,t}$	LNG supply [*MWh/day*]
$storage_{s,j,t}$	amount of stored gas [*MWh/day*]
$withdr_{s,i,t}$	amount of gas withdrawn from storage at *t* [*MWh/day*]

Table 3-4 Model regions

Node	**Country**
i1	Austria
i2	Belgium
i3	Bulgaria
i4	Belarus
i5	Switzerland
i6	Czech Republic
i7	Germany
i8	Denmark
i9	Algeria
i10	Estonia
i11	Spain
i12	Finland
i13	France
i14	Greece
i15	Croatia
i16	Hungary
i17	Ireland
i18	Italy
i19	Lithuania
i20	Luxembourg
i21	Latvia
i22	Macedonia

i23	Moldavia
i24	Netherlands
i25	Norway
i27	Poland
i28	Portugal
i29	Romania
i30	Russia
i31	Sweden
i32	Slovakia
i33	Slovenia
i34	San Marino
i35	Serbia
i36	Tunisia
i37	Turkey
i38	Ukraine
i39	Great Britain
i40	Great Britain

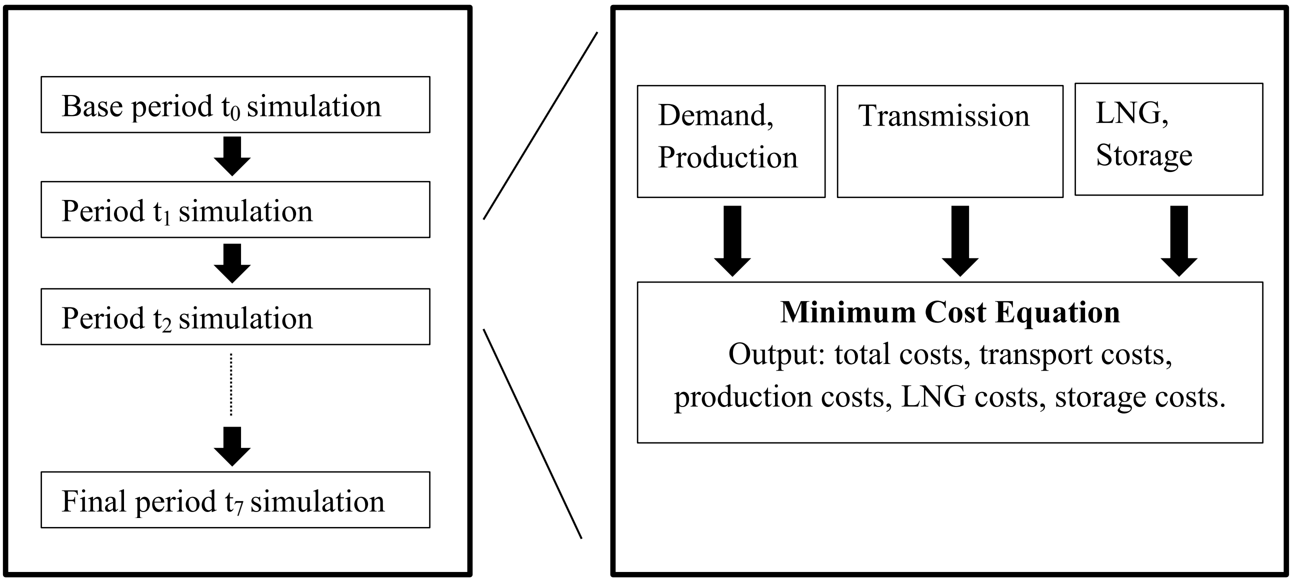


Figure 3-1 Basic HILP Model Structure

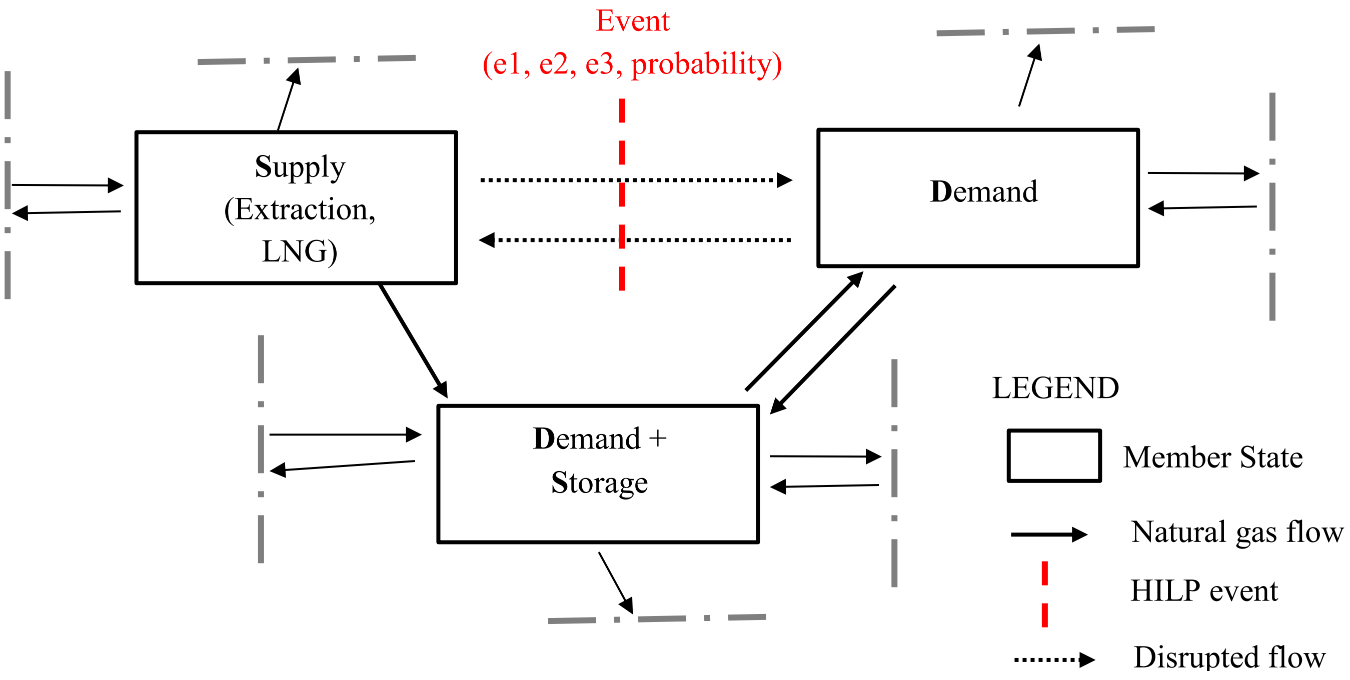


Figure 3-2 Illustrative model structure

3.2 Model formulation

This section presents a full description of the HILP model formulation detailing the constraints and objective function. It starts with the deterministic version of the model in Section 3.2.1 to then expand it to a more sophisticated version in Section 3.2.2 adopting a stochastic analysis with a two-stage approach to include event uncertainties.

3.2.1 HILP deterministic model

In this section the deterministic mathematical formulation is provided, beginning with the definition of the objective function and progressing through constraints such as energy balance and capacity limits.

The basic mathematical framework is a minimum cost LP model discretized into daily periods over a given time horizon. It describes the whole natural gas supply chain to evaluate the natural gas network resilience in the event of an emergency due to interruption in the supply or an unanticipated spike in demand. Extending the approach proposed in [37] the model dispatches natural gas at the minimum cost dispatch throughout all the phases of the natural gas supply chain including extraction, storage, LNG, transmission, and end use demand.

The proposed multi-echelon and multi-period model has a spatially-explicit description of the natural gas network based on an arc-node description, where nodes correspond to the region centers while arcs are the pipelines connecting nodes. The modeled system consists of a set of nodes i (alias j) connected through a set of arcs (i.e., pipelines, p). Natural gas can move from i to j if a pipeline (p) exists with a flow x (p,i,j,t) in a specific time *t* satisfying regional demand balance. A schematic of the supply chain is represented in Figure 3-3.

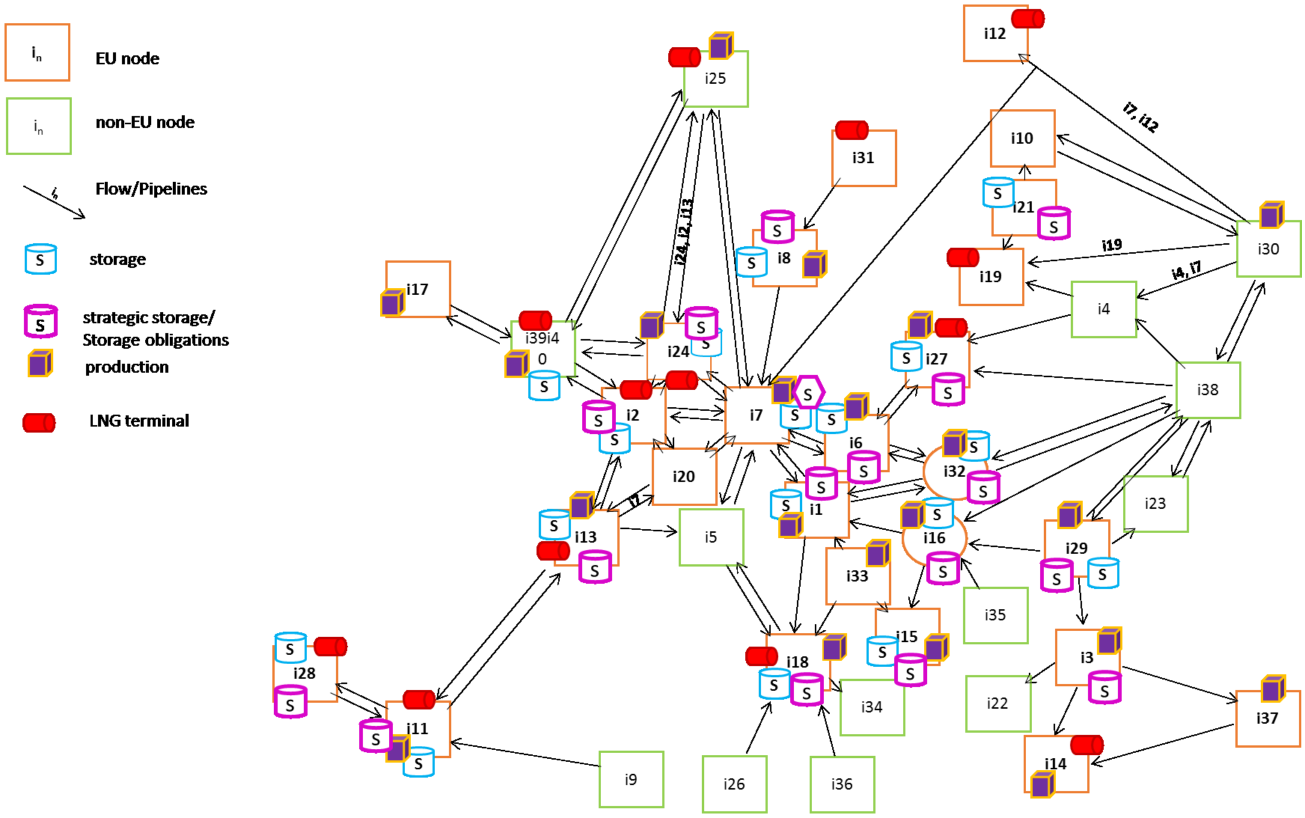


Figure 3-3 Illustrative network structure

The model has been run on daily-steps for seven consecutive day timeframe, in a 1-day step increment. The equations of the model are divided into three main blocks: objective function equations, mass balance equation, and capacity constraints.

3.2.1.1 Objective function

The objective function z (1) represents the sum of all the cost contributions across the natural gas supply chain during the simulated time horizon:

- the cost of natural gas transmission through pipelines, obtained by multiplying the unit transmission cost *c(p,i,j,t)* times the shipment quantities *x(p,i,j,t)*

- The cost of extracting the natural gas, obtained by multiplying the unit supply cost *g(i)* times the quantities of extracted natural gas *extr(i,t)*
- The cost of natural gas supplied through LNG terminals, obtained by multiplying the unit supply cost *n(i)* times the quantities of imported LNG *LNG(i,t)*
- The cost of natural gas in storage, obtained by multiplying the unit stored cost *cstor(s,i)* times the quantities of natural gas withdrawn from the storage *withdr(s,i,t)*

$$z = \sum_{p,i,j,t} c(p,i,j,t) \cdot x(p,i,j,t) + \sum_{i,t} g(i) \cdot extr(i,t) + \sum_{i,t} n(i) \cdot LNG(i,t) + \sum_{i,s,t} cstor(s,i) \cdot withdr(s,i,t) \quad (1)$$

3.2.1.2 Mass balance equation and capacity constraints

The model satisfies a regional demand balance (2). Accordingly, the system is required to fulfill the regional demand *dmd (i,t)* in each region i, at time period t, though import from regions connected through pipelines *x (p,j,i,t)*, local extraction in the supply regions *extr (i,t)*, through stored natural gas *withdr (s,i,t)*, or through the import of LNG *LNG (i,t)* times a efficiency parameter *eff (i)* applied to LNG import values to account for LNG regasification plant efficiency (i.e., approx. 90%) [122].

$$\sum_{p,j} x\,(p,i,j,t) + \sum_{p.j} x\,(p,j,i,t) + extr\,(i,t) - dmd\,(i,t) + \sum_{s} withdr\,(s,i,t) + LNG\,(i,t) \cdot eff\,(i) = 0 \quad (2)$$

Additionally, infrastructural constraints apply to:

- $extr\,(i,t) \leq F(i,t)$, (3)

  Maximum natural gas supply which can be extracted *extr (i,t)* in a region *F(i,t)*

- $pcap\,(p,i,j,t) \leq x\,(p,i,j,t)$, (4)

  Maximum shipment quantities *x (p,i,j,t)*, limited by the maximum pipeline capacity *pcap (p,i,j,t)*. In particular, the maximum value between entry/exit for each connection point in the gas network has been taken as a proxy value for pipelines capacities [44–46]

- $-storage(s, i, t) + storage(s, i, t-1) = withdr(s, i, t-1),$ (5)

  $storage(s, i, "T1") = storage(s, i, "Tlast"),$ (6)

  Withdrawable natural gas *withdr(s,i,t-1)*, limited by the availability limit of the storage -*storage(s,i,t)+storage(s,i,t-1)* (5).
  A periodic condition applies between the first *(T1)* and the last period *(Tlast)* of the analysis in order to guarantee consistency in the storage volume across time when larger time frames are considered (6)
  In particular, since the deterministic model looks at market response to disruption, in this instance the two variables *storage (s,i,t)* and *withdr (s,i,t)* refer only to commercial natural gas storage.

- $LNG(i, t) \leq LNGup(i, t).$ (7)

  Import of LNG *LNG(i,t)* upper limited by the LNG port capacity in a region *LNGup(i,t)*

3.2.2 HILP stochastic model

As mentioned, HILP event model has been designed to appraise EU natural gas SoS implications of demand spike or supply sudden and unexpected outages in the gas network caused by HILP and the value of solidarity measures (i.e., strategic storage) between MS. In its multi-echelon, multi-period two-stage stochastic version, the model consists of a short-term time horizon covering forty regions to describe the EU natural gas network (i.e., twenty-six EU MS, the UK, and major importers and transit countries), and it implements first and second stage decisions.

The mathematical framework here hypothesize is a minimum cost two-stage stochastic LP model over a defined time horizon discretized into daily periods of emergency due to short-term shock in supply or unanticipated increase in demand. It describes the full natural gas supply chain to assess whether a coordinated usage of strategic storage can serve demand while minimizing transport costs in every region considered in the scenario. The general structure of the mathematical model is based on the deterministic version described in detail in Section 3.2.1. Having a short time horizon allows to closely examine the regional reaction to the emergency and to assess the promptness of strategic storage as a solidarity measure. The mathematical formulation is proposed starting from the definition of the objective function, followed by the uncertainty modeling which includes the mass balance equation together with the infrastructure first-stage and second-stage constraints, as discussed in the following sections.

3.2.2.1 Objective function

The model minimizes cost of dispatching across all the natural gas supply chain stages, including extraction, storage (commercial and strategic), LNG, transmission, and end use demand. It includes a set of nodes (i.e., regions) connected through a set of arcs (i.e., pipelines) where natural gas can flow in a specific time satisfying regional demand balance. The model extends the approach of minimum cost dispatching across all the natural gas supply chain stages (i.e., extraction, storage, transmission, and end use demand) proposed in Section 3.2.1, by including strategic storage volumes and uncertainty of a HILP event (*prob (e)*).

$$z = \sum_{p,i,j,t} c(e,p,i,j,t) \cdot prob\ (e) \cdot x(e,p,i,j,t) + \sum_{i,t} g(i,e) \cdot prob\ (e) \cdot extr(e,i,t) + \sum_{i,t} n(i,e) \cdot prob\ (e) \cdot LNG(e,i,t) + \sum_{i,s,t} cstor(sns,i) \cdot withdr(sns,i,t) \qquad (8)$$

The parameter *prob (e)* has not been applied to storage, since the operations of withdrawal have a greater inertia than the supply chain mechanisms. In this way, while the remaining variables can be resolved at the time when the disruption entity is known, storage-related operations are decided before the disruption occurs.

3.2.2.2 Uncertainty modeling: first- and second-stage decisions

Being a two-stage stochastic model, it consists of first-stage and second-stage decisions. The former, which include level of commercial and strategic natural gas in storage and the amount of commodity withdrawn from storage, are set at the beginning of the time horizon prior to the resolution of some future uncertainty (T0), in our case a HILP event; whereas the latter which mainly relate to the commodity costs, include production, transmission, and LNG supply, are known only after the uncertainty is resolved (T1 to T7). Thus, when a random event materializes, or not, through an event probability e, then second-stage variables it is realized. Hence, the model incorporates event uncertainty for HILP supply interruptions in the form of three event probabilities (*e*) all modeled at once. To this end, no event (*e1*), equipment and infrastructure breakdowns and natural disasters with material failure (*e2*) and ground movement (*e3*) are taken as events probabilities. With *e2* it indicates a material or construction defect in one component of the infrastructure, while with *e3* a movement of the ground due to landslide, erosion, flood or similar occurrences (see Section 3.3.5). In addition, storage is evaluated at the end of each time period.

With such a structure, given that uncertainty the model is able to hedge against the possibility of the HILP event occurring by appropriately choosing infrastructure make-up to rendering the gas supply mix that minimizes the expected cost of serving gas demand with and without the use of strategic storage.

- ***Mass balance equation***

$$\sum_{p,j} x\,(e,p,i,j,t) + \sum_{p.j} x\,(e,p,j,i,t) + \,extr\,(e,i,t) - \,dmd\,(i,t) +$$
$$\sum_{s}\,(sns, withdr(sns,i,t)\,) + \,LNG\,(e,i,t)\cdot eff\,(i) = 0 \qquad (9)$$

Variables are divided into:

- First-stage decisions (a), which are implemented before the uncertainty unfolds, deal with levels of storage. They are two: level of commercial and strategic natural gas in storage *(storage(sns,j,t))* and amount of commodity withdrawn from storage (*withdr(sns,j,t))*. "Here-and now" decisions are taken at the beginning of the time horizon (t=0).
- Second-stage decisions (b), which are implemented after the uncertainty is disclosed, deal with the cost and flows. They are three: natural gas transmission (*x(e,p,i,j,t)*), natural gas production (*extr(e,i,t)*) , and natural gas supply through LNG terminals (*LNG(e,i,t)*). "Wait-and-see" decisions are taken after a number of random events *e* may realize (t ≥ 1).

The sequence of events and decisions is thus summarized as:

$$a \;\rightarrow\; prob(e) \;\rightarrow\; b(e,a)$$

where *a* is deterministic and *b* is measurable with respect to the realization of the random event *prob(e).*

- ***Infrastructural constraints***

In addition, infrastructural constraints apply to the expanded version of the model.

First-stage constraints are applied to the storage same as in the deterministic model. The terms "commercial storage" and "strategic storage" have been defined. Commercial storage represents first and foremost a valuable tool to improve market flexibility, meeting demand fluctuations, as described in more detail in Chapter 2. Strategic storage, on the other hand, is a pre-determined volume of gas taken out of the market and kept as a reserve. It serves as a buffer in the case of a market failure or an emergency, or to safeguard the transmission system's integrity in extreme conditions, and it can only be utilized to meet the needs of protected customers. Each of these first-stage constraints have been applied to both commercial (sn) and strategic storage (ss) separately, as follows:

- $-storage(sn,i,t) + storage(sn,i,t-1) = withdr(sn,i,t-1)$, *(10)*
  Level limit on natural gas in commercial storage available for withdrawal

- $-storage(ss,i,t) + storage(ss,i,t-1) = withdr(ss,i,t-1)$, *(11)*
  Level limit on natural gas in strategic storage available for withdrawal
- $storage(sn,i,"T1") = storage(sn,i,"Tlast")$, *(12)*
- $storage(ss,i,"T1") = storage(ss,i,"Tlast")$, *(13)*
  Storage volume consistency guaranteed by periodic condition on the first and last period of the analysis, hence the level of storage at the beginning of the time period (T1) is the same as the level at the end of the time period (Tlast).

Second-stage constraints are applied to production, transmission and LNG terminals, as follows:

- $extr\ (e,i,t) \leq F(i,e)$, *(14)*
  Natural gas supply extraction limit in a region

- $pcap\ (p,i,j,t) = x\ (e,p,i,j,t)$, *(15)*
  Pipeline capacity limit on natural gas shipment quantities.

- $LNG\ (e,i,t) \leq LNGup(i,e)$. *(16)*
  Upper limit on LNG import port capacity in a region.

3.3 General input data and assumptions

This section presents the general input, data and assumptions used for modeling; whereas when applicable, case specific input are included in each main applications of the model described in Chapter 4, Chapter 5 and Chapter 6 respectively.

As far as the general modeling is concerned, February 2018 is used as the reference month for data in this work. Real-world data from the Burian or Anticyclone Hartmut, a cold spell (i.e., an extremely cold weather condition with temperatures below the seasonal average) that invested the EU natural gas network between February 23rd and March 5th, 2018, have been used as input data to the model. The Burian week is used as a real-case unexpected cold weather event to more realistically illustrate the distressed of the gas network and volumes from daily injection of natural gas flows, LNG import volumes, natural gas injected/withdrawn from storage, and production volumes to construct demand. It helps to more realistically depict the natural gas availability in the network in an emergency situation. All data collected are referencing either the first quarter of the reference year or the exact period when the weather shock happened. A summary of the used data sources is provided in Table 3-5.

On the other hand, spatial resolution is regional and it is divided between EU Member States and EU major natural gas suppliers for a total of forty regions, or nodes, connected by single pipelines accounting for maximum pipeline capacity allowed by each node. In particular, each region, within the EU network, has been defined with its pipeline capacity, network pipeline length, demand, production costs, transport costs, commodity price, and when applicable commercial and strategic storage volume and price, as well as LNG volume and price taken from actual data from the Burian week. A schematic of the supply chain and network structure is illustrated in Figure 3-3.

Table 3-5 Sources for data input collection

Data	**Database**
Entry/exit NG flow	ENTSO-G Transparency Platform [123]
Pipeline length	ENTSO-G Transparency Platform; Snam Internal Database; TSO websites data [1,123]
Pipeline capacity	ENTSO-G Transparency Platform [123]
Entry/Exit NG volumes	ENTSO-G Transparency Platform [123]
LNG import volumes	IHS; ENTSO-G [123,124]
Storage	AGSI+ [52]
Production	IEA extended energy balance [125]
Demand	1,4-7; IEA, Eurostat, TSO websites data, Government data [1,123,124,126–128]
Price	ICIS, STOGIT, Snam Internal Database [1,129]

3.3.1 Pipelines capacities and length

To account for physical congestion in the pipelines, pipeline capacities *(pcap (p,i,j,t))* (4) were calculated as the maximum value between entry/exit for each connection point in the gas network (i.e., figurative points where exporting countries meet the gas volume needs of importing countries), for a total of 198 cross-border transmission interconnection points [123]. For the period February 19th to March 9th, 2018, the volumes of every single entry/exit point connecting the nodes in that specific member state were summed up. This resulted in the maximum flow value for the Burian period, which has been used as a proxy value for pipelines capacities, for 27 regions (including Norway), plus imports from major importing countries. In addition, in terms of the pipeline's primary direction, entrances have been deemed positive flows and exits have been regarded negative flows (i.e., the direction with greater volumes transported). Pipeline length data was obtained from the same database on the ENTSO-G transparency platform and cross-checked against data from Snam's internal database as well as publicly available data on the websites of major European TSOs [1,123].

3.3.2 Regional demand

EU natural gas demand volumes *(dmd(i,t))* (1) have been built as the total of all daily volumes injected into the European gas network: entry/exit natural gas flows, entry/exit LNG import volumes, and natural gas injected/withdrawn for storage and production volumes [52,123,124]. All final national demand figures have been cross-checked for accuracy using estimated data from the IEA and Eurostat, as well as national TSOs and government data [1,52,123,126–128,130].
The input parameters were gathered from several sources. LNG import volumes (LNG (i,t)) (1) (2) for the same Burian period are based on a commercial database and cross-checked for missing data against the ENTSO-G Transparency Platform, using data for terminal maximum capacity in the period Jan 2018-July 2019 [123,124]. Data for production *(extr (i,t))* (1) (2) are modeled data from IEA extended energy balance and are calculated to give a daily production value for the Burian period [125]. Finally, data for natural gas in commercial storage *withdr(s,i,t)* (1) (2) are derived from AGSI+, a GIE transparency platform on storage data [52]. As a proxy for daily maximum gas storage capacity at each node where commercial storage exits, the maximum value of yearly gas volume in storage for commercial usage divided by the number of emergency days was used.

3.3.3 Price estimate

The model includes transport cost (*c(p,i,j,t)*), commodity price (*g(i)*), LNG commodity price (*n(i)*), and storage price (*cstor(s,i)*) (1) have been included in the model. The following data was collected for the same Burian timeframe as the natural gas demand data (i.e., February 2018): (i) from STOGIT, the Italian Storage System Operator (SSO), for weighted average assignment price for storage (seasonal peak modulation from April/May 2018), since Italy has been assumed as a reference case as far as storage is concerned (i.e., Italy is the only EU country with a pure strategic storage mechanism in place, and it has the second largest storage capacity in Europe in terms of both commercial and strategic storage operated by one single SSO); and (ii) from ICIS and Snam internal database for average monthly hub (2008-2018) and average monthly LNG prices (2012-2018) to account for natural gas commodity costs [1,129]. Only the major liquid European gas hubs, such as Gaspool, NBP, NCG, PEG Nord and TRS, PSV, PVB, TTF, CEGH, and Zeebrugge, have been considered in terms of hubs and LNG entry points, as liquid hubs are the ones that the natural gas market uses to establish the price of the commodity. For MS that have no data, a proximity zones criterion has been used. Since the model is based on data from February 2018, two hubs in France were evaluated. Finally, transport costs share have been built on average hub monthly price and average transmission costs breakdown for standard gas households price (November/December 2017) in different EU capitals in each MS from ACER [1,131] (see Section 3.3.6 for further assumptions on costs).

3.3.4 Strategic storage

Other factors, such as the insurance value of storage against unexpected events and the lack of seasonal alternatives (e.g. LNG), mandatory strategic storage, a share of storage capacity already allocated long-term, and reputation loss in the event of supply disruptions, can all contribute to making gas storage a significant insurance instrument to provide flexibility.

The value of storage, as emphasized by the literature [40,44], lies also in providing a flexible response during periods of considerable high demand. Le Fevre et al. [44] reveals that even if storage in winter 2010-2011 appears to have had a lower impact in total terms as a percentage of total European supply sources, it was of critical in meeting demand during the extreme cold winter of 2012 (Jan.-Feb.) and subsequent disruption from Russian supplies, where it was accounted as the joint highest source of supply to Europe [44]. Furthermore, Skea et al. [40] shows that investments in storage are an appealing choice from a social-cost benefit standpoint, that may mitigate the impact of a natural gas shortage situation [40].

Recognizing the prominent role storage plays as insurance instrument within the gas system, the model developed in this study looks into strategic storage as a strategic natural gas reserve the EU could tap into during HILP. In its attempt to hedge against potential supply disruptions and defend national energy security during energy crisis, such a reserve mimics the concept behind the global strategic petroleum reserve held in Europe by all thirty members of the International Energy Agency either by the country itself or by a company, which was first started by the US as a strategic oil reserve in 1975 after the 1973-74 oil-embargo. The amount of oil in stock is based on average 90-day crude oil imports for the country previous year and it does not count towards a country proven oil reserve.

In particular, the Italian pure strategic storage mechanism, where storage companies take off the market 10% of storage capacity and commit it to strategic reserve, has been used as a reference in the model presented in this study. Domestic producers and importers cover all costs of the stored gas reserve and the Ministry determines the volumes, which have averaged approximately 4.6 bcm over the last five years (see Section 2.1.2). For the purpose of this work, strategic storage is implemented in those MS where storage obligations already exist (i.e., Austria, Belgium, Bulgaria, Czech Republic, Germany, Denmark, Spain, France, Croatia, Hungary, Latvia, Netherlands, Poland, Portugal, Romania, and Slovakia) and volumes in storage are parametrized on Italian volumes (see Table 3-6). The hypothesis is also in line with the objective of the EU policy towards an infrastructure integration at the EU level as mentioned in section 2.2 [18].

Table 3-6 EU strategic storage reserve maximum daily capacity per Member State (MWh)

Member State	**Maximum daily capacity (MWh)**
Austria	4,221,322
Belgium	392,181
Bulgaria	262,599
Czech Republic	1,775,929

Germany	11,209,022
Denmark	548,850
Spain	1,303,136
France	5,288,220
Croatia	275,782
Hungary	2,587,752
Italy	9,804,667
Latvia	1,146,379
Netherlands	6,559,622
Poland	1,713,331
Portugal	112,111
Romania	1,251,101
Slovakia	1,764,767

3.3.5 Event probability and magnitude

Based on Stern [132] and Chaudry et al. [107], Skea et al. [40] highlight how threats to supply can be either lasting disruptions or temporary shocks and how resilience is the most appropriate indicator to evaluate a response to the latter. In addition, after reviewing gas supply crises and accidents over the past 20 years, the authors support the vast part of the literature in saying that the majority of failure is due to equipment and infrastructure breakdown, as well as extreme weather conditions, decreasing the possibility of meeting peak demand.

Each year since 1970 the European Gas pipeline Incident data Group (EGIG), which comprise of seventeen natural gas TSO as of 2016, collects data on the natural gas transmission system to include pipeline characteristics such as diameter, pressure, grade of material and wall thickness and specific information on incidents occurred in the EU network, to include the leak size, the initial cause of the incident (e.g., external interference, corrosion, material failure, ground movement, etc…), the occurrence of ignition, and the consequences.

According to the literature, the majority of failure is caused by equipment and infrastructure breakdown, as well as severe weather conditions, which make fulfilling peak demand more difficult [40]. Historical statistics on natural gas outages, EGIG industrial database recorded 1,366 pipeline incidents from 1970-2016, indicate that ground movement are characterized by potentially severe repercussions [133]. According to the EGIG's historical data collection, the majority of incidents with serious consequences are caused by natural gas released igniting, which, depending on the size of the leak, renders the pipeline inoperable and prevents natural gas transit; thus, whether or not an unintended release ignites is a key factor in determining the magnitude of the resulting threat [133].

To be able to analyze the failure frequencies and the causes of failures, EGIG database includes for each incidents: the characteristics of the disrupted pipeline (e.g., pressure, diameter, year of construction, wall thickness, geographic location…), who detected the incident and how, the initial cause of the accident (e.g., corrosion, material failure, construction defect, hot tap, ground movement…) with additional detailed indication (e.g., location, type of defect or movement…), the leak size, the presence of ignition or else, and the consequences of the incident. Furthermore, the leak is characterized based on the diameter of the hole, the leak is defined as rupture (i.e., hole diameter ≥ pipeline diameter), hole (i.e., hole diameter > 2 cm), and crack (i.e., hole diameter < 2cm), with the former two having a larger proportion of gas release to ignite as well as the occurrence of injuries and fatalities [133].

With all the available collected data primary and secondary failure frequency of the incident are then calculate. Frequency is indicated as the number of accidents divided by total or partial exposure. Primary frequency includes the total system length of pipelines, whereas secondary frequency is calculated per class of a parameter (e.g. diameter). EGIG also compute the probability of a target to ignite and its consequences on individuals which are determined based on two scenarios that depend on the maximum level of irradiation of the ignition: lethal effects and significant lethal effect. Results are collected in a matrix helpful to evaluate the tolerability of an incident.

Since one of the ways of assigning probabilities to events is by means of the relative frequency, which is a function of historic events that reflects actual risks, hence the uncertainty estimate obtained by the model is a probability estimate that may be tested in real life events under the model assumptions [134].

To this end, Vianello et al. [135] examines the failure frequency of the equipment using data from EGIG and OGP reports with data on gas pipeline incidents in the EU, and collected ignition probability and likelihood, reporting probability of top events that can ignite the natural gas pipelines. The authors in the same study then calculated the relative frequency of occurrence, based on the events probabilities, and estimated the relative frequency of catastrophic rupture (13%) for each of the recorded occurrences.

The proposed analysis takes into consideration HILP events (e.g., equipment and infrastructure breakdowns and natural disasters), which imply serious repercussions as well as catastrophic rupture on the natural gas network supply [133]. The latter are defined as when the risk triggers ignition of natural gas released with a consequence of severe supply interruption to no natural gas transit, as well as adoption of non-market actions to supply at least protected customers (i.e., households, small and medium enterprises, and district heating installations) [136]. Since no specific data on the magnitude of such events is published in the database nor could be found in the literature, for the purpose of this study the magnitude is considered as the percentage of natural gas import loss through disrupted pipelines and it is referred to specific historical disruption cases (see Chapter 5.2).

In terms of event probability of occurrence percentages (e) for the model proposed in this study, conclusions on event types that lead to failure, from Skea et al. [40], as well as relative frequency of catastrophic rupture percentage, from Vianello et al. [135], have been taken into account and (e) have been calculated using 13% of the relative frequencies from historical database for rupture leaks, which are assumed as a reasonable approximation for e, both for material failure events (e2) (i.e., a material or construction defect in one component), and ground movement events (e3) (i.e., a movement of the ground due to landslide, erosion, flood, dike break, etc.) [133]. Additionally, there is a probability that no event occurs and demand is fully met by supply (e1), calculated as the difference to 1 of (e2+e3) (see Table 3-7).

Table 3-7: Events probabilities (e) and loss of gas import (%) (Source: Elaboration of the author on the basis of [133])

Leak size	**No event (e1)***	**Material failure (e2)***	**Ground movement (e3)***	**Loss of gas import**
Rupture	*0.999998869*	$2.86 \cdot 10^{-7}$	$8.45 \cdot 10^{-7}$	*up to 80% on multiple pipelines concurrently*

* (e) refers to the probability used in the model, whereas (e1), (e2), and (e3) are the disruption episodes considered.

3.3.6 Model assumptions

The model focuses on short-term emergencies, and therefore it concentrates on a specific network configuration (February 2018) and it does not consider how the market could affect supply/demand dynamics. Consequently, there are some limitations in the modeling of costs and deliverability with respect to both time and technical deliverability considering different stages in the supply chain.

When it comes to costs, cost discounting is not incorporated in the model. The time effect is negligible, given the short time frame (less than a week) in which the response to an emergency is evaluated, therefore costs are totaled evenly. The model studies the specific situation where market conditions do not longer hold as a quick response to the emergency is required, notwithstanding any previous agreement [37]. For this reason, the model does not include the constraints due to take-or-pay tariffs or contracts, not capital or specific operating costs for the network and storage.

In addition, as Cervigni et al. [137] mentions in their analysis of gas transmission tariffs in the EU natural gas transmission network, entry/exit tariffs (i.e., reservation of capacity from injection to balancing point and from balancing point to off-takes, through zones, which mostly coincide with MS land, instead of along contractual paths) were vital in creating a more liquid EU natural gas market at the time they were introduced in 2007 with the Third Energy Package facilitating a smooth transition from a vertically integrated market. In fact, by fostering independence of entry and exit capacities, they allowed for different gas flow patterns in Europe and a more efficient use of the gas transport system. On the other hand, the authors also indicate that in the current market scenario the existing long-term capacity reserve, which represents a solid share of the present market capacity, are not affected by the entry/exit tariff as holders of the long-term contracts pay for the transmission tariffs whether they are going to use the long-term capacity or not [137].

Hence, as a first approximation the model does not take into account actual single MS natural gas transmission entry/exit tariffs. Transport costs have been assumed to be evenly distributed across MS and are based on their share among system costs as indicated in ACER [131].

As Dieckhöner et al. [98] indicates, natural gas infrastructure models aggregating European countries into regions or into nodes without a pipeline-specific analysis of gas transport, abstract from potential congestion assuming that the transport of natural gas in the wider EU network is organized efficiently, enabling an adequate allocation of the commodity across countries. The author concludes that any load shedding identified by such models would signal inefficiency in the natural gas transport. In addition, natural gas inertia means that delivery time from supply points is higher for natural gas than other commodities such as electricity. To overcome and meet changes more rapidly, TSO keep line pack gas within the pipelines [138]. Line pack is crucial to the physical operation of the system as it helps stabilizing pressure across the network. It is higher in the winter to maximize flexibility of the system to cover for increase in demand, strong diurnal profiles, and larger daily swings. These require maintaining higher pressure in the middle of the network, hence a greater line pack to balance the system.

Hence, with respect to time deliverability, delay in the natural gas supply is not taken into account. Being HILP model an aggregate node model run in winter conditions, it can be assumed that congestion in the pipelines and line pack make delay in delivery time negligible in a daily view of the system and in a preliminary approximation a model with a daily period time horizon [133].

On the other hand, with respect to technical deliverability, in order to model the network characteristics in case of a real-world case emergency and to more closely represent the natural gas system response to such a crisis, it is essential that the model depicts the existing picture of the network, hence planning decisions related to the infrastructure expansion are not modeled as they are not relevant in this instance.

In addition, looking at the different stages of the supply chain in more detail, although anomalies in the supply are addressed through the modeled shock in the natural gas supply, the dynamics of natural gas extraction are out of the scope of the analyses. The existing daily maximum level of natural gas coming from production during the Burian period used in the model gives the volume of commodity available to soundly render the reaction of the network in case of HILP. With regards to storage, the model does not model its physical characteristics in full. Storage capacity is based on gas levels in storage at the time of the real-world crisis considered by the model (February), which account for storage utilization losses from the start of the stored gas delivery period (November -

April), and thus can be assumed to realistically depict the actual deliverability allowed by the storage at that time in a short-term natural gas outage [17]. Finally, although the model enables LNG imports to fulfill the energy demand and takes in to account the efficiency of LNG liquefaction/regasification plant, it does not model the full LNG chain. In a short-term emergency, actual LNG volumes in LNG terminal at the time of the crisis are a close approximation of LNG availability for the system; hence delays in attracting LNG cargoes are minor in the early disruption.

Finally, although recognizing economic effects of a severe disruption and the importance of indirect costs when dealing with HILP events [139,140] and that excluding them from the model could lead to an underestimation of the overall damage of HILP, given the uncertainty of their estimation, they have not been taken into account at this stage being the social costs and the macroeconomic activities of countries related to commodity price shocks outside of the scope of this work.

In the following chapters, the deterministic and the two-stage stochastic linear programming version of the model explore different applications that show an EU-wide optimized coordinated first non-market based response to security of supply issues. Starting by appraising the value of LNG oversupply in the EU market and reflecting on its interaction with storage in case of unexpected demand shock during a cold spell (see Chapter 4), the analysis then moves to investigating both supply outages during HILP modeling uncertainty in the gas supply chain (see Chapter 5) as well as the resilience of the EU natural gas network to HILP when strategic storage reserve are used in a coordinated and supportive fashion throughout the EU by Regional Risk Groups (see Chapter 6).

The commercial software GAMS v31.2.0, CPLEX solver, has been adopted for implementing and solving all three applications.

Chapter 4. LNG and storage complementarity in securing EU gas network resilience

This chapter presents a modeling analysis of the EU natural gas network resilience in case of short-term supply disruption or unexpected increase in demand looking at the value of LNG in the system, introduced in Section 4.1. For this application the deterministic version of the model, as described in Section 3.2.1, which solves for the most cost effective transmission of gas flows, capacity and storage utilization in an interconnected EU gas system, has been adopted. In Section 4.2 and 4.3 the model is validated by comparing the base case results with other projections from the literature. Following this, sensitivity analysis results are discussed focusing on price and volumes for natural gas, LNG and storage in Section 4.4.

4.1 Framework of analysis

Current consumption of natural gas (NG), which accounted for 25% of the energy mix in 2016 [2], is anticipated to rise further. In the short-term, decommissioning of coal-fired power plants will drive natural gas demand growth, followed by increased penetration across the energy demand sectors [5], with global natural gas consumption reaching roughly 4200 bcm per year by mid-century [3].

Natural gas sources have been shifting over time. On one hand, services related to consolidate commodity consumption (i.e., gas storage) have evolved to provide a liquid and integrated market. On the other hand, not only LNG share in the EU energy mix has increased, but also other renewable low-carbon gas (i.e., hydrogen and biomethane) have been introduced into the gas network more forcefully as of 2019 to reduce the carbon intensity of gas in view of the long-term climate targets the EU has set to reach.

4.1.1 Evolution of LNG in the EU market

In an Europe where decarbonization of the sources is going to play a vital role up to 2050, residual natural gas shares are going to be met both by imports, especially from Russia, and LNG volumes, with their relative proportion based on the balance of economics, security of supply, and developments in the global LNG market. On a worldwide basis, LNG is already a significant supplier of gas. It accounts for 10.7 % of the global natural gas supply, and it is projected to play a significant role in demand growth. LNG has had the greatest increase among natural gas sources over the last decade, and this trend is anticipated to continue. International LNG supply will most likely be led by projects in Australia and Russia, as well as the expansion of American LNG projects, while import demand is projected to rise in markets throughout Asia, including China, Pakistan, and Bangladesh [141].

Similarly, LNG has the potential to play a significant strategic role in the European natural gas market. European countries are largely reliant on natural gas imports due to declining domestic production in Europe (from 134 bcm in 2015 to a predicted 108 bcm in 2020), and unevenly distributed reserves. Germany, Italy, and France are among the top ten importers in the world, accounting for 20 % (on a volume basis) of global imports. There is a need for diversification of supply sources, as 60% of natural gas demand in Europe is met by a small number of gas suppliers (i.e., the largest ones being Norway and Russia) [124,142]. In particular, in 2019 LNG represents 23% of the total EU gas imports, from 12% in 2018, which exposes the EU to global natural gas market dynamics more and more. Nonetheless as of 2019, 24 large-scale terminals are operational and 18 more are planned to be constructed across Europe and running in the next five years, contributing to security of supply, diversification, greater market competition, as well as to flexibility of the system operation [143,144].

Looking at the evolution of the LNG traded volumes to Europe, in the second quarter of 2019, EU large-scale terminals have seen their import volumes dramatically increasing if compared to the same quarter in 2018 (e.g., +300% in Norway and Greece in one year). The primary source of LNG waterborne trade in Europe in 2019 was Qatar, which supplies almost half of the LNG in the EU. This is almost double the volumes from Russia, and almost three times the volume of Algeria, US, and Nigeria [1]. In addition, starting in 2017 LNG demand have been decreasing in Asia, an historical strong LNG attracting market, and so has price spread between the Asian and the European market, importers such as the US, Middle East and North Africa have lean towards Europe as an alternative more liquid market. Concurrently, the US and Australia have increase their liquefaction capacity adding volumes to the global supply [143].

Consequently to the substantial evolution of the European LNG market, LNG imports from the US and Australia have grown importance (i.e., the US became Europe’s major LNG supplier in 2020), adding volume to the present surplus in LNG imports to Europe enhancing diversity and security of supply [2,5,143].

4.1.2 Value of LNG during disruptions

Although gas demand has been stagnant in early 2019, Europe registered record levels of LNG imports in the third quarter of the year. The position of LNG within the EU gas market has been strengthened by both increasing the LNG capacity of Europe and also providing additional services and products that allow for more flexibility in the market as well as attract more LNG importers, with terminal utilization rate and regional market integration and supra-national competition growing leading to increased gas flows between different countries in the EU as well as overall system efficiency [143]. This increasing trend is expected to continue, driven by structural changes in the natural gas market and the EU Green Deal “net-zero” legal obligations. On one hand, the demand for natural gas is likely to grow up to 2030 when natural gas is supposed to maximize switch from coal to gas in heat and power sectors [2,5]. On the other hand, LNG could make natural gas a much more flexible commodity, improving market liquidity. Ease of substitution between one LNG cargo and another enables the exchange of natural gas in a way similar to that of oil and this contributes to enhance LNG security of supply potential. LNG can aid in balancing seasonality, managing shorter-term natural gas (and electricity) demand variations, and diversify the European natural gas supply [145].

In the last decade as an aid to EU energy security, LNG has aided in responding to the market signals to accommodate increased heating demands during unprecedentedly cold winter events as well as to surges in demand in case of severe supply interruptions. Few cases exemplify this:

- In February 2012, the intensely cold weather conditions, along with the interruption of the transit route to Western Europe from Ukraine resulted in a 13% increase in LNG imports in Europe in 2011, with the Netherlands increasing their LNG demand by 237% [146].
- In March 2013, the market responded by importing more volumes of LNG due to a disruption in the Nyhamna plant (Norway), together with a concurrent cold spell and a brief Interconnector outage (UK). Although the market price level reaction was rapid enough to attract LNG volumes, LNG cargoes were unable to respond quickly enough to the abrupt shock, which was initially cushioned by storage, UK Interconnector capacity, and demand-side response [6].
- Finally, in January 2017, during Europe coldest days of the year, LNG freight delays caused gas supply shortages in the continent’s southern regions [7].

In their historical review of gas supply interruptions, [40] report that there has been 11 gas supply crises and accidents in the EU gas grid from 1998 to 2011. There have been additional four accidents between 2012 and 2018, the majority resulting from infrastructure deficiencies and extreme weather [1]. As the impacts of climate change become more evident, regions such as Europe will not only see a rise in global average temperatures, but will also be more vulnerable to extreme and unpredictable cold weather events, where energy supplies will be difficult to organize to meet energy demands and they would need to be working harmoniously to overcome the crisis.

As ad hoc methodologies for assessing energy security in Europe and defining metrics to measure the resilience of the European natural gas network become more relevant, this application introduces a modeling framework to assess the integration of natural gas, storage, and LNG supply in emergency events characterized by exceptionally cold weather and spike increase in natural gas demand. It takes into account a real-world case study built on the recent exceptional cold weather which hit Europe in February 2018 causing the European natural gas demand increases more rapidly than the natural gas supply sources. Gas network resilience enhanced via storage and LNG uptake is evaluated as a means to address the urgent growth of demand.

4.2 Model application to EU natural gas network resilience to demand spike

Due to the oversupply of LNG imports in the EU, the issue of whether this resource may be useful for the EU natural gas network in reacting to unexpectedly strong cold weather has arisen. The research on the EU gas network focuses on three primary issues: (i) supply flows in reaction to import interruptions as a mix of multiple hypothetical accessible options, (ii) infrastructure capacity investment, and (iii) the economic effect of supply disruptions.

As highlighted in Chapter 2, Section 2.4.1, the literature shows a clear gap in the methodological development of techniques capable of adequately modeling natural gas systems' supply-demand crises and analyzing the relative resilience of the network over short-term periods, which would prevent the system from shutting down. This application presents a thorough aggregated infrastructure model for assessing the short-term resilience of the whole European natural gas network in the event of a non-hypothetical demand spike induced by Anticyclone Hartmut, commonly known as Burian. By assessing the EU natural gas network resilience over short-term shock in supply, the proposed modeling framework allows studying the essential complementarity between LNG and storage during natural gas demand crises, thereby providing an optimization-based approach to revealing the value of LNG in the natural gas EU network.

Attention has been drawn to LNG because of the oversupply in LNG the EU has been experiencing in the past few years as reported at the time of writing. The model, as fully describe in Chapter 3, has been adopted in its deterministic version (see Section 3.2.1) to evaluate the network resilience to demand spikes during a cold spell, an extremely cold weather conditions with temperatures below the seasonal average.

As mentioned, natural gas extraction, LNG imports, storage, pipelines, and demand are all represented in the model. In an interlinked EU gas system, the proposed LP model minimizes the cost of gas delivery. It investigates the system's flow configuration in order to assess the network's resilience in securely supplying gas to each of the countries considered in the scenario. Gas transported from one node (country-region) to another, production at the relevant node, storage working volumes and LNG terminals volumes are all included inflows; whilst outflows include flows to other nodes, including storage withdrawal, or to demand at a given node, as illustrated in Figure 3-2 and Figure 3-3. Real-world data are used to validate the modeled natural gas flows in Section 4.3. Following, a sensitivity analysis on key parameters of the natural gas infrastructure is presented and some concluding remarks in Section 4.4.

To address the value of LNG in the natural gas EU network during a cold spell, three scenarios are analyzed: (1) the *baseline* scenario carried out to reflect the actual costs and flows configuration of the EU gas network during a cold spell and to validate the model; (2) a *sensitivity analysis* carried out to assess the variables responsible of the major system responses during an extreme cold event, with particular focus on: natural gas and LNG prices, commercial storage costs, LNG import and commercial storage volumes; and (3) an *LNG cost* optimization carried out imposing extreme LNG prices aiming at defining the remit of the role of LNG.

In (1) *baseline* the model validation is presented taking demand, supply, commercial storage volumes and prices, commodity prices, and transport costs during Burian and comparing them against actual monthly/seasonal traded volumes and prices/costs. Building up from (1), in (2) *sensitivity analysis* the impact of LNG availability in the EU natural gas network during an extreme cold event is depicted. The analysis has been built calculating variations from average yearly data with regard to average data from the Burian week on all of the parameters that constitute the baseline optimization, specifically demand, production, commercial storage volumes and prices, commodity prices, and transport costs [1,124]. Finally, in (3) *LNG cost* optimization LNG cost are analyzed to assess their impact on total system costs, using maximum and minimum average monthly LNG prices taken from the global LNG market.

4.3 Baseline optimization scenario analysis

The effects of the unprecedented and unexpected out of average cold spell that blasted in Europe in February 2018 had repercussion both on natural gas volumes availability and prices fluctuations. In particular, the following variations were recorded during the Burian week compared to average monthly/seasonal values as applicable: +40% commodity prices from the average monthly price at the different European hubs (2008-2018); +20% LNG prices from average monthly LNG prices at the different European hubs (2017-2018); and -35% availability of storage volume from storage maximum capacity at the different European storage sites (Oct.-Nov. 2017) [1,52,129,147,148]. In the baseline scenario, variations in LNG and storage volume and prices, commodity prices, and transport costs during Burian have been taken as a benchmark to define and validate a scenario against which to build the analysis on network resilience and LNG value in responding to demand shock through the sensitivity analysis and the LNG cost optimization scenarios (See Table 4-1).

Table 4-1 Parameter variations in the baseline scenario compared to the Burian values

Natural Gas Parameter			**Variation in *baseline* scenario**
Demand	Volumes	*dmd (i,t)*	None
Production	Volumes	*extr (i,t)*	None
Commodity	Prices	*g* (*i*)	+40%
LNG	Volumes	*LNG (i,t)*	-5%
	Prices	*n* (*i*)	+20%
Commercial storage	Volumes	*withdr (s,i,t)*	-35%
	Cost	*cstor* (*s*)	None
Transport	Cost	*c (p,i,j,t)*	None

The exceptional cold that hit Europe in February 2018 brought the gas system to an undersupply condition with exceptionally high hub prices, especially in Northern Europe at The Title Transfer Facility (TTF) in the Netherlands (i.e., the most liquid virtual trading point for natural gas in Europe), at National Balancing Point (NBP) in the UK and at the Punto di Scambio Virtuale (PSV) in Italy, with TTF reaching 85 €/MWh on the worst day of the Burian week from 20 €/MWh on the day prior to the disruption, NBP almost tripling the natural gas day ahead price from pre-crisis, and PSV doubling it. In addition, not only different European hubs saw an average 40% price increase, but also difficulty of attracting LNG with little notice (e.g. the first cargo from Qatar to Italy only a week later from the first day of Burian). In particular, during the Burian week, increases in commodity price also attracted flows from Spain, which became a net exporter of LNG to Central Europe in that period [1,147,148].

In the UK the NBP traded at an intra-day high, which had not been reached since 1997, as a consequence of an unprecedented demand and concurrent natural gas unavailability in the UK system. If on one hand internal natural gas demand was at 0.4 bcm record, which had not happened since the disruption from Ukraine 2012; on the other hand the UK system experienced gas unavailability (i.e., flow interruption of both the South Hook LNG terminal and Rough storage facility, which has been converted to a production field; decrease of internal production due to the problem at Bacton gas terminal) [1,147,148].

The results were validated by considering the main directions of the natural gas flows in those European countries with the highest gas recall during Burian (i.e., Germany, Italy, France, Poland, UK, Belgium, Spain, The Netherlands, and Austria) and the total system cost breakdown as well as its variations compared to the real natural gas volumes traded and observed costs during the Burian week. The model reflects the actual costs and flow configuration of the EU gas network during Burian. Main flow directions coming from the model mirror the main routes in the European gas network (see Figure 4-1 and Figure 4-2).

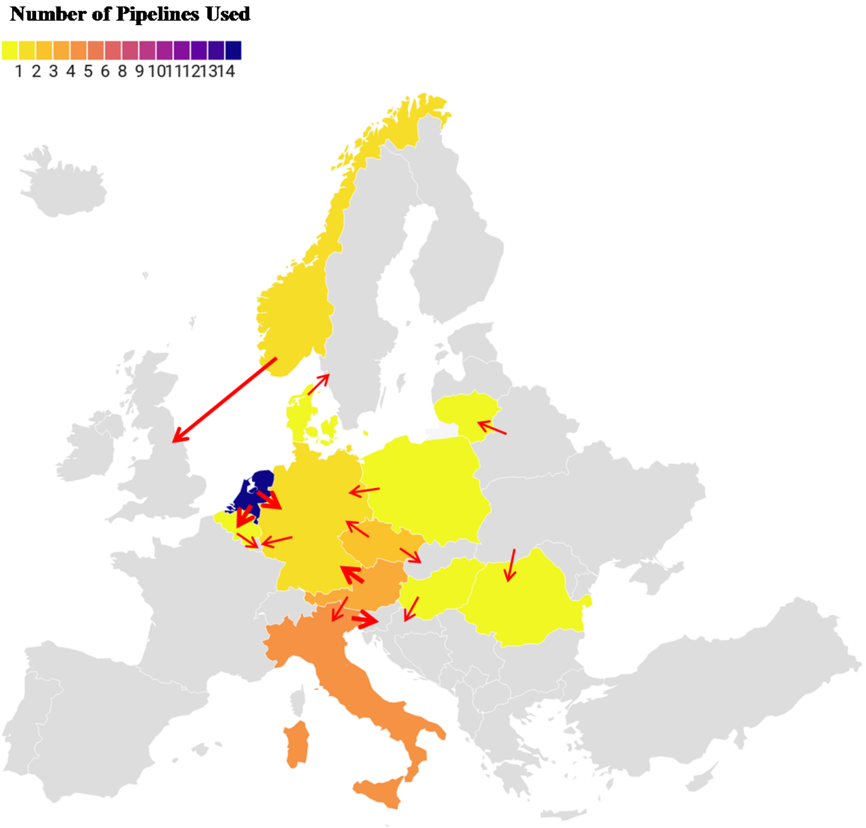


Figure 4-1 EU Gas Flows: Baseline Scenario

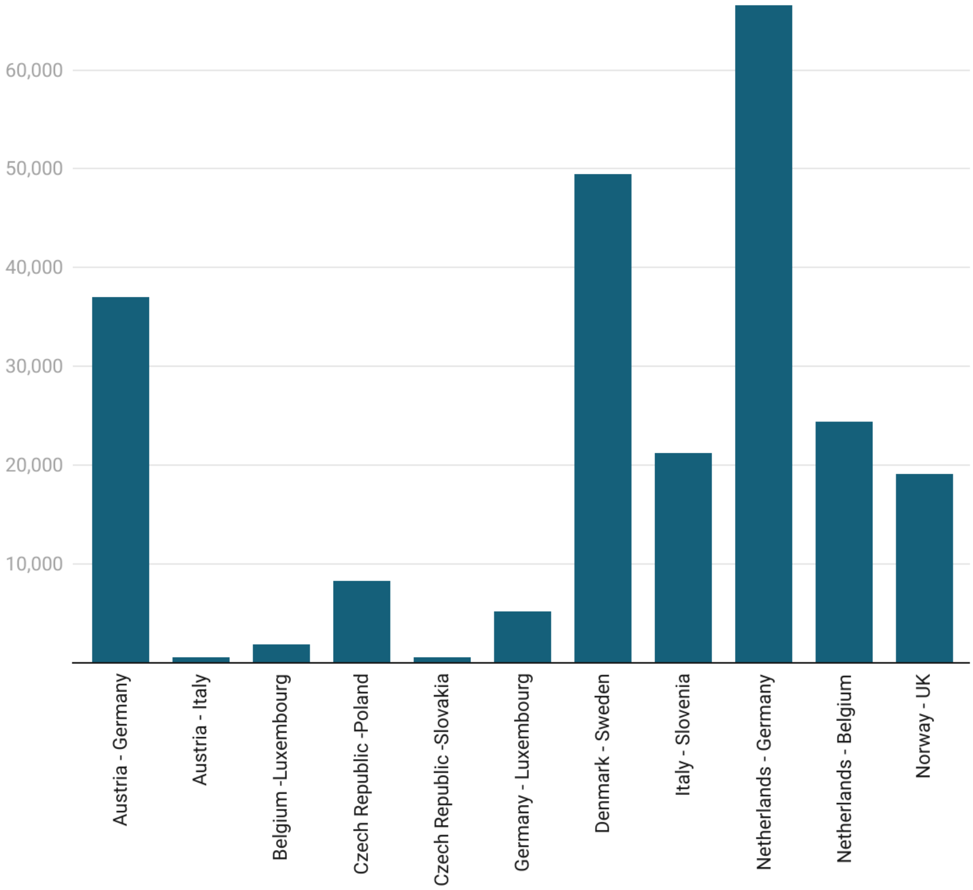


Figure 4-2 Pipeline flow among Member States in the baseline scenario (MWh)

Table 4-2 Volume of LNG recalled in the baseline scenario

Country	**Volume (GWh)**
Belgium	1066
Spain	988
France	1165
Greece	164
Italy	4145
Lithuania	214
Norway	59
Portugal	207
Russia	169

As Figure 4-1, Figure 4-2 and Table 4-2 show, in the baseline scenario main flows are recorded in Central Europe, whereas the model reflects little to no flows in UK, Italy, Spain, and France. In accordance with the major natural gas trends observed during the presented cold spell, the model indicates no pipeline flows coming to Central Europe from either Spain or the UK with the former depending on LNG supplies and the latter suffering from natural gas undersupply.

Spain LNG volumes, in particular, show a substantial increase in the model, from approx. 172GWh on the first day of the crisis (T1) to approx. 988GWh on the second day (T2) (see Table 4-2). The model also depicts flows from Norway to the UK to meet the unprecedented demand (1,9107MWh), as well as from Northern Europe to Italy (570MWh). Flows from the North of Europe shrank owing to a lack of storage capacity available, and flows nearing full capacity to the Italian Passo Gries, Mazara and Gela terminals as well as the highest storage withdrawal trend for the whole winter (57% vs. average 46%). Finally, the model indicates the majority of the flows recalled from the Netherlands, which not only possesses Europe's most liquid hub in Europe (TTF), but also an LNG terminal (90,965MWh) [1,147,148].

Although, the validation results revealed that the model accurately reflects main natural gas flows trend occurred in Europe during Burian (i.e., NG recalled from the Netherlands, and from Austria to lower Bavaria, Germany; no NG flows coming either from Spain or the UK), additional observed flows, particularly in Eastern Europe, are not aligned with reality.

To this end, in the Luxemburg, Slovenia, and few Eastern Europe Member States, such as Poland, Czech Republic, Romania, the Baltic Region, and Slovakia, deviations from real observed gas flows can be identified. Among them, the model recalls gas from nearby exporting MS, therefore showing incoming flows for countries with no gas mix type diversification, such as Luxembourg - importing from Germany (5170 MWh) and Belgium (1850MWh) - and Slovenia - importing from Italy (21,180MW) . The model employs local resources as a first response measure to the import disruption in nations with either low domestic demand or internal resources that may be tapped into, such as Poland, Romania or Slovakia. The model then redistributes the imported gas, through pipeline and LNG, to other countries with demand that cannot be met fully domestically or via LNG.

On the one hand, the divergence between the baseline scenario and actual flows in the EU could be due to limitations in the infrastructure modeling to capture additional barriers beyond the technical features related to capacities and network availability which could affect the EU NG flows at specific MS. In particular, as mentioned in Section 3.3.6, the model does not take into account specific agreements between MS or entry-exit tariffs. This might lead to over or underestimated flows in some areas of the network if compared to the existing natural gas market, hindering effective cross-border gas trade. Transmission tariffs are based both on the reservation capacity and the gas volumes traded across borders between balancing zones and they are set at the national level for each MS. Hence, not including them might render a different allocation of natural gas volumes across the EU then the one the natural gas market is witnessing since overall tariff revenues in the existing market are non-homogenously divided among routes and system operators when entry/exit tariffs are in place [137].

On the other hand, in addition to the assumption on natural gas storage and its technical deliverability (see Section 3.3), the modeling of the local availability of gas reserves proved to be subjected to a high uncertainty in costs, quantities of the reserves, as well as the actual availability of the reserve, which could also be additionally conditioned by local regulations. Finally, due to the short timeframe of the analysis carried out, effects of contracts and the relative take-or-pay tariffs are considered to not have an influence on the natural gas flows.

The model's outputs were further weighed in economic terms, comparing the cost component shares to the existing available literature. To this end, the validation revealed a model response that is consistent with the reported aggregated costs trends at a European level in the baseline scenario. In particular, the model shows proportions between different costs (i.e., production, transport, LNG and storage costs) are aligned with those provided by ACER for the reference household gas price (±3%), calculated as in Section 3.3.3. Results show that transport costs share is significantly lower (8%) than that of production (92%), which represents by far the highest costs. Storage costs, on the other hand, account for the smallest share in the total costs (< 0.01%), due to the lower commodity price of gas when stored for commercial purposes. Furthermore, transport costs in the base scenario are almost entirely represented by LNG costs, which were to be expected given that higher volumes of LNG were drawn during Burian, particularly from Spain. (See Table 4-3)

Table 4-3 Baseline Scenario Cost Share (€)

Costs (€)	***Baseline* Scenario**	***Baseline* Scenario (%)**	**ACER Household Price (%)** [131]
Total	3,225,714,500	100	100
Production	2,989,750,900	92	89
Transport	4,200,802	8	11
LNG	231,762,552		
Storage	259	< 0.01%	NA

4.4 Discussion on *sensitivity analysis* and *LNG costs* optimization scenarios

A *sensitivity analysis* was constructed to evaluate the model response to the price and volumes dynamics that happened during the Burian week, and are indicative of the natural gas market trends that actually occurred in that period. The sensitivity analysis was built by varying the input data as reported in Table 4-1.

In the sensitivity analysis, LNG and storage volume and prices, commodity prices, and transport costs have been increased and decreased to examine the impact of those parameters on the total natural gas network transport costs, highlighting the role of storage, of the natural gas price, and LNG price and volumes in the EU natural gas network, as well as to evaluate the model sensitivity to changes (see Table 4-4)

Table 4-4 Parameters variations from baseline optimization scenario

Parameter in *Baseline* Scenario			**Variation in *Sensitivity Analysis***
Demand	Volumes	*dmd (i,t)*	None
Production	Volumes	*extr (i,t)*	None
Commodity	Prices	*g* (*i*)	±40%
LNG	Volumes	*LNG (i,t)*	±5%
	Prices	*n* (*i*)	±20%
Commercial storage	Volumes	*withdr (s,i,t)*	±35%
	Cost	*cstor* (*s*)	None
Transport	Cost	*c (p,i,j,t)*	None

The implications of the variations in the sensitivity analysis of natural gas LNG prices and LNG price and volumes, as well as of storage volumes have been the focus of the analysis and have been looked at in detail. Results show a significant increase in liquefied natural gas (LNG) costs (+40%) when commodity price increases (+40%) and LNG prices decreases (-20%), and an equally significant decline in transport and LNG costs (-30%,-50%) when storage volumes varies (-35%, +35%).

As results from the effects of natural gas prices variations in the sensitivity analysis show, LNG alone is unable to compensate for the gas shock demand due to the effects on the total cost. During the cold spell, the gas market has experienced a 40% price increase at the different European hubs as well as difficulties in attracting LNG on short notice (e.g., the first cargo from Qatar to Italy only a week later from the first day of Burian) [147,148].

When the change in commodity price is positive, the spike in hub prices and the LNG input in Europe from Spain during Burian are reflected by the model results with an overall decrease of 57% in total transport costs. Moreover, when the shift in LNG price is negative (-20%), findings reveal an approximate 40% rise in LNG costs, which corresponds to 375,099,987 €, confirming that the natural gas network was undersupplied in terms of both gas flows and gas from LNG terminals during Burian, and therefore higher LNG costs are to be expected. Similar findings were discovered in [13], where more bidirectional EU gas pipelines are required if additional imports of LNG are to enter the EU gas network and LNG uptake in Europe is highly influenced by price (see Figure 4-3, Table 4-7 Table 4-4 and Table 4-6).

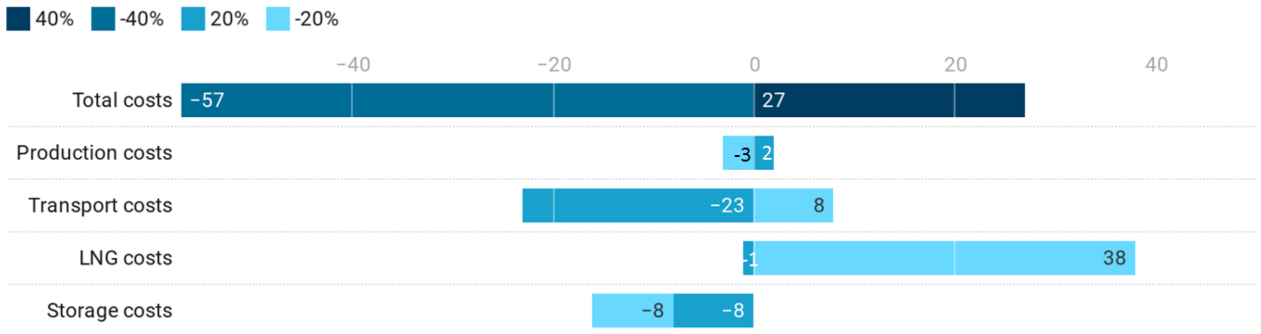


Figure 4-3 Variations of total costs and LNG costs due to the variations in commodity price (dark blue bar and medium dark blue bar, ± 40 %) and LNG price (medium light blue bar and light blue bar, ±20 %) from the baseline scenario (%)

Table 4-5 System cost breakdown in the sensitivity analysis due to variation in commodity and LNG price (10^3€)

Cost (€)	*Baseline* Scenario	Price			
		Commodity		LNG	
		40%	*-40%*	*20%*	*-20%*
Total	3,225,715	4,429,944	2,051,482	3,317,021	3,197,703
Production	2,989,751	2,893,053	3,059,091	3,037,477	2,893,053
Transport	4,201	4,570	3,504	3,416	4,570
LNG	231,763	375,100	212,523	230,106	375,100
Storage	0.26	0.24	0.24	0.24	0.24

Table 4-6 System cost breakdown in the sensitivity analysis due to variation in LNG and storage volumes (10^3€)

Cost (€)	*Baseline* Scenario	Volumes			
		LNG		Storage	
		5%	*-5%*	*35%*	*-35%*
Total	3,225,715	3,269,163	3,269,329	3,103,712	3,382,813
Production	2,989,751	3,007,011	3,009,722	2,919,154	3,032,176
Transport	4,201	3,571	3,571	3,237	3,090
LNG	231,763	258,581	256,035	181,321	347,547
Storage	0.26	0.24	0.24	0.40	0.21

Given that network costs are significantly impacted by LNG price and volumes, and that Europe is experiencing an LNG glut, with the US expected to become an increasingly important market for Europe (see Section 4.1.1and Section 4.1.2), a *LNG costs optimization* scenario has been developed to further evaluate the value of LNG in assisting the network in responding to a cold spell.

To this end, both LNG volumes and prices have been closely examined. When LNG volumes are relaxed from the *baseline* scenario, the *LNG costs optimization* scenario sees a variation in LNG prices, where maximum LNG capacity has been adopted. Subsequently, LNG prices are first increased, using data from the global LNG market with highest average monthly LNG prices

(Japan), +20% from the average monthly European LNG market price; and then decreased, using data from the global natural gas market with the lowest hub prices (US, Henry Hub) - 65% from the average monthly European LNG market price [1,129].

In the *LNG costs optimization* scenario, when relaxing LNG volumes from the baseline scenario, LNG costs see a reduction in both the case where prices are increased (Japan LNG prices) and decreased (US LNG prices) from the average monthly European LNG market price. With both the Japan and the US LNG prices, LNG costs reach a +50% reduction when compared to the LNG costs figure under the maximum LNG import capacity. Total cost is indeed affected; especially when LNG price is negative, but not as strongly as the sensitivity analysis would have indicated (see Figure 4-4, Table 4-8and Table 4-7).

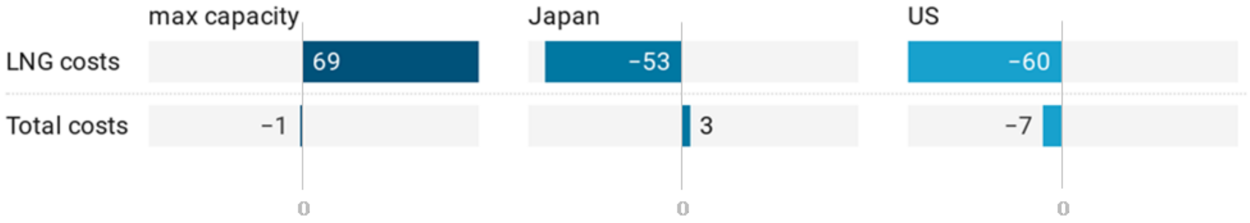


Figure 4-4 Effects on LNG costs and total costs assuming LNG import capacity equal to the maximum import capacity (dark blue); and LNG prices equal to Japan import (medium blue) and to US export (light blue) prices (% from baseline scenario)

Table 4-7 LNG scenario highlights (% from base scenario)

Cost (%)	LNG Volume	LNG Price	
	Capacity	**Japan**	**US**
	max%	*25%*	*-25%*
Total	-1	3	**-7**
Production	-6	7	**-3**
Transport	-5	7	0
LNG	**69**	**-53**	**-60**
Storage	0	0	0

The limited impact of LNG volume and price variation on system costs, suggests that variations in storage costs might be responsible to a higher degree in total system costs reduction than LNG ones are. Hence a sensitivity analysis with a focus on storage costs has been conducted, to appraise the impact of storage volumes on system costs during an unexpected disruption.

The analysis demonstrates how critical storage is for the gas market's ability to function in demand shock circumstances. When storage levels vary (±35%), transport and LNG costs fall significantly (approx.-30%), but storage costs rise by +35% (see Table 4-6 for cost breakdown in euros). Furthermore, reduced storage availability causes LNG supplies to be recalled, raising LNG costs. When compared to other system costs, storage costs are negligible, thus their increase has a less significant impact than the profit generated by a similar, or larger, reduction in other costs (e.g. LNG costs) (see Figure 4-5 and Table 4-8).

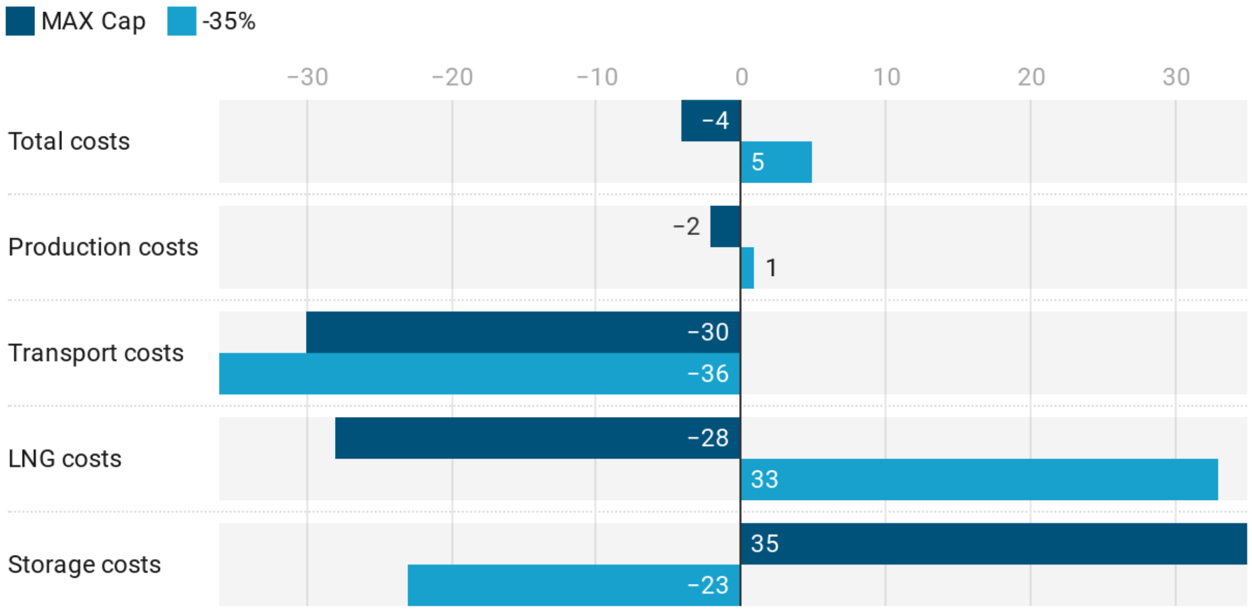


Figure 4-5 Variations of system costs breakdown (i.e., total costs, production costs, transport costs, LNG costs, and storage costs) due to changes in storage volumes, either set to the maximum capacity (dark blue bar) or reduced by 35 % (medium blue bar) from the baseline scenario (%)

Table 4-8 Sensitivity analysis highlights based on changes in price and volumes from the base scenario (%)

Cost (%)	**Price**				**Volumes**		
	Commodity		**LNG**		**LNG**	**Storage**	
	+40%	*-40%*	*+20%*	*-20%*	*±5%*	*+35%*	*-35%*
Total cost	**27**	**-57**	3	-1	1	-4	5
Production costs	-3	2	2	-3	1	-2	1
Transport costs	**8**	**-20**	**-23**	**8**	**-18**	**-30**	**-36**
LNG costs	**38**	**-9**	-1	**38**	**10**	**-28**	**33**
Storage costs	**-8**	**-8**	**-8**	**-8**	**-8**	**35**	**-23**

The relevance of diversification of supply sources for gas network resilience is emphasized in the analysis of the results, as it has been previously noted in prior studies on natural gas supply emergencies in European, such as [15,23]. In studying the interdependency of LNG and natural gas storage to enhance resilience in the EU gas network, this application provides an optimization-based approach looking at the value of LNG oversupply to Europe to assess the natural gas network resilience in case of a real-world emergency due to short-term supply shock or unexpected increase in demand. It employs a deterministic linear programming model that minimizes overall gas transportation costs in the EU gas network on daily time-steps to analyze the value of LNG availability in the EU natural gas network during an extreme cold event from a supply flow standpoint.

The analysis highlights a complementary role between LNG and storage in ensuring a cost-effective response to a natural gas supply shock. It also indicates that LNG alone is inadequate in providing system resilience in case of an emergency in supply, stressing the importance of storage in the gas market and its intrinsic value in the system. The application emphasizes the need to further investigate the reliability and value of gas storage to reinforce energy security in Europe, which will be discussed in Chapter 5.

Chapter 5. Strategic storage and its coordination among EU Member States

This chapter considers whether a coordinated use of strategic storage among EU Member States is economically desirable to provide security of gas supply during HILP. A modeling analysis of strategic storage as a non-market based solidarity measure in case of an HILP disrupting the EU natural gas network is introduced in Section 5.1. For this application, the two-stage stochastic cost minimization gas transport version of the model, as described in Chapter 3, Section 3.2.2, has been adopted. The application, in Section 5.2, is constructed to study the short-term resilience of the network to supply shocks from the Trans Austria Gas (TAG) pipeline and the most cost effective transmission of gas flows, capacity and storage utilization in an interconnected gas system. Following this, results are discussed in Section 5.3 focusing on the reliability and value of gas storage to reinforce energy security in Europe.

5.1 Framework of analysis

In what it is a highly electrified energy system, due to the increase need in operating flexibility and reliability introduced by the increasing share of weather-driven renewables in the system and the use of gas-fired power plants over the last decades, EU natural gas and electricity security are becoming more and more interdependent. In addition, from retiring of coal in power generation in favor of low-carbon and renewable gases (e.g., natural gas, biomethane, hydrogen), to promoting low-carbon sources in power generation (e.g., wind, solar, sustainable biomass, and nuclear power), a significant system transformation is required to reach the EU 2030 targets to climate neutrality by 2050. Having a natural gas significant share in the EU energy mix (in 2017 it is the second-largest primary energy source, and accounts for 25% of the total EU energy mix and 20% of electricity generation and 37% of heat), not only it can play a role both in end uses that are difficult to decarbonize and as a flexible energy source for coal phase-out and renewable back-up, but also its existing infrastructure can support the transition to cleaner sources, blending with hydrogen and biomethane, as mentioned in Chapter 4, Section 4.1 [149,150]. In fact, a gas crisis could have repercussions both in gas and electricity markets.

Most EU MS rely heavily on natural gas with little diversification of sources, with 11 MS having a national total primary energy supply of natural gas above 25% and as high as 40% (i.e., in Italy and in the Netherlands) in 2018. This, together with a heavy import dependence and the impact of the declining indigenous production on market seasonality and flexibility, as mentioned in Chapter 2, could jeopardize the natural gas supply, threatening energy security in the EU in case of HILP, mega-disasters (i.e., failure in the infrastructure system due to technological faults, natural disasters, or political turmoil) that are not likely to occur, but where the market is unable to cover the demand and policy intervention is required, having a massive immediate impact with possible longer-term structural impact in the way they can reshape the supply chain in permanent ways [2,5,20].

To this end, energy security at national levels requires special plans to be in place, particularly when it comes to face HILP. As discussed in more detail in Chapter 2, Section 2.2, the concept of energy security in the EU has progressed in the past 30 years. Starting from the creation of an internal market to then arrive at a European Energy Union, with concept such as coordination and solidarity to be the focus of the most recent Regulations of 2010 and 2017 [13,15,151].

In particular, when dealing with crisis, Regulation 2017/1938 [151] makes a distinction between market-based and non-market based measures. The former are both supply and demand side measures that while immediately addressing the gas crisis should not put an undue burden on the natural gas system nor reflect negatively on the internal gas market; while, when a state of emergency is declared and market-based measure implemented in the early stage of the crisis are insufficient to meet the remaining gas demand, non-market-based measures need to be introduced to safeguard protected customers. Reverse flow, LNG terminal capacity, commercial storage, increasing production flexibility, fuel switching, load shedding, interruptible contracts, etc. are all examples of market-based measure, whereas strategic gas storage and enforced market-based measures are categorized as non-market based measures.

As Sovacool [23] concludes in his study on energy security performance, international trade alliances as well as supra-national coordinated national policies are key to promoting energy security. The 2016 Energy Security Package calls for the urgency of a comprehensive integrated plan where political and economic rationales intertwine with cooperative and coordinated responses to supply failures in relation to the concept of solidarity in emergency situations included in the EU 2015 Review of the Security of Supply (SoS) Regulations [24].

Despite the fact that the literature on energy security has not been extensively focusing on governance and infrastructures, Boersma [19] pinpoints how a solid institutional foundation is paramount for the gas system to properly function. The non-quantifiable threats on energy security and in particular, as observed by Stern [20] and Kopp [21], those potential HILP events that could impact prices and reliability of supply for final consumers, need to be managed by governments [152].

5.1.1 The use of storage during supply threatening events in the EU

Examples of supply uncertainties (e.g., social and political instability, technology failure, commercial disputes, and natural calamities) that might unexpectedly shock the natural gas system have been documented during the last 20 years. Sixteen disruptive incidents, primarily caused by infrastructure failures and weather periods, have endangered gas supply in the EU for a period ranging from a few days to a couple of weeks [1,40] (see Table 5-1).

For example, due to a reduction in supply from Ukraine to Western Europe paired with very cold weather conditions, European LNG imports surged by 13% in February 2012, with Dutch LNG demand increasing by 237% [146]. Similarly, in January 2009, the EU's natural gas imports from Ukraine were reduced by an average of 80% owing to the most serious of numerous disputes between Russia and Ukraine over sales and transit during the last 20 years, affecting customers in various East European States [153].

More recently, on December 12th, 2017 the explosion at the Baumgarten facility in Austria due to a technical accident required the shutdown of the facility for few days. Consequently, as natural gas from Austria through TAG represented half of Italian natural gas imports that year, coming from a snowy cold weather week Italy was forced to declare a state of emergency in energy supplies, as per EU Regulation 1938/2017, for four days till December 15th, 2017, with gas prices almost tripling in one day, up to 80€/MWh [149,154].

Finally, due to the unexpected cold (i.e., Burian) that hit Europe in February 2018, the EU natural gas market reacted with spike in hub prices (+40%) and recalling of LNG cargoes from Qatar and the US, which inevitably increased LNG prices (+20%). In addition, storage volumes were tapped in during the two weeks crisis leading to capacity depletion (-35%) (see Chapter 4 for a more detailed description of the Burian crisis) .

Table 5-1 List of European supply threatening events over a ten-year period [40,149,154]

Date	**Location**
February 2018	Europe-wide
December 2017	Austria
September/January 2011	Norway
April/June 2010	UK
2004, 2007, June 2010	Belarus
2002, 2006, January 2009, 2014, 2015	Ukraine
2003, 2005, 2006, February/March 2008	UK

EU-wide joint actions are needed to implement that solidarity principle among MS that the EU Regulation 1938/2017 has called upon. Gas storage is one of the underutilized options for dealing with supply disruptions. Not only it can be a rapid emergency response measure, but it could also play a major insurance role in providing flexibility within the liberalized gas market [44].

Investigating the benefits of investment in gas infrastructures in the UK energy market, Skea et al. [40] concludes that strategic gas storage investment could significantly reduce supply shocks in the region. Among those MS that have storage capacity, only Italy has strategic storage additional reserves put in place, which are used as readily available gas stock set aside from the market to smooth out supply disruptions when a state of emergency is declared [45,55] (see Chapter 2, Section 2.2 for details on storage market and non-market measures in the EU).

Furthermore, in the 2016 EU Security Package gas storage was described as a feasible non-market-based measure to help security of supply. A centralized management of gas storage may allow a more integrated approach to the subject of energy security and supply uncertainty, as Buchan et al.

[26] suggest, by analyzing not only the potential and practicalities of gas demand and supply aggregation, but also mapping energy security aspects into the analysis.

Looking at the dynamics of the EU gas market in the past few years, the role of gas storage in it is being consolidated by three trends: (i) heavy import dependence, (ii) little source diversification, and (iii) the effect of decreasing domestic production (see Chapter 2). These features not only highlight the growing role of storage in response to European output caps and decline, but they also highlight its significance in the overall gas market structure, both from a market and policy viewpoint. The first two aspects are closely related to the insurance value of storage and its role in policy as a risk hedge (i.e., the role it can play when it comes to SoS), while the third aspect is related to the market value of storage and its role in the gas market (i.e., its competitive position in the gas market as a tool for providing flexibility, as opposed to other flexibility tools) [2,5].

The insurance value of storage against unforeseen incidents, lack of seasonal alternatives (e.g. LNG), mandatory strategic storage, share of storage capacity already allocated long-term, and reputational risk in case of supply outages, are all factors that, aside price incentives, can strengthen the role of gas storage in the system, making it a significant insurance instrument to provide flexibility.

Storage is also proved important in providing a flexible response during times of severe high demand, as the literature emphasizes [40,44,155]. Le Fevre [44] reveals that even if storage in winter 2010-2011 appears to have had less impact in total terms as a percentage of total European supply sources, it was critical in meeting demand during the bitterly cold winter of 2012 (Jan.-Feb.) and the resulting disruption in Russian supplies, when it was the second-highest source of supply to Europe. Moreover, Skea et al. [40] shows that from a social-cost benefit perspective investments in storage are an attractive option and could avoid the impact of a natural gas shortage emergency. Finally, as unveiled in the first application of this work (see Chapter 4) storage plays a key role in favor of gas network resilience in conjunction with LNG volumes during an unexpected shock in demand due to extremely cold weather conditions.

5.1.2 Model stochastic approach to strategic natural gas storage coordination among EU Member States

When dealing with the EU natural gas network modeling authors have mostly used stochastic failure estimation frameworks [156]. In particular, while most of the literature on gas focuses on supply flows guaranteed through market mechanisms, energy security must be complemented with additional means, which could relate to infrastructure adequacy, robustness and policy effects [30]. As mentioned in the literature review on model section of this work (see Chapter 2), in the context of natural gas supply modeling, only few examples representing market competition as a Cournot oligopoly, have dealt with the impact of natural gas demand and supply fluctuations and flow allocation strategies on energy security in the EU [156].

Another factor that has been largely overlooked when modeling gas crisis is the integration of what Vivoda et al. [33] calls “international” and “policy challenges”. In particular, while few studies have included aspects related to uncertainties on the supply side due to the EU climate policy effects on a single MS (e.g. Hauser et al. [157]), incorporating in the model considerations on whether a member state is committed to cross-border cooperation on energy related issues (e.g. regional cooperation) is an especially crucial aspect, as Giuli [34] points out, since the external supply choice remains under MS jurisdiction.

Instead, when looking at a gas crisis, authors mostly have either investigated long-term gas systems’ adequacy and robustness in response to disruptions and uncertainties of imports or demand [31,158]; or to a limited number of external disturbance events [29] (e.g., extremely low temperatures for a long period of time in a number of MS, loss and uncertainty in demand [159] and supply [160], and the impact of investment in upgrading the cross-border natural gas network [161]); or internal disturbances [32], (e.g., component failures happening at the cross-border points, connections or long-duration pipeline shutdown or failure [162], including component maintenance scheduling [163]).

Although not specific to the natural gas supply chain, examples of alternative approaches to natural gas supply modeling can be drawn from the supply chain optimization field. Collaboration, multiple sourcing strategies, multiple transportation channels, and backup suppliers are all key factors in preventing negative effects of disruption on the entire supply chain and building resilient networks, according to findings from the field of supply chain resilience (SCR) [118]. However, limitations of traditional risk management approach in characterizing HILP can be found (i.e., perfect reliability of facilities and optimal facility locations) [164].

Most SCR optimization problems that are related to real-world problems are influenced by uncertainty parameters. Depending on the information available for the uncertainties and the goal of the decision maker, uncertainty can be addressed in one of two ways: stochastic linear programming (SLP) and robust optimization (RO) [165]. In the latter, the uncertainty set is chosen at the discretion of the modeler, so the outcome is not completely independent of this choice. As a result, robust optimization has not been well studied to depict uncertainty from supply chain disruption. Furthermore, Maggioni et al. [114] analyzing the effects of the two approaches for a real case of transportation supply planning problem under uncertainty with a scenario based framework methodology to compare the performances of the two approaches minimizing expected transportation costs, demonstrated that a two-stage stochastic programming approach allows for 20% cost saving compared to RO when dealing with the same supply planning problem involving demand uncertainty. RO is optimizing for the worst case (of vehicle demand), which would lead to lower capital. Hence, in cases where sales grow, not being able to meet demand would result in a deteriorating investment. The study shows that RO results in larger objective function values than the stochastic programming approach due to the certitude of constraints satisfaction and more conservative decision strategies on the number of booked vehicles.

According to a systematic review of recent literature on quantitative methods for SCR by Hosseini et al. [38], the most appropriate way to deal with supply uncertainty and unmet demand caused by supply outages risks is to employ two-stage stochastic scenario based optimization models to design resilient distribution networks. The aim is to improve SCR in two ways: by having redundant inventory (absorptive capacity) and by having backup suppliers (adaptive capacity). Namdar et al. [119] build a bi-objective two-stage stochastic model to underpin the importance of multiple sourcing back-up and spot purchasing in a resilience strategy. In a two-stage stochastic supply model developed by Khalili et al. [112], risk mitigating options for a production-distribution planning issue under supply disturbance include rerouting, excess inventories, and transportation power. Torabi et al. [86] use a bi-objective two-stage stochastic model to build a resilient supply base at the global supply chain level, looking at back-up surplus and capability of suppliers under natural and man-made operational and disruption threats. Turnquist et al. [120] focus on infrastructure security and network resilience and look at distribution centers using a stochastic optimization model that simultaneously explores pre- and post-disruption design choices while taking into account distribution center extra capacity and restoration capacity, as well as additional connections between distribution centers and customers.

Further Saghaei et al. [166], create a two-stage stochastic programming model that optimizes fixed and variable costs of biomass electricity generation while achieving a reliable supply chain under uncertainty in material supply, both availability and quality-wise. The model examines the durability of the system as well as the effects of various safety stock and inventory on system efficiency. Finally, using a two-stage stochastic scenario-based model, Ghelichi et al. [167] investigates the architecture of a renewable, complex, and optimized multi-echelon biodiesel supply chain network under feedstock supply and demand uncertainties while taking real technological assumptions and greenhouse gas emissions regulation into account.

From this, it appears that there is a void in the methodological creation of techniques capable of adequately representing a regional organized response to transient supply-demand shocks in the EU natural gas network, which at the same time examines the absorptive capacity of the natural gas system to supply uncertainty through network resilience. In addition, as shown in Chapter 2 of this work, very little research connecting storage and security of supply has been conducted. Studies focusing on the advantages of optimal control of a shared European market for strategic storage are largely missing. As mentioned in Chapter 2, so far strategic gas storage has predominantly been established at the country level, primarily as a storage obligation, with no consideration given to a mutual and integrated management of a solidarity gas storage reserve in light of energy security in the European gas sector.

5.2 Model application to solidarity in response to disruption in the TAG pipeline

The question of whether a coordinated use of a non-market-based measure, such as strategic storage, may have value within the EU natural gas system has emerged as a result of threatening events in the natural gas supply network and the need for solidarity measures to be put in place when it comes to energy security at the EU level. The relationship between strategic storage and supply security has received little attention in the literature, as it has the issue of integrating energy security and policy aspects, especially solidarity, into a modeling framework.

This application fills this literature gap by extending the temporary shock approach of operational supply chain and SCR to the gas network and energy security modeling frameworks. If SCR is a stochastic and time-dependent concept [38], so is energy security [40] (see Chapter 2), hence the two-stage stochastic optimization-based version of the HILP model has been used to investigate SoS in the EU natural gas network to assess solidarity as a coordination mean to counter supply disruption in the natural gas network resilience over short-term supply shocks.

The model application has been designed to study an optimized coordinated first response to security of supply issues after market-based interventions have failed in the event that a drastic disruption occurs in conjunction with gas demand peaks, beginning with a non-market measure such as strategic storage in the event of an HILP over short-term periods. Specifically, it allows for the consideration of the absorptive capacity of the natural gas system to supply uncertainty as well as the coordinated use of strategic gas storage. As detailed in Chapter 3, the model includes forty regions, divided between European countries (i.e., twenty-six EU MS, plus the UK, Switzerland, and Norway), and major importers and transit countries (i.e., Russia, Ukraine, Belarus, Algeria, North Africa, Tunisia, Serbia, Moldavia, Macedonia, and the Republic of San Marino). A timeframe of seven days (T1-T7) has been considered (see Table 3-4).

In the context of short-term energy security, the application focuses on the role of strategic storage as a means of achieving security of supply through solidarity, as well as how this might support the EU new agenda of combining security of supply objectives with solidarity and cooperation among MS. Thanks to the constructed scenario-based analysis, the HILP model is capable of analyzing uncertainty in gas supply volumes at various intensity levels, as well as depicting the ability of the system to yield efficient cost and distance allocation of the resource in the event of demand disruption, both of which are critical considerations when working with HILP.

Although event probability (e) is very low (see Chapter 3, Section 3.3.5), the magnitude of HILP events and a supply uncertainty on the network is significant (e.g., effect on natural gas prices (+70%), loss of delivered natural gas volumes (-80%), LNG demand increase (+237%)) and lack of gas supply would need to be met in different ways.

The fact that the EU natural gas infrastructure is a network with nodes and links (i.e., a sum of the performances of the various network components) determines a challenge in depicting the impact of uncertainties on natural gas security of supply. To this purpose, the authors relied on percentage deviation of data from a base or average reference value gathered from historical disruptive occurrences in the natural gas network, which may be classified into four major impact categories: spike in hub prices, demand shocks, loss of import flows, and operations reduction [40,149,154].

The general structure of the mathematical model has been described in detail Chapter 3. The model has been adopted in its two stage stochastic LP version (see Section 3.2.2) to account for event uncertainty and disruption risks, hence to evaluate the short-term network resilience to supply shocks and the most cost effective transmission of gas flows, capacity and storage utilization in an interconnected gas system during a HILP. As shown by the literature review, in Section 5.2, a two-stage stochastic optimization has been mostly adopted in SCR when studying uncertainty in demand, with solutions that generally benefit both the players and the system. The stochastic formulation is based on a scenario approach, in which an ensemble of mutually exclusive events alongside their probability of occurrence is used to model selected failures of the natural gas supply causing supply-demand unbalance. Key scenarios of a coordinated response to security of supply using strategic gas storage are presented the current sections; while Section 5.3 offers a discussion on sensitivity analysis and disruptions scenarios and some concluding remarks

To examine the impact of uncertainties in the inputs to the optimization, two case studies (i.e., Case 1 and Case 2) in two instances (i.e., *baseline* and *solidarity*) are employed with a range of sensitivity analyses. In particular, under Burian gas demand Case 1 and Case 2 consider different real-world cases of loss of gas import, rupture event probability, hub natural gas price increase, and loss of pipeline capacity in specific EU regions. In addition, the *baseline* instance is where the system is without strategic storage reserve, whereas the *solidarity* instance the system can count on strategic storage to survive the shock. Different scenarios are then simulated with changes in constraints and parameters in the sensitivity analysis. Scenarios comparison gives the impact of changes in the exogenous conditions.

To illustrate the applicability of the proposed model, in addition to a base scenario, *Burian* scenario, which takes into account actual Burian data for volumes and costs and has a 100% event probability only in the *baseline* instance, two hypothetical supply shock HILP scenarios based on several real-world cases were selected and run both in the *baseline* and *solidarity* instance: Scenario "*Two disruptions*", and Scenario "*Three disruptions*", each with increasing supply outage intensity and uncertainty. Where the former includes Burian week and Case 1 conditions and material failure event probability; the latter also includes Case 2 conditions and ground movement event probability. To determine their effect on system costs, the sensitivity analysis was completed by including variations in all of the parameters that impact the system costs, specifically commercial storage volumes and prices, commodity prices, LNG volumes and prices, and transportation costs, using average annual data compared to average data from the Burian week.

5.2.1 <u>Case hypothesis and scenario construction</u>

When considering HILP affecting pipelines, sudden supply/demand shocks due to political, technical and commercial risks should be taken into account all together. In constructing the scenarios of the analysis to get a more realistic view on the consequences of abrupt and unforeseen outages in natural gas supply/demand, attention has been posed on main natural gas supply routes to Europe potentially exposed to multiple risks simultaneously. One of the routes potentially subject to all three above-mentioned risks concurrently is Trans Austria Gas (TAG) pipeline originating from Russia and arriving in Italy, through Tarvisio. Gas from this pipeline supplies Austria, Italy and Slovenia.

Three events each referring to a different specific event probability can be traced in the last ten years along that route as follows:

- Political threats resulting from disruptions in gas supplies from Russia have occurred many times in the last two decades as a result of the Russia-Ukraine conflict, the most recent of which occurred in 2014. The most extreme was in 2009, when supply to Europe was reduced by 80% in the first six days of the 22-day-long crisis [153].
- Furthermore, in 2017, a technical accident (e2) occurred at the Baumgarten natural gas hub in Austria, which had a commercial effect on gas supply in Europe. Due to an explosion triggered by gas escaping from the seal on the cap of a newly mounted filter separator, operators were forced to close the plant. As a result, Italian hub prices increased by 70%, and Italy, importing 36% of its gas from Russia through TAG, declared an energy supply emergency [154].
- Finally, physical certainty on gas flows delivery has to be taken into account. Having the pipeline to cross mountain passes to enter Italy, in the Udine area, it encounters risk of ground movements (i.e., landslides) (e3), with 4568 landslides reported between 2000 and 2019 [168]. The local authorities have classified the risk of landslides in the Tarvisio area as high (P4 on a scale of P1 to P4, with P1 being the lowest and P4 being the highest, based on the severity of the phenomenon, the velocity, and the material involved) [168]. To this end, from July to December 2010, Transitgas pipelines on the Netherlands-Italy route were closed due to a landslide at Passo Gries IP in Italy, which occurred along the Transitgas route in winter 2010. As a result, when compared to the same period in winter 2009, the utilization rates of available capacity of the TAG pipeline increased by approximately 10% [169].

Two cases, Case 1 and Case 2, have been developed assuming the above-mentioned incidents occurring at the same time, resulting in higher supply risks. Cases include an 80% loss of import flow from the Easter gas pipes, e2 and e3 rupture event probabilities (i.e., 2.86·10-7 and 8.45·10-7 respectively), no flows from TAG into Italy, a 10% rise in flows on Passo Gries, Italy, and a 70% increase in gas hub prices in all affected regions [1,124]. Due to the gas network structure, the impact of such an HILP event directly affects supplies in Austria, Italy, and Slovenia, as well as Germany and Hungary through various interconnection points (IP) (see Table 5-2).

Table 5-2 Scenarios hypothesis

	Case 1	**Case 2**
Magnitude		
Loss of gas import	• -80% from Russia; • -6% to Germany; • -36% to Italy	• -80% from Russia; • +10% from TAG to Italy
Hub gas price in affected regions (i.e., Austria, Italy, Slovenia, Germany, and Hungary)	+70%	+70%
Gas demand	Burian data (See Table A2).	Burian data (See Table A2).
Loss of pipeline capacity in specific EU regions	No flows from TAG to Italy, Slovenia, and Germany	No flows from Passo Gries (Italy)
Event probability		
Rupture event probability	$2.86\cdot10^{-7}$	$8.45\cdot10^{-7}$

Hungary is only marginally impacted by the Mosonmagyaróvár IP outage since it imports 90% of its gas directly from Russia. However, despite the fact that the West Austria Gasleitung (WAG) pipeline branching out from Baumgarten represents just 6% of the total German network supply via Oberkappel IP, it is the main gas supply for lower Bavaria due to German network layout and internal bottlenecks. As a result, a decline in WAG pipeline supply could have a significant effect on gas feed in the country [21,129].

Furthermore, for the purposes of the case study, not only is supply expected to be under stress, but demand is also assumed to be under stress due to real-world climatic conditions, such as the Burian cold spell that hit Europe in February 2018. Actual demand, price, import, LNG, and storage data for the Burian period were gathered from various sources as explained in Chapter 3 (see Table 3-5).

In particular, as mentioned in Chapter 4, Burian brought with it higher internal demand, gas unavailability and by contrast increase in commodity prices. Not only gas demand in the UK was at about 400Mm3, share never reached after the disruption from Ukraine in 2012, but also Spain became a net exporter of LNG to central Europe and the storage capacity saw the highest withdrawal trend for the whole winter (57% vs. average 46%).

Furthermore, the unexpected cold spell resulted in: +40% commodity prices from average monthly prices at different European hubs (2008-2018); +20% LNG prices from average monthly LNG prices at different European hubs (2017-2018); -5% LNG volumes from average monthly imported volumes (2017-2018); and -35% availability of storage volume from commercial storage facilities (Oct.-Nov. 2017).

5.3 Discussion on sensitivity analysis and disruptions scenarios

Results are discussed highlighting the impact of strategic storage as a solidarity measure in case of emergency on the EU natural gas network when event probability, and production, commodity, LNG, storage, and capacity volumes and prices change.

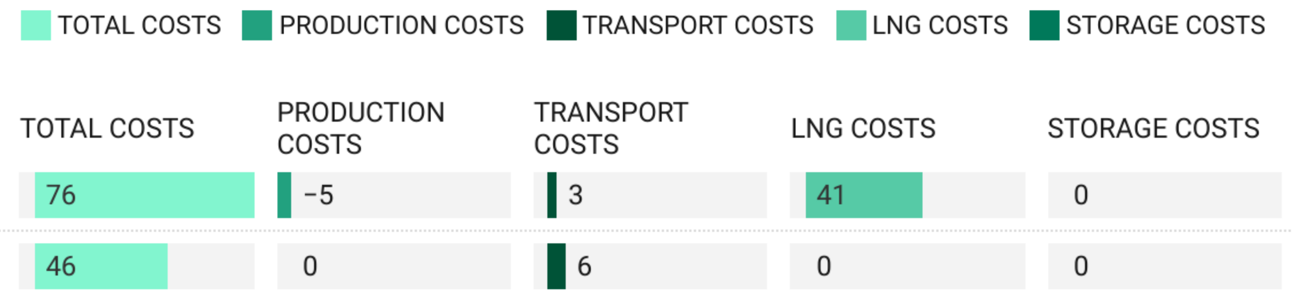
The sensitivity analysis included demand, supply, commercial storage volumes and prices, commodity prices, and transport costs during Burian with 100% event probability, as well as depicting the impact of strategic storage coordinated consumption in the EU natural gas network during multiple disrupting events occurring simultaneously in the gas network with different event probabilities. The study was based on estimating deviations from average annual data with respect to average data from the Russia-Ukraine conflict, the technical accident at Baumgarten, the landslide at Passo Gries, and Burian week on all the parameters that characterize Case 1 and Case 2 (see Table 5-2), specifically demand, production, storage volumes and prices, commodity prices and volumes, and transport costs and volumes with e1, e2 and e3 happening both concurrently and not to closely depict the severity of HILP events. Given that the effect of disturbance events on demand is primarily due to fluctuations in natural gas prices and volumes, demand volumes are historical data taken from the Burian week and have not been adjusted by any percentage in the sensitivity analysis (see Table 5-3).

Table 5-3 Parameter variations for *Burian*, *Two disruptions* and *Three disruptions* scenarios

Parameter in the Scenario			**Variation in sensitivity analysis**		
			Scenario “*Burian*” *(Baseline)*	Scenario “*Two disruptions*” *(Baseline and Solidarity)*	Scenario “*Three disruptions*” *(Baseline and Solidarity)*
Event Probability	e		100%	*e2*	*e1,e2,e3*
Demand	$dmd\ (i,t)$	Volumes	None	None	None
Production	$extr\ (e,i,t)$	Volumes	None	-80%,-6%,-36% (Case 1)	-80%,-6%,-36%; +10% (Case 1; Case 2)
Commodity	$g\ (i,e)$	Price	±40% (Burian)	±70% (Case 1)	±70% (Case 1)
LNG	$LNG\ (e,i,t)$	Volumes	±5% (Burian)	±5% (Burian)	±5% (Burian)
	$n\ (i,e)$	Price	±20% (Burian)	±20% (Burian)	±20% (Burian)
Storage	$withdr\ (s,i,t)$	Volumes	±35% (Burian)	±35% (Burian)	±35% (Burian)
	$cstor\ (s)$	Cost	None	None	None
Transport	$c\ (e,p,i,j,t)$	Cost	None	None	None
	$pcap\ (i,j,p,t)$	Volumes	None	-10%,-30%,-10% (Case 1)	-10%,-30%;-10% (Case 1)

In particular, as results of the effects of natural gas price and volume fluctuations in the sensitivity analysis, strategic storage is able to compensate for an HILP event due to effects on system costs.

Total costs rise by 76% in scenario "*Burian*", which corresponds to 27,135,013 10^3€, when the shift in commodity and LNG prices is positive, reflecting the market reaction to Burian at the time, with hub prices spiking and trouble attracting LNG, which saw an increase in import from Spain (see Figure 5-1and Table 5-4).



+40%; +20% (upper bars); -40%;-20% (lower bars)

Figure 5-1 Commodity and LNG price variations (± 40 % and ±20 % respectively) and their impact on system costs (%) in Scenario "Burian" (see Table A1 in Appendix A for breakdown of system costs in base scenario (€))

Table 5-4 System costs breakdown in Burian scenario with commodity and LNG price variation (+40%, +20%; -40%,-20%) (10^3€)

Cost (€)	***Baseline Instance(+)***	***Baseline Instance (-)***
Total	27,135,013	12,035,059
Production	3,549,497	3,708,829
Import	5,091	5,229
LNG	1,818,989	1,072,201
Storage	0.10	0.10

In response to HILP a market-based measure is predicted to incur higher system costs than a non-market-based measure. In particular, the worst-case scenario in the study, scenario "*Three disruptions*" reduces overall systems costs by approximately 30% if compared to the *solidarity* (with strategic storage) and *baseline* (without strategic storage) instances. This suggests that adding gas volumes to the system and allowing them to freely allocate inside the system during an emergency is a cost-effective way to compensate for unexpected gas supply shortages. It contributes to system balancing by offering a price-insensitive volume reserve to deal with outages caused by unforeseen supply-demand volume and price shocks.

Specifically, the concerted use of strategic storage as a solidarity measure within the EU has proven to be cost-effective in terms of system costs, mitigating the effects of supply disruptions and demand spikes, while robust cooperation among MS is required. In the event of shifts in commodity prices, LNG prices, LNG volumes, and storage volumes, overall total system costs were decreased by -13% and -28% for scenario "*Two disruptions*" and scenario "*Three disruptions*" respectively, in instances with and without strategic storage. Solidarity, which entails cooperation and interconnection among MS, as well as the use of strategic storage within the EU network to provide energy security, is effective in addressing peak demand and coincident supply outages.

Strategic storage lowers total costs in both scenarios with varying commodity and LNG prices and volumes, scenario "*Two disruptions*" and "*Three disruptions*". When comparing system costs between *baseline* (without strategic storage) and *solidarity* (with strategic storage) instances, the latter sees a 400% reduction in total costs (see Table 5-5 for systems cost breakdown).

In scenario "*Three disruptions*" where two large-scale disrupting incidents occur at the same time, the cost differential between the two instances is around 30% in favor of solidarity. Specifically, although the scenario "*Three disruptions*" sees a small rise in transport costs (+20%) in favor of the baseline instance, presumably due to the re-routing indicated by the coordinated usage of the extra storage volumes required to resolve the interruption, LNG costs are significantly reduced in both scenarios, hitting -60% and beyond. When all other costs in the two scenarios are considered, scenario "*Two disruptions*" and scenario "*Three disruptions*", using strategic storage in a coordinated manner results in substantial cost savings for the system, especially in the *solidarity* instance, highlighting strategic storage as an efficient cost-cutting measure for the natural gas network in the event of HILP (see Figure 5-2 and Figure 5-3).

In particular, results show how a market-based measure in response to HILP is expected to involve greater system costs than a non-market based one. As Figure 5-2 and Figure 5-3 reveal, in the worst-case scenario considered in the study, Scenario "*Three disruptions*", total system cost reduction is up to approximately 30% between the solidarity (with strategic storage) and baseline (without strategic storage) instance, which accounted for 24 €/MWh and 28 €/MWh respectively (see Table 5-6 and Table 5-5). This suggests that injecting extra gas volumes to the grid and allowing it to selectively allocate inside the system during an emergency is a cost-effective way to compensate for unexpected drops in gas supplies.

Demand elasticity is not modeled; however, the commodity substitution is modeled as a result of the model approach aimed at cost minimization. As a consequence, to evaluate the model result in economic terms, unit natural gas cost is presented as a proxy of prices. The dynamic of natural gas costs, in particular, is consistent with the market dynamics of supply/demand, where price signals arise from fluctuations in demand and supply. To this end, compare the value in presence of a stochastic event (i.e., "*Three disruptions*" scenario) as opposed to a deterministic case with no rupture, results show higher costs for the former (28 €/MWh and 24 €/MWh for *baseline* and *solidarity* instances) and lower for the latter (21 €/MWh), where increasingly higher volumes of LNG and storage were recalled into the system. LNG volumes were mostly recalled in the *baseline* instance (over 80%, which in volumes corresponds to 57,000,000 MWh), whereas storage withdrawal was higher in the *solidarity* instance (90%, which in volumes corresponds 500,000,000 MWh) (see Table 5-5, Table 5-6, Figure 5-4, and Table A3 in Appendix A).

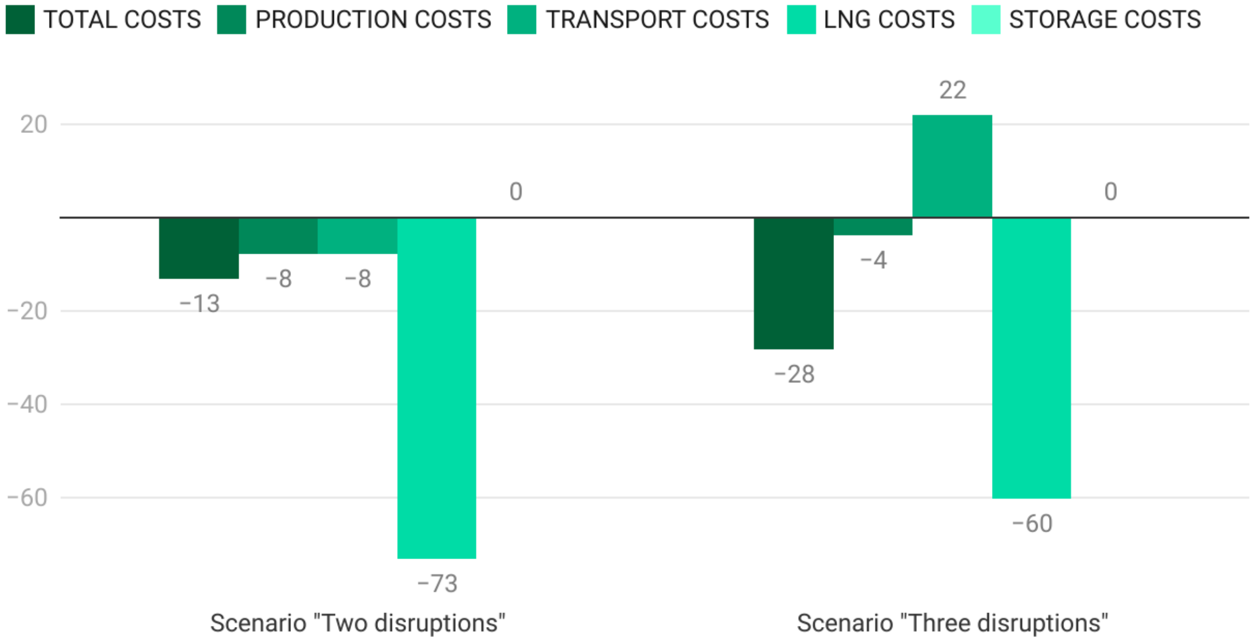


Figure 5-2 Cost efficiency between Baseline and Solidarity instances in Scenario "Two disruptions" and Scenario "Three disruptions" (%). The "Two disruptions" scenario bars represent the difference in percentage between the value with and the value without strategic storage reserves of the scenario. The "Three disruptions" scenario bars represent the difference in percentage between the value with and the value without strategic storage reserves of the scenario. (Negative values are in favor of strategic storage) (see Table A2 in Appendix A for breakdown of system costs for "Two disruption" scenario (€))

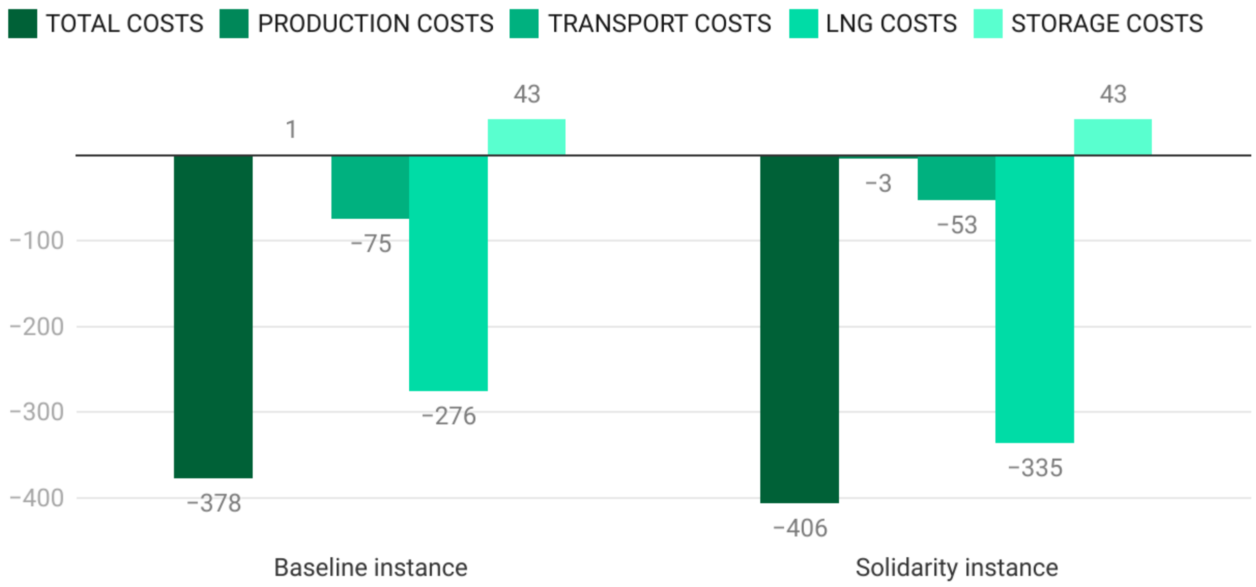


Figure 5-3 System costs in instances with (solidarity) and without strategic storage (baseline) with respect to base scenario in Scenario "Three disruptions" (%) (see Table A2 in Appendix A for breakdown of system costs for "*Two disruption*" scenario (€))

Table 5-5 System costs breakdown in Scenario "Three disruptions" with price and volumes parameter variations in the baseline (B) and solidarity (S) instances (10^3€)

Cost (€)	***Pre-disruption***	**B**	**S**	**B**	**S**
Total	6,484,720	1,355,422	1,280,736	6,548,146	6,324,958
Production	3,709,399	3,747,285	3,601,643	3,436,373	3,405,202
Transport	4,920	2,816	3,215	4,297	3,419
LNG	1,072,201	285,525	246,285	585,013	443,913
Storage	0.10	0.18	0.18	0.18	0.18

Table 5-6 Unit natural gas cost comparison (€/MWh)

	***Baseline* instance**	***Solidarity* instance**
Deterministic case with no rupture	21	-
Scenario "*Three disruptions*"	28	24

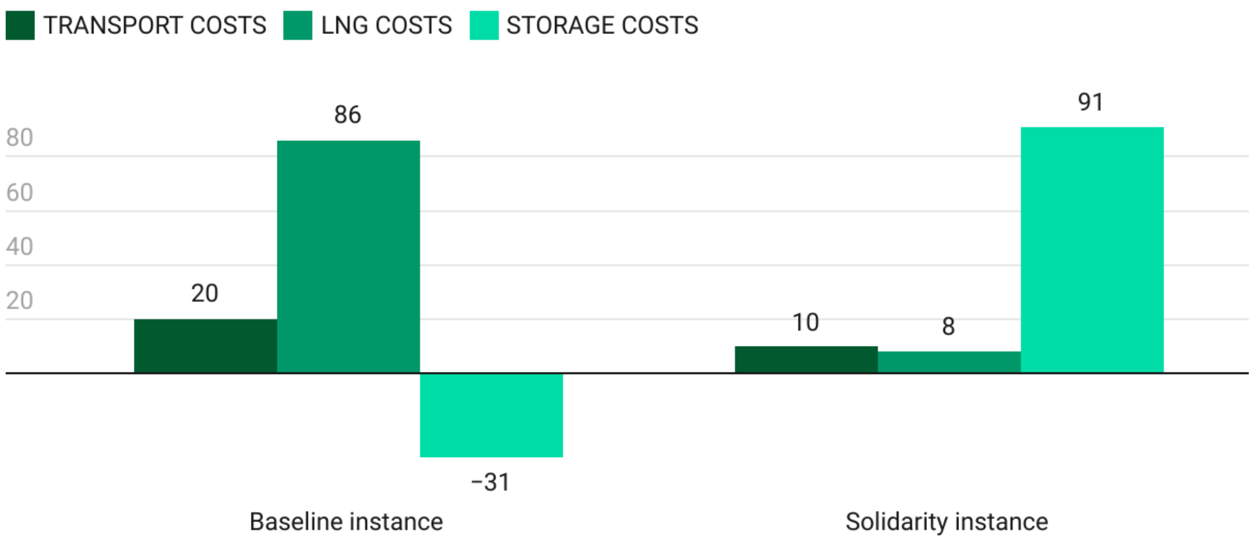


Figure 5-4 Natural gas volume share in Scenario "Three disruptions" with respect to a deterministic case with no rupture (%) (see Table A1, A2 in Appendix A for breakdown of system costs for different disruption scenario (€))

Furthermore, the sensitivity analysis shows the efficacy of strategic storage when a state of emergency is declared in the event of demand and supply shock scenarios. When storage volumes are set to their full capacity, adding strategic storage as a non-market measure still results in a lower total cost. This is not the case if there is no strategic storage involved in the emergency (i.e., *baseline* instance).

The analysis shows how the introduction of strategic storage during disruptions is significantly cost effective in reducing system costs if compared to scenarios and instances with no strategic storage involved (see Figure 5-2 and Figure 5-5). When the costs of the two instances are contrasted, while there is a small rise in storage costs for both options (+45%) (see Figure 5-3), which are marginal costs when compared to other system costs, transport costs and LNG costs are substantially reduced (-30% and -60%, respectively, which correspond to 4,300,000€ and 3,500,000€ for the former, and 585,000,000€ and 444,000,000€ for the latter respectively), leading to the reduction in overall system costs (-3%) (see Figure 5-5 and Table A3 in Appendix A).

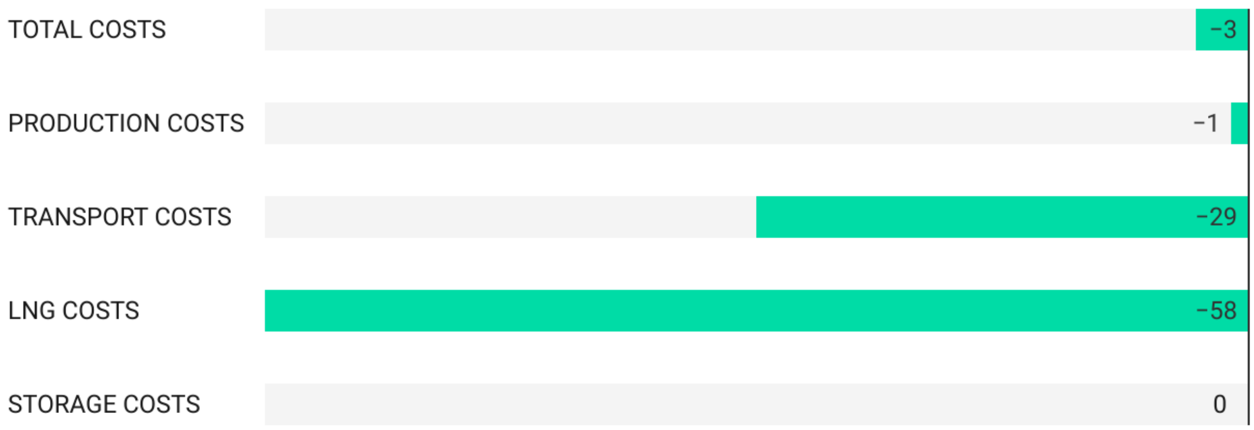


Figure 5-5 Cost efficiency between Baseline and Solidarity instances when storage volume is at maximum capacity in scenario "Three disruptions" (%) (Negative values are in favor of strategic storage) (see Table A3 in Appendix A for breakdown of system costs for each disruption scenario (€))

Finally, the results show that as storage volumes rise, LNG costs drop the most of all system costs (-60% and over) (see Figure 5-3and Figure 5-5). The same exist between recalled volumes of LNG and storage if compared to pre-disruption values. Not only there is a greater share of LNG and storage if compared to natural gas transport, but also they balance one another out in responding to the disruption, namely when no strategic storage is in place there is an increase in LNG and vice versa (+86%, -31%; +8%, +91% respectively for LNG and storage, which correspond to 57,000,000 MWh, 180,000,000 MWh, 500,000,000 MWh, and 33,000,000 MWh) (see Figure 5-4and Table A3 in Appendix A). Thus, when it comes to EU security of supply in the event of a market failure, storage and LNG complement each other. The findings emphasize the importance of not only infrastructure diversification, but also strategic storage, an underutilized emergency choice with utility in the natural gas network and insurance value in HILP cases. Storage as a strategic reserve can ensure supply in the event of any delay in LNG delivery, particularly in the event of unexpected and sudden supply shocks, as happened in March 2013 and again in January 2017 [9]

The research emphasizes the reliability and intrinsic value of gas storage in securing energy to the system in an emergency and provides insight into the interplay between storage and LNG. It points out how non-market base measure can be a cost-effective alternative to market based measures. The application emphasizes how the role of strategic storage, as a solidarity gas supply reserve with an insurance value against unforeseen events, deserves more attention in an increasingly interconnected EU energy market and system. Hence, a more detailed analysis of whether such a solidarity measure could support EU Regional Risk Groups in the event of supply crises, as well as expanding the geographical and temporal reach of the model, will be addressed in Chapter 6.

Chapter 6. EU Regional Risk Groups and solidarity mechanism

This chapter focuses on strategic storage as a solidarity measure in response to short-term HILP disruptions in the EU gas supply from major suppliers (i.e., Ukraine, Russia, Norway, and North Africa), assuming its implementation in selected MS. Section 6.1 incorporates a framework analysis of the repercussions of loss of import volume due to unanticipated events shaking the EU natural gas network with a focus on ripple effects and solidarity measures at the supra-national level. As for the previous application (see Chapter 5), the two-stage stochastic cost minimization gas transport version of the model, as described in Chapter 3, Section 3.2.2, has been adopted here as well. The application, in Section 6.2, is constructed to investigate the ability of the network to withstand supply shocks in the short term, evaluating the impact of HILP events on the level of demand curtailment, survival time, and the natural gas supply mix of EU regional risk group. Following that, in Section 6.3, findings are addressed with an emphasis on the desirability of the coordinated use of strategic storage in balancing the natural gas network during emergencies and in providing system resilience.

6.1 Framework of analysis

In the short term, the 2019 EU Green Deal targets the rolling out of innovative technologies and modern infrastructures with intervention from all sectors of the economy (e.g., transport, buildings, and electricity among others) required to reach a clean and climate neutral economy. Growth strategies include: (i) no net emissions of greenhouse gases by 2050; (ii) decoupling of economic growth from resource use; and (iii) total inclusion and support of all regions and biodiversity in the roadmap. To this end, the EU Green Deal encourages natural gas over coal in power generation, with a series of actions to increase cross-border and regional cooperation and move the EU to a fully interconnected, clean, and secure energy market largely based on renewable sources by 2050 [149,170,171].

Considering that the majority EU MS heavily depend on natural gas, a disturbance in supply could jeopardize European economic growth, development, sustainability, and survival at both end of the natural gas supply chain [2,5]. To this end in 2017, the EU energy security agenda culminated in the establishment of regional risk groups to counter natural gas supply shocks and resilience, as well as to present the idea of solidarity mechanisms to ensure supply to the most vulnerable customers even in the event of extreme gas supply outages, with storage suggested as a potentially underutilized and cost-effective solution.

As experience has demonstrated, HILP disturbances do exist, but they must be factored into European-level security of supply planning. To that end, the EU has enacted legislation over the last three decades to include gas security of supply and close regional cooperation when it comes to disruptions on the natural gas network, even going so far as to promote solidarity mechanisms among MS in the most recent security of supply regulation [18] (see Chapter 2, Table 2-4).

As discussed in mode depth in Chapter 2, Section 2.2, since 1980, the EU has been trying to shape its gas system institutional framework, with privatization and liberalization of the European gas market with competition (i.e., unbundling), cross-border integration, and harmonization, being a priority in the political agenda [58].

The European Commission aims to set common guidelines for the transmission, distribution, supply and storage of an internal natural gas market through the First Gas Directive (1998/30/EC), the Second Gas Directive (2003/55/EC), and the Third Energy Package in 2011. To address market distortions and improve transparency (i.e., the formation of ACER in 2009), a better stance on integrated energy company unbundling is needed first and foremost The aim is to strengthen cooperation at the EU level, as well as to harmonize and liquefy the natural gas market, while stressing the importance of allowing customers to freely switch gas suppliers in a well-functioning market [8–12].

Nonetheless, despite the attempts of the EC to create a self-contained and competitive internal natural gas market and to maintain supply stability, energy security remained primarily a national concern until the mid-2000s [19]. From the Gas Protection of Supply Directive 67/2004 to the Gas Regulation 994/2010, the EC has attempted to transfer responsibility for energy security from the national to the EU level [13,63].

Aalto et al. [62] demonstrate how concept of energy security of Europe has evolved in a cooperation direction, from self-interest and mere coexistence of MSs in the 1990s to a supportive union in the 2000s, and eventually to what they describe as a more "converging energy security society" with the Third Energy Package in 2009.

As address in Section 2.2, Regulation 994/2010 is the fundamental component of the EU gas supply security [38]. It requires each MS to have provision and supply requirements in effect in order to assess its readiness to deal with gas supply outages and protect consumers. This include the N-1 standard, which is used to determine risks to the gas supply in the EU; permanent bi-directional capability (i.e., reverse flow and obligations); and the Risk Evaluation, Preventive Action Plan, and Emergency Plan [64].

With considerations such as expectations of security and degree of import dependency ranging from MS to MS, the so-called 2016 Energy Security Package has been proposed in an attempt to create a single norm that could function with all MS and establish an Energy Union. Its primary goal was to provide MS with shared guidelines on how to execute internal, but primarily external, policy goals to promote tangible integration among states [14–17].

The EU took a step forward in addressing the external dimension of energy security with the Energy Security Package in 2016, followed by Regulation (EU) 2017/1938, which deals with external sources of supply and their passage beyond EU borders (e.g., Morocco, Algeria, Turkey, Ukraine or Belarus), to provide a common guidance to MS on how to foster a tangible integration among States. Regulation 2017/1938, originating from the Energy Security Package, moves away from national approaches and toward more Europeanization and regional approaches, including solidarity mechanisms [18,69].

As a result, in order to ensure that national decisions on supply security do not have a negative effect on neighboring Member States, the latest legislation attempts to bridge the gap between MS and EU forces [34,69]. To enhance regional coordination, it implements a solidarity principle, obligatory regional prevention, and emergency plans [14–18]. In terms of solidarity and collaboration, EU Member States are grouped into regions based on a variety of factors, the most important of which are spatial proximity, shared supply lines (e.g. supply patterns), and interconnection of their energy systems (e.g., market maturity, infrastructure standards, and bidirectional capacity) [24]. Regulation 2017/1938 identified four regional risk groups focused on the major transnational threats to gas supply protection and the key gas supply sources and routes of the EU, as follows [18]:

1. <u>Eastern gas supply risk groups</u>:
    (a) *Ukraine: Bulgaria, Czech Republic, Germany, Greece, Croatia, Italy, Luxembourg, Hungary, Austria, Poland, Romania, Slovenia, Slovakia;*
    (b) *Belarus: Belgium, Czech Republic, Germany, Estonia, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Slovakia;*

   - *(c) Baltic Sea: Belgium, Czech Republic, Denmark, Germany, France, Luxembourg, Netherlands, Austria, Slovakia, Sweden;*
   - *(d) North-Eastern: Estonia, Latvia, Lithuania, Finland;*
   - *(e) Trans-Balkan: Bulgaria, Greece, Romania.*
2. North Sea gas supply risk groups:
   - *(a) Norway: Belgium, Denmark, Germany, Ireland, Spain, France, Italy, Luxembourg, Netherlands, Portugal, Sweden, United Kingdom;*
   - *(b) Low-calorific gas: Belgium, Germany, France, Netherlands;*
   - *(c) Denmark: Denmark, Germany, Luxembourg, Netherlands, Sweden;*
   - *(d) United Kingdom: Belgium, Germany, Ireland, Luxembourg, Netherlands, United Kingdom.*
3. North African gas supply risk groups:
   - *(a) Algeria: Greece, Spain, France, Croatia, Italy, Malta, Austria, Portugal, Slovenia;*
   - *(b) Libya: Croatia, Italy, Malta, Austria, Slovenia.*
4. South-East gas supply risk groups:
   - *(a) Southern Gas Corridor — Caspian: Bulgaria, Greece, Croatia, Italy, Hungary, Malta, Austria, Romania, Slovenia, Slovakia;*
   - *(b) Eastern Mediterranean: Greece, Italy, Cyprus, Malta.*

While it must be noted that the 2017 Regulation prefers market processes as security measures over mandatory solidarity ones, creating an EU market for what Tagliapietra et al. [25] call a “gas security margin” may be a more successful step before a complete implementation of a liquid internal gas market is in operation. The authors conclude putting emphasis on overlooked existing alternatives, proposing to extend natural gas mandatory storage obligations currently enforced in some MS to the majority of them, as well as reducing EU fragmentation when it comes to security of supply, that can ensure supply security in case of supply shortages [25].

To this end, both the 2014 and the 2017 ENTOS-G Energy Stress Tests, as well as the subsequent 2020 addendum, revealed that the coordination of measures implemented by MS in emergencies would significantly improve security of supply. The tests evaluated the effect on the EU energy system of total or partial interruptions of supplies from major contributors to the EU natural gas network.

It concluded that in a functioning market, market-based measures to cope with disruptions should be the guiding principles, but non-market measures (i.e., measures introduced to safeguard protected customers when a state of emergency is declared and market-based measure have failed) in a cooperative scenario, one with equal (relative) burden sharing, are paramount in emergencies when the market fails. Hence, government intervention should be planned on a regional-basis and only utilized in those emergencies when the market fails.

The model regarded commercial storage as a vital supply-security measure, but cautioned that long-term crises could rapidly deplete storage reserves, necessitating the use of other security of supply measures to protect customers [14,66,172,173].

Gas storage was described as a potential supply-side non-market dependent measure to sustain SoS in the 2016 Security Package and subsequent Regulation 2017/1938 [14–18]. The European Parliament stresses the importance of cross-border access to gas storage in order to enforce solidarity during supply crises overspreading in various MS, as well as exploring ways to efficiently and economically exploit such an advantage at the EU and regional levels. Furthermore, it stresses how a regional storage definition can only be realized by overcoming current regulatory obstacles [17]. Thus, the concerted use of an ignored option such as strategic storage at the EU level can be listed as a solidarity measure, and its effects on demand curtailment, survival time, and natural gas supply mix under increasing impact of gas supply disturbances in the EU network during HILP are examined for the regional risk groups in the following application.

6.1.1 Ripple effects of supply disruptions and solidarity in the EU

Given that natural gas imports, whether by pipelines or LNG, account for 78% of EU domestic natural gas demand, gas dependency exposes the EU to vulnerabilities in the event of extreme and unexpected supply interruptions triggered by low probability incidents, both technological and political, as well as cold weather events. From 1998 to 2011, Skea et al. [40] recorded eleven global gas supply crises and hazards, and since then, four more incidents triggered by infrastructure failures and harsh weather conditions have interrupted supply in the EU [1].

Natural gas price and volumes fluctuate dramatically as a result of emergencies, with hub prices skyrocketing and extreme supply reductions. The 2009 Russia-Ukraine conflict culminated in a 50% or greater decrease in gas supply in some MS with little or no diversification, such as Bulgaria (100%), Slovakia (97%), Greece (80%), Austria (66%), Czech Republic (71%), Slovenia (50%), and Southern Germany (60%). Whereas, the earthquake and nuclear accident in Japan in 2011 resulted in contraction the EU LNG market as a consequence of higher LNG demand (+18%) and prices in Asia, with 7% of global LNG cargo redirected from the EU to Japan [154,174].

While HILP incidents cannot be forecast with confidence, they have a major impact on natural gas SoS across the EU. As a consequence, steps aimed at improving flexibility and resilience in the design of a secure and dependable EU natural gas network deem necessary [40,175]. As mentioned in Chapter 2, Section 2.5, HILP events are described as major occurrences that are unlikely to occur, such as infrastructure system collapse due to technical failures, natural disasters, or political instability, that necessitate policy intervention rather than market intervention to be resolved [20].

Furthermore, the key goal of EU Regulation 994/2010 is to ensure gas supply by exceptional measures when the market is unable to deliver the required volumes of gas. To that end, as described in Section 2.2, Article 10 of the Regulation defines three crisis thresholds to assist in categorizing the severity of the emergency the latter of which (i.e., emergency where market measures deem inadequate to cope with the crisis) can be categorized as an HILP event [13,20].

As shown in Table 6-1 on notable most recent gas supply disturbances, two main factors must be considered when looking at the EU supply crisis: significance and time extent. In terms of the first, sharp increases in production, costs, and supply demonstrate how satisfying peak demand has become a critical factor when coping with such occurrences [132]. Whereas in relation to the latter aspect, it demonstrates how, depending on the cause of disturbance, shocks have primarily been transient, lasting from days (i.e., the Burian cold snap in February 2018) to a few months (i.e., decreased LNG supply from Qatar in April/June 2010), to which, as [40] points out, network resilience is the most effective solution (see Table 6-1).

Table 6-1 Major gas supply disruptions in recent years in Europe (Source: Elaboration of the authors on the basis of [4,6,8])

Date	Location	Cause	Significance	Time extent
February 2018	Europe [149]	Extreme weather conditions	Spike in hub price and in demand	Several days (7)
December 2017	Baumgarten facility in Austria[149,154]	Material failure	Reduced operations and supply	Several days (3)
September /January 2011	Kollsnes facility in Norway [40]	Material failure	Reduced operations and supply	Few months
April/June 2010	UK [40]	Material failure	Spike in hub price	Few months

While outages have mainly occurred in isolated areas of the grid, there is a ripple effect that must be considered when looking at disruptions, especially HILP disruptions. Since the gas network is interconnected, an interruption in one portion of the system is likely to ripple and impact other MS supply, where supply for that MS transits that portion of the network.

In the supply chain, ripple effects are influenced by robust reserves (i.e., resistance), the speed and scale of recovery resolutions, and are regulated by mitigations strategies on quantities (e.g., inventory and capacity buffers), systems (e.g. flexibility), and structures (e.g. backup facilities). Proactive planning is often essential, which includes concerted plans and interventions to ensure supply, stabilize the system, and allow for system resistance and short-term recovery [175].

Modeling the effects of loss of import volume during unforeseen incidents enables analysis of the effect of disturbance to gas supply, stressing the adequacy and robustness of the natural gas network in reacting to internal and external disturbances. When analyzing the resilience of the gas network in maintaining supply security through supply/demand shocks, authors focused on a number of considerations, including market position and economic transactions [108,109], substitute supplies and import options [27,110], EU infrastructure improvements [106], and impacts on power system operations [105].

Outages in the supply of gas volumes to Europe have been investigated in the literature in recent years focusing on the role of network infrastructure and component resilience: from the loss of Bacton gas terminal in the UK [40], to the disruption of Russian natural gas supply to Europe [108], to the effect of improved natural gas EU infrastructure on supply crisis [31], and to component failures [32]. In addition, outages of natural gas supply to the protected consumers have been considered by the EC in Regulation 994/2010, and Union-wide simulation of gas supply and infrastructure disruption scenarios have been tested by ENTSO-G Energy Stress Tests [16,172,173].

In all these works authors investigated only one disruption at a time in a worst-case extremely high demand period. Nonetheless, results from these studies have shown that the effect of such scenarios would still have a substantial disruptive ripple effect on the system under consideration.

Gas dependency exposes the EU to vulnerabilities in the event of supply disruptions in an increasingly intertwined EU energy sector and system. For the last three decades, the EU has enacted legislation to provide gas supply reliability and strong regional interactions when natural gas supply outages occur. Efforts also resulted in the establishment and promotion of solidarity mechanisms among Member States, with storage identified as one of the most underestimated non-market initiatives to assist during possible crises.

From this, it appears there is currently very little research linking solidarity measures to outages in the supply of gas. In particular, there is a lack of research on the benefits of strategic storage in mitigating the ripple effect of natural gas supply disruptions on the EU natural gas system. So far, strategic storage has been ignored as a solidarity measure to ensure natural gas supply to the EU network, and the implications of a coordinated use of a solidarity gas storage reserve on EU regional risk groups during HILP events have not been discussed.

6.2 Model application to EU regional risk groups solidarity in response to HILP using strategic storage

Building on from Chapter 5, were the EU natural gas network resilience has been investigated under the lenses of a regional coordinated response to intermittent supply-demand shocks in the EU natural gas network to assess solidarity among MS, this application fills the void by proposing an impact assessment to evaluate the significance of solidarity processes on the EU regional risk groups’ configuration, with an emphasis on short-term HILP supply shocks.

Moreover, it explores the role of strategic storage in maintaining a cost-effective and safe supply of natural gas to the highly integrated EU energy grid, utilizing the two-stage stochastic optimization-based version of the LP minimum cost HILP model (see Chapter 3 for a detailed description of the general form of the mathematical model). With an estimated probability distribution of uncertainty, as it is in the applied model, stochastic programming outperforms robust optimization methodologies adapting to how uncertainty reveals and making it more apt for strategic design decisions [176,177]. As emphasized by the literature, employing two-stage stochastic optimization models to construct resilient distribution networks through absorptive and adaptive capacity of the supply chain is the most effective modeling of supply uncertainty and unmet demand induced by supply disruption especially when event probability is known or estimated as it is with the HILP model used in this application [120,166].

To do this, it is expected that those MS that already have commercial storage will install a supplementary strategic storage reserve and use it in a structured manner across Europe. Concurrent with [18] and the Third Energy Security Package [15–17], the analysis indicates both the EU natural gas supply mix (which will mitigate the effect of HILP incidents on network supply) and the extent of demand curtailment in the EU regional risk groups while a solidarity system, such as strategic storage, is in operation.

The model application has been designed to study the benefit of solidarity measures in the supply of gas in the case of HILP events. In doing so it examines a coordinate usage of strategic storage as a first non-market based measure in mitigating the ripple effect of natural gas supply disruptions on regional risk groups in the EU system over a seven-day time horizon. To this end, in each MS, which already possess a commercial storage, has been added a strategic storage reserve. The reserve has been assumed to work the same way it is implemented in Italy, which is the only MS to have a strategic storage reserve system in place.

To illustrate the applicability of the proposed model, the application make use of the HILP event model to evaluate the impact of shocking events on demand curtailment in EU regional risk groups when MS use strategic storage in a coordinated fashion. To do so, starting from a *Reference* scenario, the application considers four additional supply disruption scenarios (i.e., *Ukraine disruption*, *Russia disruption*, *Norway disruption* and *North Africa disruption*), focused on the loss of gas transit routes from major EU natural gas importers under unprecedented exceptional weather shocks (i.e., Burian week) and different event probabilities (*e1-e3*), affecting demand, survival time, natural gas supply mix and network costs. The disruption scenarios are all tested in two instances: with and without strategic storage reserve; and they are considered in three subsequent steps of the crisis aside the pre-disruption phase, (i.e., Burian, day 1 and week 1 of disruption). Aside the reference scenario that gives a benchmark on the reaction of the EU to a disruption against which to evaluate the other scenarios constructed; each scenario is analyzed to gain a different insight on the response to HILP from the EU. The *Ukraine disruption scenario* gives an insight into HILP response from Easter gas supply dependent MS; *Russia disruption* scenario is constructed to analyses MS with little diversification of sources or alternative fuel; *Norway disruption* scenario sheds a light on the core of the EU gas market and how it copes with major supply interruptions; and finally *North Africa disruption* scenario looks at the response to HILP from the peripheral EU gas network perspective.

Being a two-stage stochastic model, the model consists of first-stage and second-stage decisions (see Chapter 3). The former are two variables: level of commercial and strategic natural gas in storage and the amount of commodity withdrawn from storage, and they are set at the beginning of the time horizon (T0) prior to the resolution of some future uncertainty, in our case a HILP event. Whereas the latter second-stage variables are three variables: production, transmission, and LNG supply, and they are known only after the uncertainty is resolved (T1 to T7). Thus, when a HILP event materializes, or not, then the second-stage variables are realized. The model incorporates event uncertainty for HILP supply interruptions in the form of three probabilities of no event (*e1*), equipment and infrastructure breakdowns (*e2*), and natural disasters (*e3*) all modeled at once. With such a structure, given that uncertainty the model is rendering the gas supply mix that minimizes the expected cost of serving gas demand with and without the use of strategic storage in five different disruption scenarios: Reference scenario, Ukraine disruption scenario, Russia disruption scenario, Norway disruption scenario, and North Africa disruption scenario (see Section 6.2.1 for scenarios definition and Chapter 3 for model equations and constraints) [40,133,135].

The model has been initially run on a seven-day timeframe in a 1-day step increment. The timeframe has then been modified with daily increase to evaluate the survival time of regional risk groups during HILP events until demand curtailment is deemed necessary for one or more MS in a regional risk group. Having a short time horizon allows one to closely examine the regional reaction to the emergency and to assess the promptness of strategic storage as a solidarity measure.

The model has also been adapted to assess regional risk groups as opposed to single independent regions. MS have been analyzed according to the groups formulated by [18] (see Section 6.1).

Three different regional risk groups based on geographical proximity, transmission risks to SoS, points of gas supply import and main natural gas flow directions, and encompassing all EU MS have been constructed, taking the first regional risk sub-group of each group as reference, as follows: (1) from the Eastern gas supply risk groups: Bulgaria, Czech Republic, Germany, Greece, Croatia, Italy, Luxembourg, Hungary, Austria, Poland, Romania, Slovenia, Slovakia, Estonia, Latvia, Lithuania, Finland; (2) from the North Sea gas supply risk group: Belgium, Denmark, Germany, Ireland, Spain, France, Italy, Luxembourg, Netherlands, Portugal, Sweden, United Kingdom; and (3) from the North African gas supply risk group: Greece, Spain, France, Croatia, Italy, Austria, Portugal, Slovenia.

General input data and assumptions for the model are discussed in length in Chapter 3, Section 3.3; a brief recap is presented following. Each region has been defined with its pipeline capacity, network pipeline length, demand, production costs and volumes, transport costs, commodity price, and when applicable commercial and strategic storage volume and price, as well as LNG volume and price taken from actual data from the Burian week. As in the two previous applications (see Chapter 4 and Chapter 5), the Burian week is used as a real case of an unexpected cold weather event, to more realistically illustrate the distressed the gas network and volumes from daily injection of natural gas flows, LNG import volumes, natural gas injected/withdrawn from storage, and production volumes to construct demand (see Chapter 3, Table 3-5 for details on data input).

Again, given the short-term nature of the emergency assessed by the model, costs included reflect: weighted average assignment price for storage (seasonal peak modulation from April/May 2018); average monthly hub (2008-2018) and average monthly LNG prices (2012-2018) for commodity price; and average hub monthly price and average transmission costs breakdown for standard gas households price from ACER (November/December 2017) for transport costs.

Moreover in terms of infrastructure, the maximum value between entry/exit for each connection point in the gas network has been taken as a proxy value for pipelines capacities [52,123,124]. Whereas, an energy efficiency parameter has been applied to LNG import values to account for the overall LNG chain efficiency (i.e. 90%) [122,178] (see Chapter 3, Section 3.2.2).

Finally, strategic storage is implemented in those MS where commercial gas storage already exist and volumes in storage are parametrized on Italian volumes, which is taken as reference system, having Italy a pure strategic storage mechanism already in place. In addition, storage is evaluated at the end of each time period (see Chapter 2).

6.2.1 Case hypothesis and scenario construction

As a close estimate for an HILP disrupting example and to illustrate the implications of strategic storage on regional risk groups demand curtailment, time survival and natural gas supply mix, the current work suggests the lack of import volume during a severe cold weather occurrence, along with material breakdown and ground movement incidents occurring simultaneously in regional risk groups within the EU natural gas network.

A total of five simulations were used to analyze the actions of EU regional risk groups as well as the impact of concerted usage of strategic storage reserves on the EU gas network when HILP incidents occurred.

The scenarios develop from a reference, which models a real-world disruption natural gas demand shock due to an unusual cold wave which hit Europe during the Burian week in February 2018 (1) and concurrently on material failure and ground movement event probability, and increase the level of severity accounting for further reduction in the supply from extra EU major supply countries in different regional risk groups, which together account for approx. 60% of all EU imports [179], as follows: (2) Ukraine in regional risk group 1.a. (Ukraine disruption scenario), (3) Russia in regional risk group 1.d. (Russia disruption scenario), (4) Norway in regional risk group 2.a. (Norway disruption scenario), and (5) North Africa in regional risk group 3.a. (North Africa disruption scenario). In particular, scenario (2) and (3) account for 32% of EU gas import, scenario (4) for 21%, and scenario (5) for 6% (see Table 6-2).

Furthermore, each scenario was formed in two versions, first in the absence and then in the presence of strategic storage, specifically:

- *Reference* scenario (1), Burian week (February 2018) weather conditions and without strategic storage in place to gain insight on how the EU gas network would react to a more dramatic disruption using a solidarity gas reserve.
- In the first disruption scenario, *Ukraine disruption* (2), all connections from Ukraine to Europe are interrupted, preventing Russian natural gas from reaching many EU MS (13) for seven days in a row. Bulgaria, Slovakia, and Greece were the countries most affected by a similar outage in 2009, with a 75% and over of disruption in their supply and little diversification of sources or substitute fuel [151].
- In the second disruption scenario, *Russia disruption* (3), all pipeline deliveries of natural gas from Russia to the North-Eastern Europe are not possible. Baltic countries and Finland are

among the MS impacted by this event, when the majority of their natural gas supply is cut: Estonia, Finland, and Latvia rely on Russian imports by 98%, 91% and 82% respectively, whereas Lithuania, which has been diversifying its supply with LNG since 2014, depends on import from Russia by 26% [163].

- In the third disruption scenario, *Norway disruption* (4), natural gas export from Norway is not available. The core EU gas market, with most liquid hubs and extensive interconnections and diversification of sources, is affected. To meet demand, alternate import routes (e.g., from Russia or from Algeria), LNG (e.g., in Northwest Europe, Italy, and Spain), and storage capacity (e.g., in Germany and Italy) are available. Belgium (34%), Germany (30%), France (27%), the Netherlands (25%), and Italy (13%) are the top EU importers from Norway [163].
- In the fourth disruption scenario, *North Africa disruption* (5), no gas from Algeria and Libya is arriving to Europe. MS that are immediately affected are Spain, Portugal and Italy, with 28%, 16% and 7% of imports respectively [163]. However, although the latter is well connected to the EU gas network, Spain and Portugal are not and would have to rely on LNG imports as an alternate source of natural gas.

Table 6-2 Scenarios hypothesis

a) Disruption scenarios

Scenario Variant	**Parameter**	*Reference* Scenario	*Ukraine disruption* Scenario	*Russia disruption* Scenario	*Norway disruption* Scenario	*North Africa disruption* Scenario
Loss of gas transmission	Volume	**-10% TAG** to Slovenia **-30% TAG** to Germany **-10% Passo Gries** to Italy (see Table 3b for further details)	**-100% Ukraine** to Bulgaria, Czech Republic, Germany, Greece, Croatia, Italy, Luxembourg, Hungary, Austria, Poland, Romania, Slovenia, Slovakia	**-100% Russia** to Estonia, Latvia, Lithuania, Finland	**-100% Norway** to Belgium, Denmark, Germany, Ireland, Spain, France, Italy, Luxembourg, Netherlands, Portugal, Sweden, United Kingdom	**-100% North Africa** to Greece, Spain, France, Croatia, Italy, Austria, Portugal, Slovenia;
Gas reserve	Volume	None	+ Strategic storage	+ Strategic storage	+ Strategic storage	+ Strategic storage
Insight on response to HILP		Reference EU reaction to a disruption	Easter gas supply dependent MS	MS with little diversification of sources or alternative fuel	The core of the EU gas market	The peripheral EU gas network

b) Reference scenarios

Key indicators *(Applied to each time period)*		*Reference* Scenario [133,135,153,154,169]
Event probability		
Rupture	Event probability	*No event = 0.999998869* *Material failure = 2.86·10-7* *Ground movement = 8.45·10-7*
Magnitude		
Gas demand	Daily rates	Burian data *[Data source: see Chapter 3, Table 3-5]*
Loss of gas import	Volumes	-80% from Russia (*Compared to the average 2009 natural gas import volumes, in all regions importing from Russia)*; -6% to Germany; -26% to Italy
Hub gas price in affected regions (i.e. Austria, Italy, Slovenia, Germany, and Hungary)	Price	+70% *[Data source: see Chapter 3, Table 3-5]*
LNG Import	Volumes	-5% *[Data source: see Chapter 3, Table 3-5]*
	Price	+20% *[Data source: see Chapter 3, Table 3-5]*
Gas reserve	Volumes	-35% *[Data source: see Chapter 3, Table 3-5]*
Loss of pipeline capacity	Volumes	-10% from TAG to Slovenia -30% from TAG to Germany -10% from Passo Gries to Italy

In terms of supply, natural gas volumes reductions are considered in both imported volumes and pipeline capacity. Data were gathered from the 2009 Russia-Ukraine conflict, the 2017 Baumgarten (Austria) crash, and the 2010 Passo Gries landslide (Italy). All of these events, like Burian, have resulted in a rise in product prices (+70%) and LNG value imports (+5%), as well as a decline in storage volumes (-35%) (see Table 6-2).

Finally, the reference period taken into account is that of a short-term emergency, i.e. seven days. Both demand and supply are predicted to be strained in the *Reference* scenario as a result of multiple events happening simultaneously and with differing incident probability. Demand is focused on Burian real-world extraordinary weather conditions data on demand, price, import, LNG, and storage to provide a more accurate depiction of how natural gas is recalled in a stressed gas network. They were collected from a number of databases and networks, both publicly and privately accessible (see Chapter 3, Table 3-5 for details on data input).

6.3 Discussion on *disruptions* scenarios

The results suggest that geographical proximity alone does not assess the energy flexibility or capacity to withstand supply shocks of a country. The model simulations showed that in most situations, geographic risk groups were unable to deal with HILP-caused disturbances for more than 9 days. This confirms that key factors to consider when dealing with an HILP incident are very case-specific for single Member States, and much more so when aggregated in geographical risk categories. They are concerned with the relative importance of gas in the energy mix, as well as any infrastructure limitations that may prohibit links to the natural gas network of other countries.

The application demonstrates that solidarity among regional risk groups in coping with an HILP incident significantly reduces its effects. During a one-week crisis time, there was no market curtailment, and overall infrastructure costs were 15% lower than if no strategic storage was in operation. In turn, strategic storage allows for more stability in bolstering the gas network during outages, potentially doubling the survival time of area risk groups and raising it to 14 days.

The reliability and insurance value of coordinated strategic gas storage usage was observed. It stops the system from shutting down unexpectedly after the HILP incident, allowing for the free allocation of additional and cheaper gas to help stabilize the system and dampen the ripple effect within the EU.

In addition, a strong interplay between LNG and strategic storage during emergencies is crucial to balance the system in both a volume- and cost-effective way. Results have confirmed that with increasing storage volume withdrawals during a HILP event, LNG costs and volumes are affected. The increase in available storage volumes within the gas network does not significantly influence the recall of LNG to the EU (average +15%), with a consequent reduction of up to 70% in LNG costs if compared to a reference scenario without strategic storage in place. It is thus shown from the results how a price-insensitive volume reserve helps mitigate the consequences of unexpected and impactful events, but it assumes supportive cooperation and interconnection between both Member States and regional risk groups.

Following results are discussed considering the impact of strategic storage as a solidarity measure in case of HILP disrupting the EU natural gas network with a focus on demand curtailment in regional risk groups; survival time to the crisis; and changes in the EU natural gas supply mix.

6.3.1 EU natural gas supply mix as a result of disruptions

Looking at the total EU natural gas supply mix for production, import, LNG and storage during every time step of the crisis (i.e., Burian, day 1 and week 1 of disruption) compared with pre-disruption levels, there is a reduction in natural gas import in favor of both storage right from the start of the emergency, as well as production as the EU further enters the emergency (see Table 6-3 and Figure 6-1). Natural gas import more than halves from pre-disruption levels (from 50% to 20%), whereas production spikes up at 60% at seven days into the crisis from 10% in the pre-crisis.

As a general trend, in the four disruption scenarios the system sees an overall decreasing in costs from the *Reference* scenario while increasing storage and LNG volumes if compared to the *Reference* scenario. In particular, the EU aggregate increase in storage withdrawal during disruption (+32 at day 1 and +16% at week 1 disruption) is counterbalanced by a significant increase of EU aggregate LNG import. Average LNG volume increase over a one-week emergency period for major importers is 30% (i.e., France, Spain, and Italy). Whereas costs see a significant LNG costs reduction of up to 70% and a total system costs reduction up to 15% when strategic storage is introduced if compared to scenarios without the reserve being adopted (see Figure 6-2, Table 6-4 and Table B1 in Appendix B).

In particular, looking at different disruption scenarios, greater LNG volume increase across MS is seen in the *Ukraine disruption* scenario with terminal in Belgium, the Netherlands, Lithuania, and Poland more than doubling their imports. Whereas for the remaining scenarios LNG volumes are attracted following the import dynamic of the MS included in the regional risk groups affected by the disruption. To this end, in the *Russia disruption* scenario as well as in the *Norway disruption* scenario central Europe is recalling more LNG volumes, with the majority of MS increasing their import to 40%; whereas in the *North Africa disruption* scenario Portugal sees the highest percentage volumes increase (95%) followed by Spain and Italy at 30% (see Table 6-5 and Figure 6-3 and Table B2 in Appendix B).

In addition, as far as storage is concerned commercial storage sees an average 40% withdrawal across all four disruption scenarios, whereas strategic storage sees the highest withdrawal during the *Russia* (68%) and *Ukraine* (60%) *disruption* scenarios, compared to a 45% and a 55% of the *North Africa* and *Norway disruption* scenario respectively. This is an indication that the system heavily relies on additional storage reserve during disruption from major importers to optimize system costs (see Table B2 in Appendix A).

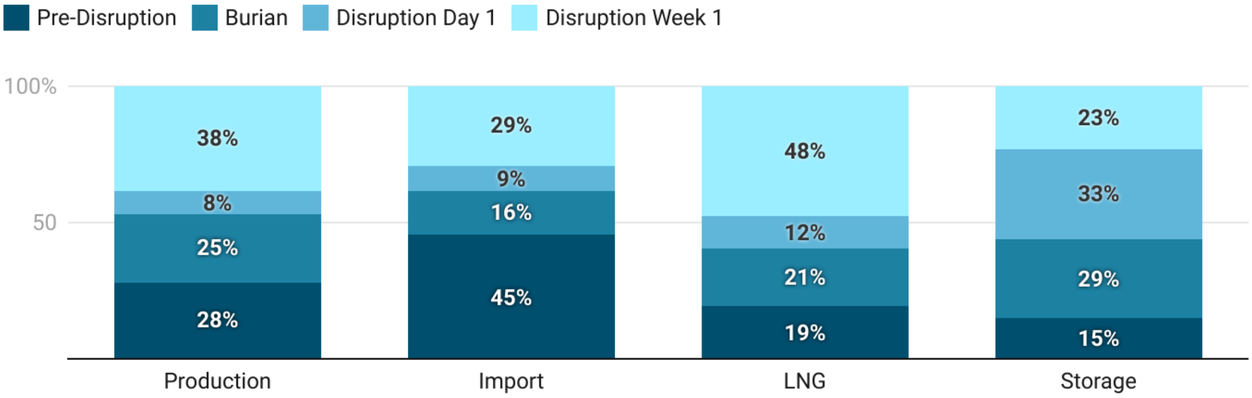
To this end, as Table 6-3, Figure 6-4 and Table 6-4 depict in more detail, the analysis reveals a EU aggregate increase in storage usage, both commercial and strategic, across the whole week of disruption. Strategic storage is utilized close to the full extent (60% and over) in every scenario by most MS with a reserve as this is assumed to be the cheapest and most readily available natural gas (see Table 6-3, Figure 6-4 and Table 6-4).

Figure 6-1 shows storage usage doubled in the first period of the crisis (i.e., reference scenario) and then remained at the same level almost thorough the entire crisis period, with strategic storage accounting for 65% of the storage usage at day 1 of the crisis (32%). Although storage is a preferred option for the system right at the start of the Burian week, its costs does not see a decrease until the system starts using strategic storage at Disruption Day 1. Only then with similar supply percentage (32% vs. 35%), there is a close to 50% storage cost reduction (see Table 6-3, Figure 6-2 and Figure 6-1).

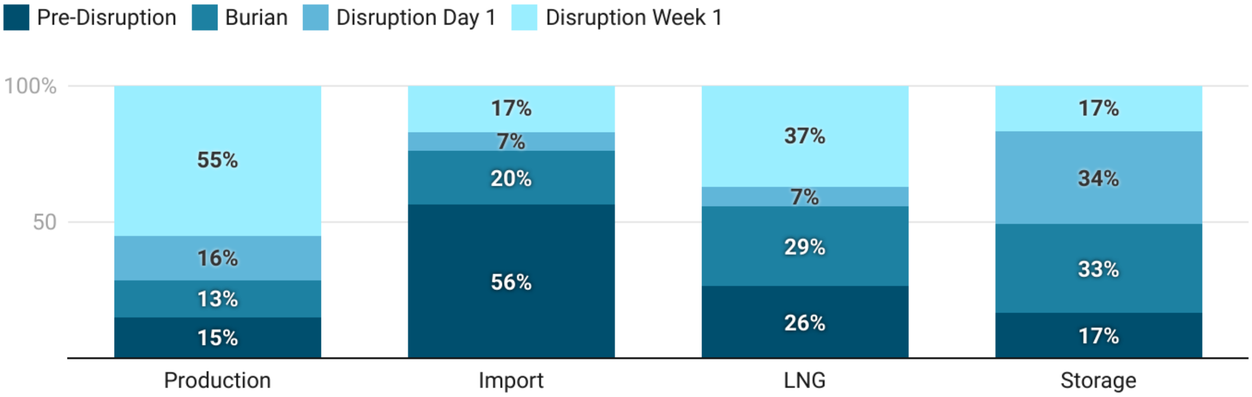
Table 6-3 Natural gas supply mix at European level comparison *(%)*

	Pre-Disruption	**Burian**	**Disruption Day 1**	**Disruption Week 1**
Production	13	12	13	43
Import	2	1	0	1
LNG	7	8	5	10
Storage	41	80	82	46

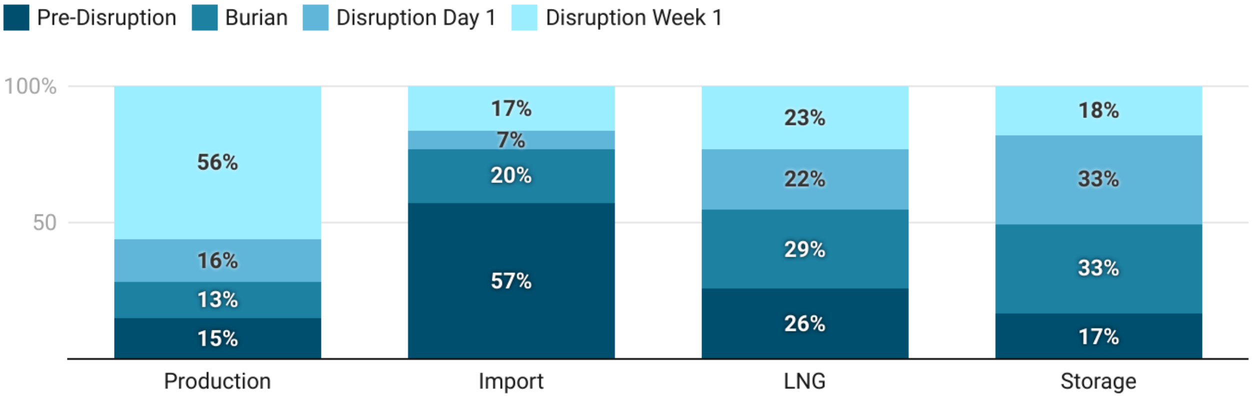
a) *Ukraine disruption scenario*



b) Russia disruption scenario



c) Norway disruption scenario



d) North Africa disruption scenario

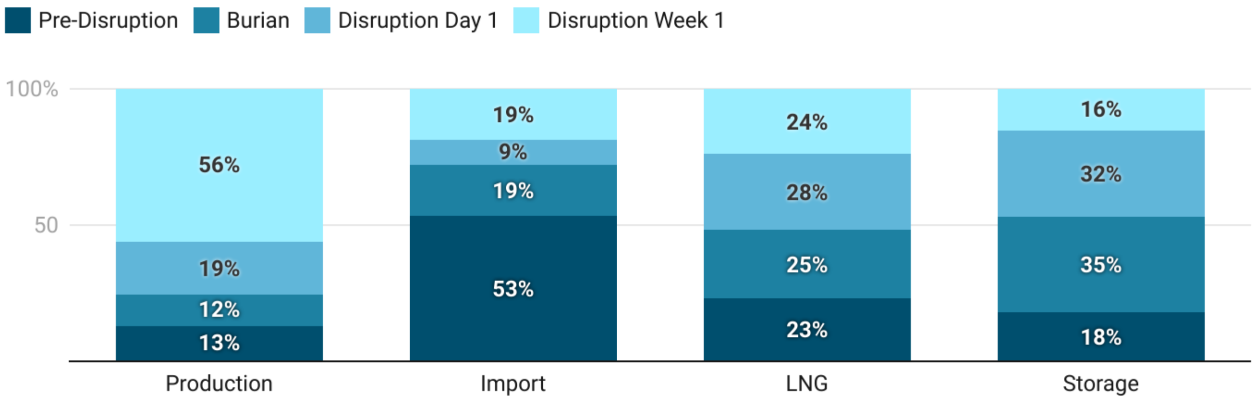
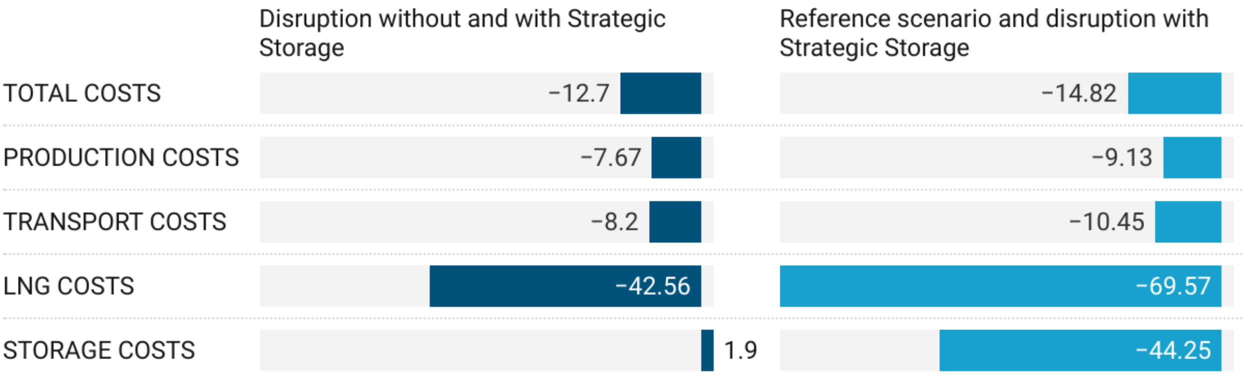
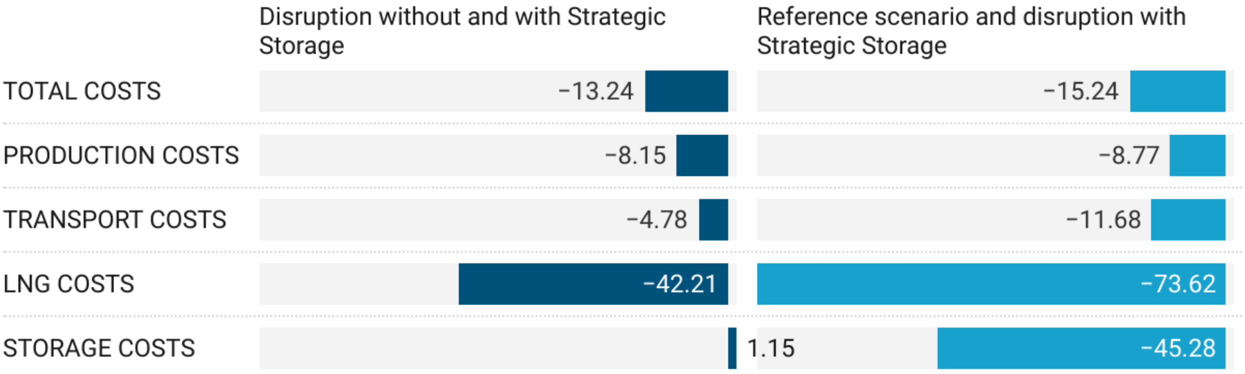


Figure 6-1 Natural gas supply mix for each disruption scenario comparison (%) (a)-d)). Pre-Disruption and Burian are run with no strategic storage in place as oppose to the other two scenarios, with average data from the four disruption scenario discussed in the chapter, where strategic storage is included

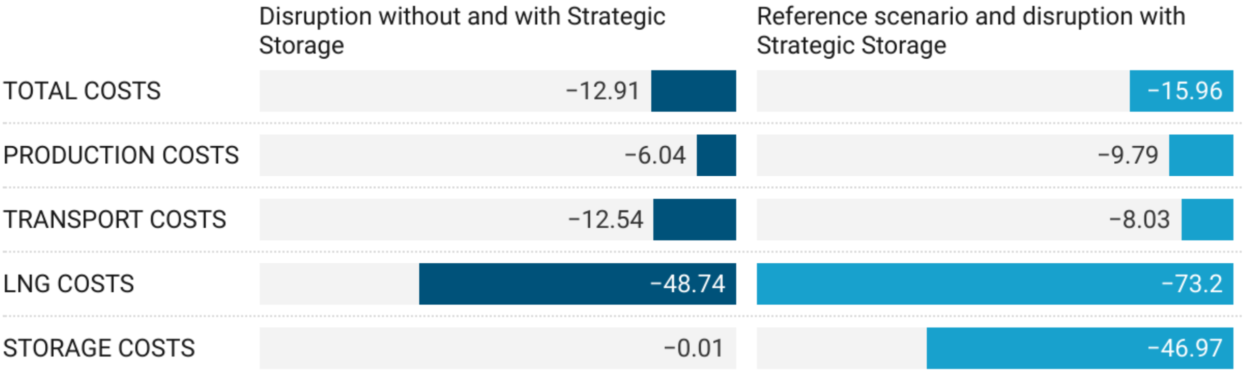
a) *EU level comparison*



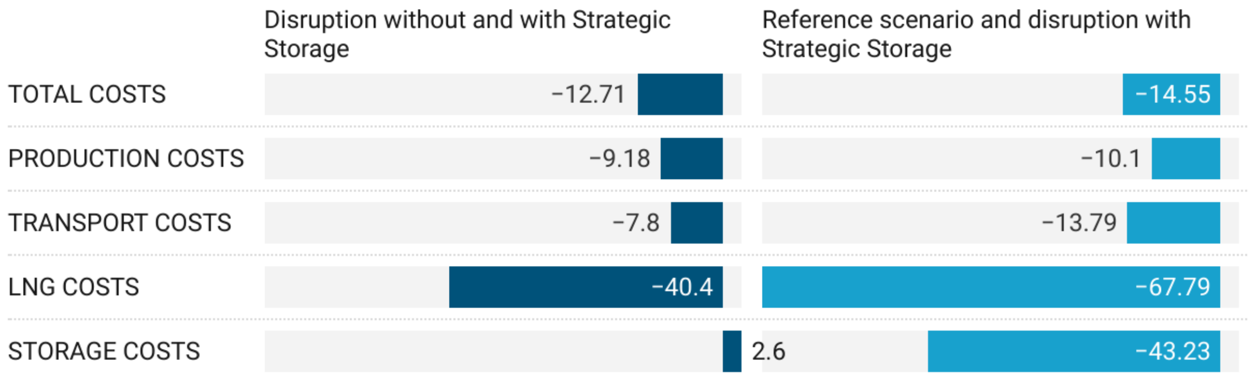
b) *Ukraine disruption scenario*



c) *Russia disruption scenario*



d) *Norway disruption scenario*



e) *North Africa disruption scenario*

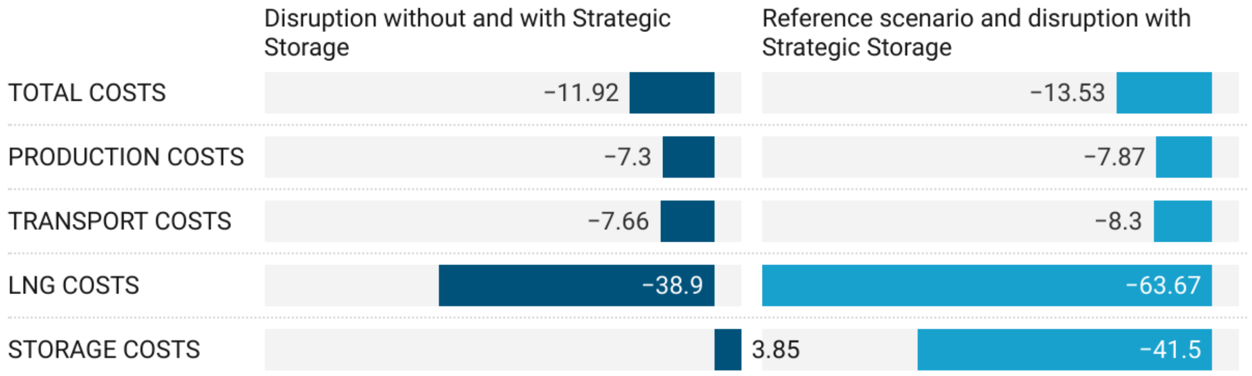


Figure 6-2 Cost efficiency between scenarios without and with strategic storage at European level and at each disruption scenario comparison at disruption week 1 (%) (a)-e)). The graph shows how the introduction of strategic storage during disruptions is significantly cost effective in reducing system costs if compared to scenarios with no strategic storage involved. The dark blue bar represents the difference in percentage between average value of disruption scenarios with and average value of disruption scenarios without strategic storage reserves. The light blue bar represents the difference in percentage between the reference scenario without strategic storage and average values of disruption scenarios with strategic storage reserves (see Table B2 in Appendix B for natural gas storage volumes for each disruption scenario (MWh))

Table 6-4 System costs breakdown in North Africa, Norway Russia, and Ukraine disruption scenarios (10^3€)

Cost (€)	***Pre-disruption* Scenario**	***Reference* Scenario**	***North Africa disruption* Scenario**	***Russia disruption* Scenario**	***Norway disruption* Scenario**	***Ukraine disruption* Scenario**
Total	4,240,000	7,597,357	6,691,832	6,551,670	6,632,368	6,592,518
Production	3,660,000	3,707,009	3,436,473	3,376,473	3,367,018	3,408,121
Import	4,115	4,894	4,519	4,530	4,301	4,382
LNG	576,941	1,075,456	657,092	620,947	640,947	619,441
Storage	0.152	0.152	0.108	0.104	0.106	0.105

Table 6-5 Increase in LNG import at European level by MS and for each disruption scenarios in aggregate compared to Burian period LNG import values after disruption of 1 week (%) (a)-b)). Percentage indicates percentages difference between different disruption scenarios (see Table B3 in Appendix B for LNG import volumes for each disruption scenario (MWh))

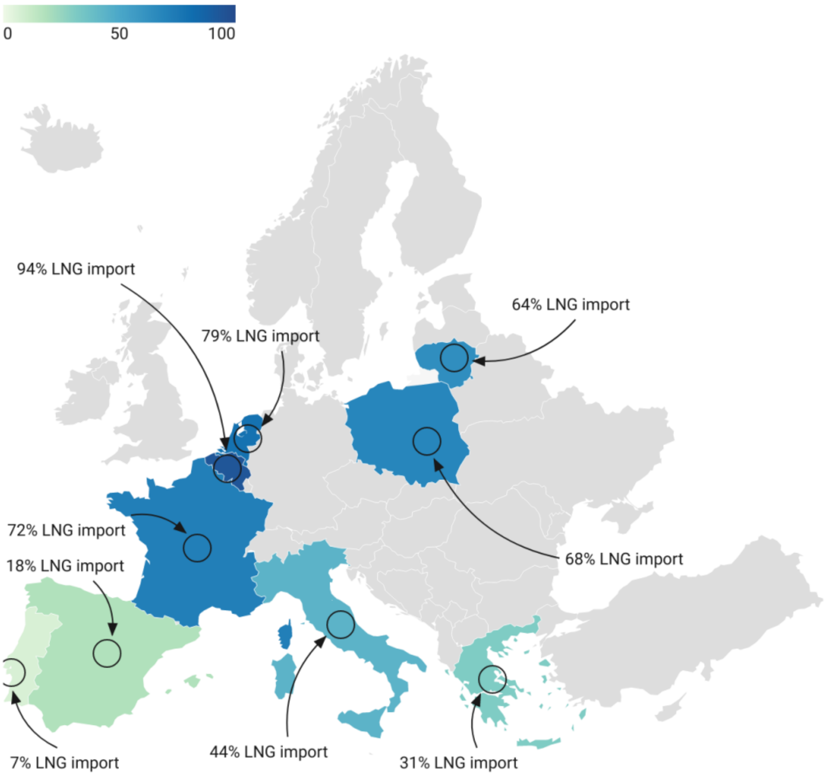
a) *EU level comparison by MS*

	Average EU LNG import after 1 week disruption (%)
Belgium	77
Spain	16
France	40
Greece	22
Italy	31
Lithuania	55
Netherlands	20
Poland	54
Portugal	33

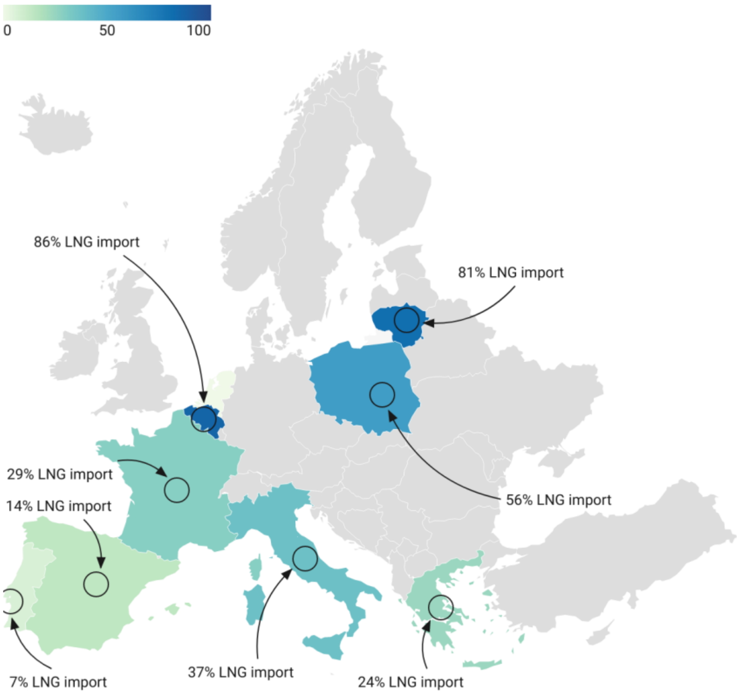
b) *Disruption scenarios MS aggregate*

	North Africa disruption **Scenario**	***Norway disruption*** **Scenario**	***Russia disruption*** **Scenario**	***Ukraine disruption*** **Scenario**	***EU aggregate***
Average LNG Import after 1 week disruption (%)	30	34	37	53	39

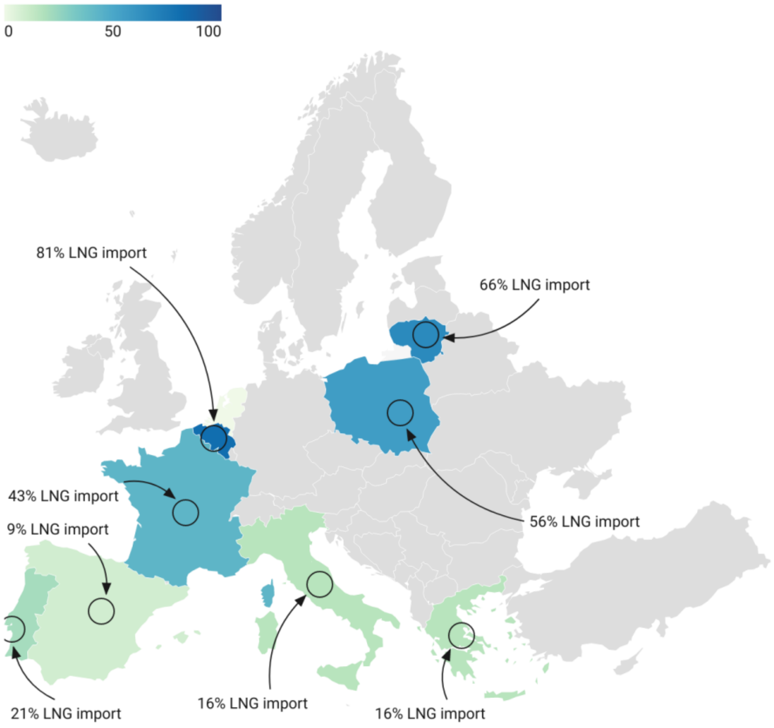
a) *Ukraine disruption scenario*



b) *Russia disruption scenario*



c) *Norway disruption scenario*



d) *North Africa disruption scenario*

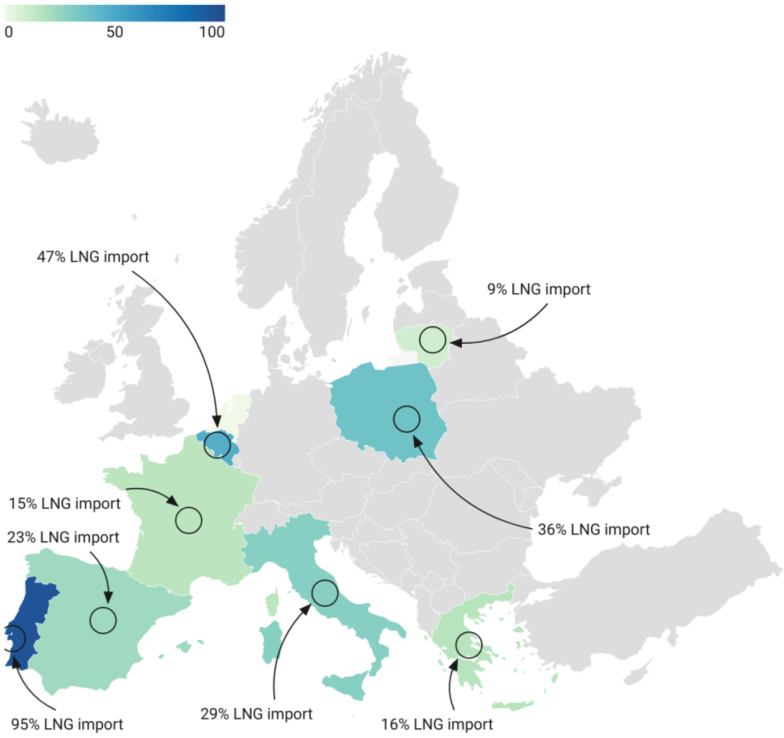


Figure 6-3 Increase in LNG import for each disruption scenarios compared to Burian period LNG import values after disruption of 1 week (%) (a)-d)) (see Table B3 in Appendix B for LNG import volumes for each disruption scenario (MWh))

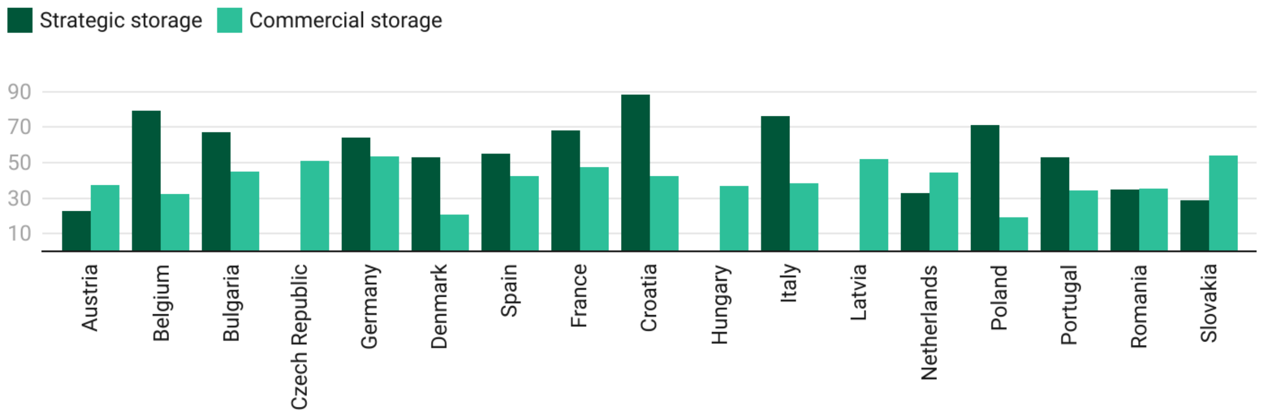


Figure 6-4 Increase in storage, both commercial and strategic, usage during the disruption week 1 (%) when compared to the pre-disruption period. The bars represent the percentage of strategic (dark green) and commercial (light green) storage utilized over a 7-day period of emergency (see Table B2 in Appendix B for natural gas storage volumes for each disruption scenario (MWh))

6.3.2 EU demand curtailment and survival time to the crisis as a result of disruptions

The analysis of the four disruption scenarios reveals that if no solidarity measure (i.e., strategic storage for the purpose of this study) is in place, demand is unmet at some point during the first 9 days into the emergency. Exactly when this happens depends on the scenario considered. The model, which operates on a cost basis, has been run over a seven-day daily timeframe in February 2018 for each disruption scenario with additional daily increments to show when demand curtailment occurs.

Without a coordinated use of strategic storage reserves Slovakia, Latvia and France are the first MS to experience unmet demand, mainly due to their primary energy profile and infrastructure limitations. In particular:

- Slovakia sees an unbalance in supply/demand both in the *Ukraine disruption* scenario and in the *North Africa disruption* scenario. 25% of total primary energy supply is met by natural gas. It imports close to 85% of its gas from Russia through Ukraine and exports around 65% of it to Western and Southern Europe. Although, storage experiences an increase in withdrawal over the crisis period (from 65%% at day 1 to 10% at day 7 for both disruption scenarios), Slovakian gas network faces infrastructure limitations. In particular, it is not sufficiently interconnected to surrounding countries, which could help mitigating the supply shock, hence at day 8 in the *Ukraine disruption* scenario and at day 9 in the *North Africa scenario* demand has to be curtailed for the system to be able to secure natural gas flows in the regional risk group in both scenarios.

- Latvia sees an unbalance in supply/demand in the *Russia disruption* scenario. Natural gas is the main source of power generation in the country. It accounts for 65% of total demand, with the country importing 90% of the commodity from Russia. In addition, Latvia only interconnects with Estonia and Lithuania. Both are heavily dependent on imports from Russia (98% and 65% respectively) and reliant on their gas imports for power generation with little to no natural gas demand share export (0% and 3% respectively). Hence, they are unable to help mitigating the impact of the disruption in Latvia, which experiences demand curtailment at day 6 of the emergency.

- France sees an unbalance in supply/demand in the *Norway disruption* scenario. Although France is mostly relying on nuclear power (40%) to meet its energy needs, 15% of French total primary energy supply is met by natural gas. It mostly covers residential and commercial (45%), as well as industry (30%) and (15%) of power generation demand share. To this end, even if the natural gas supply is significantly diversified (Norway, Russia, LNG, the Netherlands, and UK), the majority of the commodity is imported by Norway via pipeline (35%). To counteract the supply disruption, the country is attracting high quantities of LNG at day 1 through day 3 of the crisis, and then subsequently it is relying on its storage. Nonetheless, being unable to rely on additional gas flows, coming from surrounding countries, which are experiencing the same outages as France, to supply primary energy, at day 9 France sees demand curtailment to balance flows among MS in the affected regional risk groups.

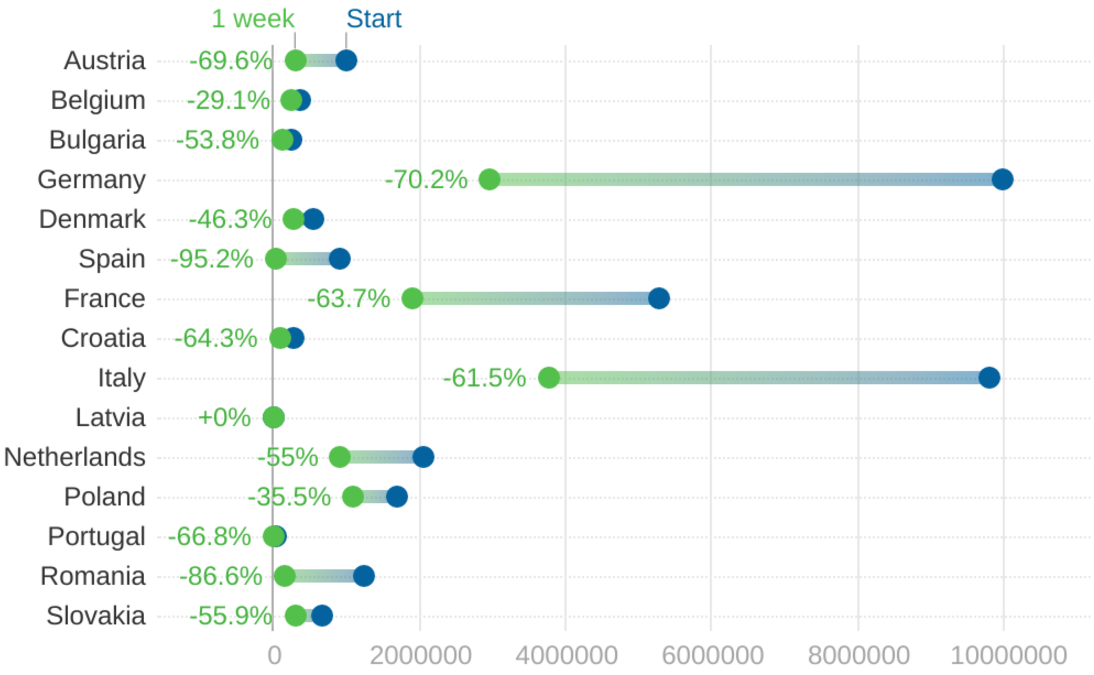
Whereas when strategic storage is in place, no demand is unmet for up to two consecutive weeks. As Table 6-6 and Figure 6-5 demonstrate, most of the MS withdraw over 50% of their storage volumes. The distance between the dots in Figure 6-5 gives an indication of the absolute value of the storage used in each country on day 1 (blue dot) and day 7 (green dot) of the emergency, showing that those MS which own the largest storage reserve in the EU (i.e., Germany, Italy and France) witness the biggest EU aggregate depletion in terms of volumes (60% and over, which in volumes corresponds to 7,500,000 MWh, 6,000,000 MWh and 3,000,000 MWh respectively) (see Table B1 in Appendix B).

Although, overall storage depletion in 1 week emergency (i.e., reference timeframe for the study) it is considerable in the vast majority of countries that have a reserve in place, the strategic reserve left in storage helps them secure natural gas supply to the system for additional 7 days if compared to a scenario with no strategic storage.

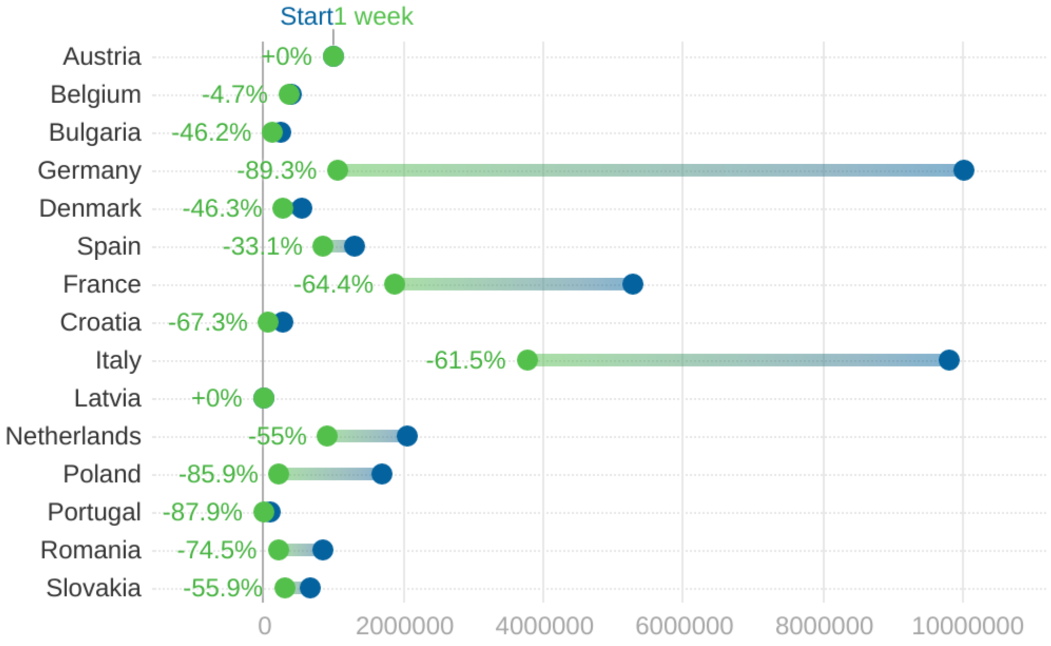
Table 6-6 Strategic storage depletion during a seven-day emergency at European level (%) (see Table B2 in Appendix B for natural gas storage volumes for each disruption scenario (MWh)).

	Strategic storage depletion at day 1 (MWh)	**Strategic storage depletion at 1 week (MWh)**	**Strategic storage depletion in a seven-day emergency (%)**
Austria	1,008,017	405,093	59.8
Belgium	297,687	218,032	26.8
Bulgaria	227,297	109,654	51.8
Germany	10,012,280	2,503,946	75
Denmark	548,850	245,851	55.2
Spain	1,205,274	445,977	63
France	4,808,440	1,901,953	60.4
Croatia	275,782	86,333	68.7
Italy	9,804,667	3,776,200	61.5
Netherlands	2,074,703	985,640	52.5
Poland	1,546,047	630,611	59.2
Portugal	94,286	16,924	82.1
Romania	1,136,518	214,626	81.1
Slovakia	691,179	304,978	55.9

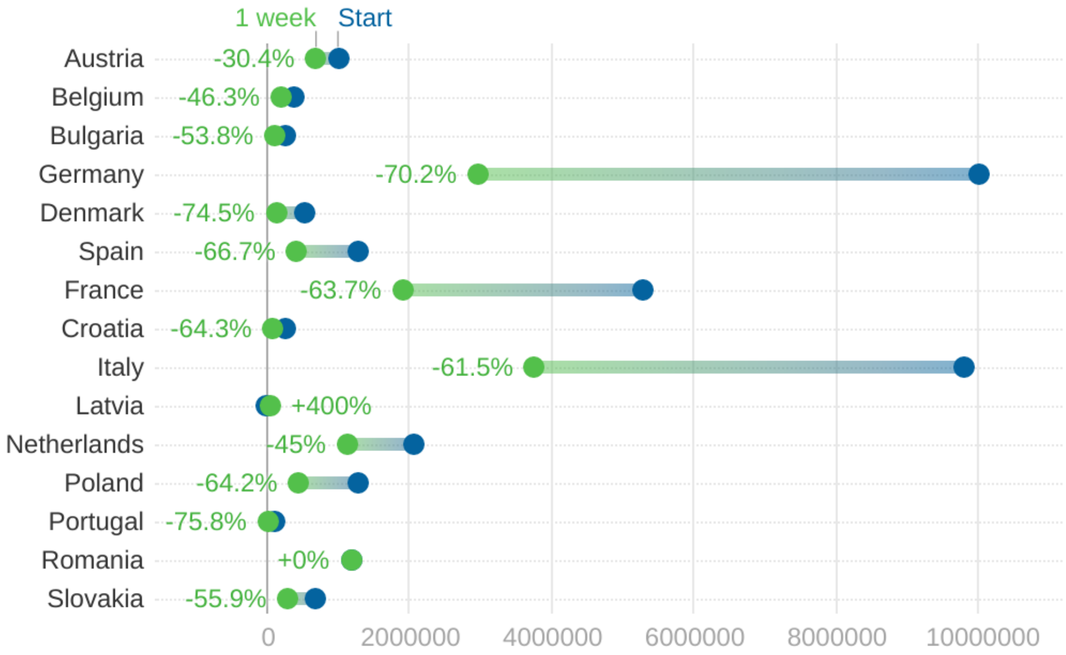
a) Ukraine disruption scenario



b) Russia disruption scenario



c) Norway disruption scenario



d) North Africa disruption scenario

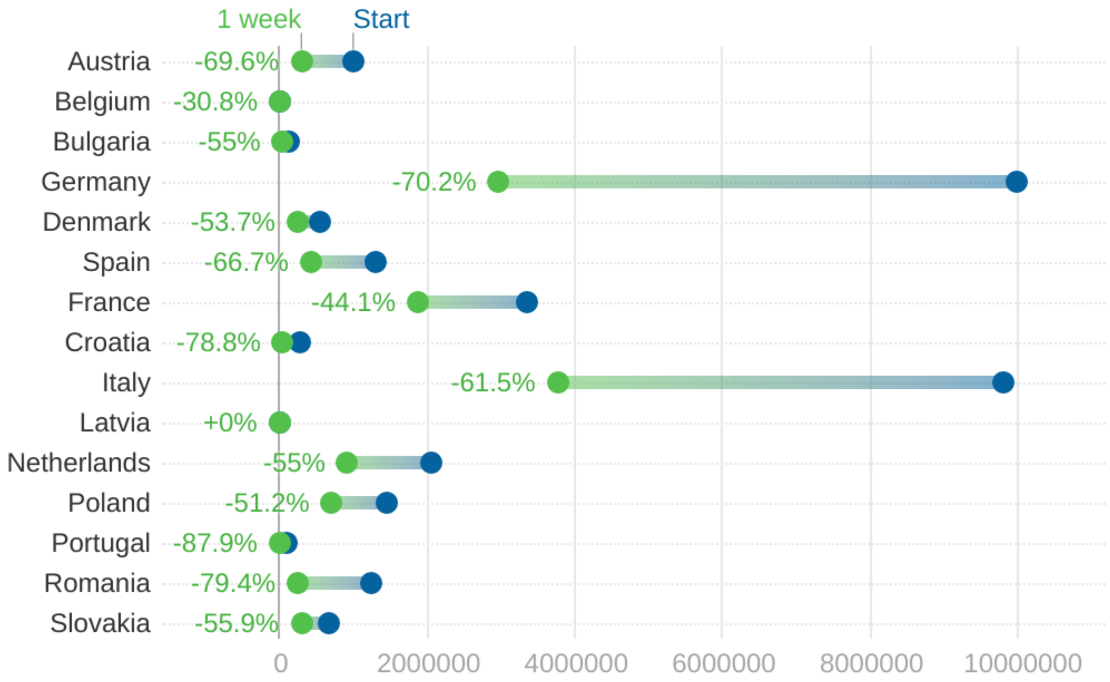


Figure 6-5 Strategic storage depletion during a seven-day emergency for each disruption scenario (a)-d)). The blue dot represents storage at day 1 of the disruption and the green dot represents storage after 1 week of disruption. The percentage figure represents the % depletion over 7 days. The horizontal axis represents the overall amount of natural gas in storage in energy terms for each MS (MWh) (see Table B2 in Appendix B for natural gas storage volumes for each disruption scenario (MWh))

The study highlights the role of organized strategic storage usage in balancing the natural gas network during crises, and it provides additional data supporting the EU legislative route toward Energy Union.

To that end, not only are infrastructure availability and source diversification critical pieces in the picture, but solidarity, and especially strategic storage, gains considerable value as an underutilized alternative in response to the possibility of HILP events. To assess the importance of strategic storage as a solidarity security of supply measure for the EU and to assist the EU in its preparations for a more "convergent energy security supra-national society" a complete cost-benefit study of non-market based alternative solutions (e.g., forced fuel switching or load shedding) with a wider variety of shock scenarios and their occurrence probability could be expanded in future studies.

Chapter 7. Conclusions and future work

The conclusion of this thesis is given in this chapter. Section 7.1 discusses how this dissertation contributes to the discourse on natural gas network resilience to unexpected and abrupt natural gas supply shocks. The main perspectives and key findings from the three model applications on the resilience of the EU natural gas network to HILP events are then presented in Section 7.2. Following that, in Section 7.3, the drawbacks and possible future study directions of the work are discussed.

7.1 General conclusions

Stemming from the need to investigate the reliability and value of gas storage to reinforce energy security in Europe and EU gas infrastructure security, this work proposes a novel modeling framework that focuses on the role of strategic storage in presence of HILP events impacting the EU natural gas supply. To this end, the literature reveals a clear gap in the methodological improvement of modeling approaches to supply-demand crises of the natural gas systems to analyze the relative resilience of the network over short-term periods, which would support the functioning of the EU natural gas system.

No literature has been found to propose a detailed infrastructure model analyzing the short term resilience of the whole European natural gas infrastructure when facing a non-hypothetical demand surge, produced by Burian. Furthermore, no work was found relative to the EU new agenda combining supply security objectives with solidarity and collaboration among MS in respect to the natural gas supply network and relating solidarity measures, in the form of a coordinated use of strategic storage, to gas supply interruptions.

As a result, there is a methodological gap in the creation of modeling frameworks that appropriately depict a regional coordinated reaction to transient supply-demand shocks in the EU natural gas networks, as well as the considerable disruptive ripple effect they have on the system. In addition, strategic storage has been disregarded as a solidarity measure to safeguard natural gas supply to the EU network, and the impacts of a coordinated usage of a solidarity gas storage reserve on EU energy security during HILP events have not been addressed.

This work fills a gap in the literature by applying the temporary shock approach of operational supply chain and supply chain resilience to the gas network and energy security modeling frameworks. The model adds to the literature by offering a unique modeling framework to examine strategic gas storage as the first non-market-based solidarity solution to deal with HILP occurrences that interrupt natural gas supply/demand flows throughout the linked EU natural gas network over short time periods. The predicted HILP events weight significantly on natural gas supply because they reflect supply disruptions that occur concurrently with demand peaks, culminating in post-market failures.

The model developed incorporates all the natural gas supply chain stages (i.e., extraction, storage, transmission, and end use demand) to simulate optimal natural gas flow configuration within the EU natural gas network in the event that a dramatic disruption occurs in conjunction with gas demand peaks minimizing expected system costs of gas supply in a multi-country region (i.e., the EU gas network). This model is unique in that it captures not only the benefits of the coordinated employment of an unused alternative, such as that of strategic storage, during supply emergency related crisis, but also the policy-related dynamics among MS in the EU supporting the EU legislative path towards an Energy Union.

In particular, the model studies supply security in the EU natural gas network to appraise resilience and solidarity, seen as a coordination means to counter short-term supply disruptions to the natural gas system, and it also provides a unique impact assessment to measure the benefit of solidarity mechanisms on the structure of EU regional risk groups, with an emphasis on short-term HILP supply shocks.

At first, the deterministic version of the model allows evaluating the critical complementarity between LNG and storage during natural gas demand crises by minimizing the cost of gas delivery in an integrated EU gas system. It provides an optimization-based approach both to unfold the value of LNG in the natural gas network by assessing the EU natural gas network resilience over short-term shocks in supply and to assess the resilience of the network in safely providing natural gas to every country considered in the scenario.

Following, the two-stage stochastic optimization-based linear programming minimum cost HILP version of the model is employed to optimize the absorptive capacity to uncertainty in supply of the natural gas system and estimate the value of the coordinated use of strategic gas storage. Not only, uncertainty in the gas supply volumes at different severity levels is examined by this version of the model, but also the capability of the system to yield efficient cost and distance allocation of the resource in case of demand disruption within the context of an emergency short-term timeframe is depicted.

The model has been used to investigate three main applications concerning disruptions with increasing intensity in the EU natural gas network, demonstrating the benefit of solidarity measures within the EU. Results have shown that a strong complementarity between LNG and strategic storage during emergencies exists and it is critical to balance the system in both a volume- and cost-effective manner. However they have also demonstrated how non-market base measure can be a cost-effective alternative to market based measures, emphasizing the reliability and insurance value of an overlooked emergency option such as gas storage in securing energy to the system in a timely fashion as oppose to different alternatives such as LNG.

Results have also indicated that geographical proximity alone does not determine the energy flexibility of a country and its ability to absorb supply shocks, but that solidarity among regional risk groups in dealing with a HILP event significantly lessens the impact of that event. Hence the coordinated use of strategic storage as a solidarity measure among MS within the EU has proved to be efficient in terms of survival time and overall system costs, mitigating the effects of supply disruption and demand spikes, though strong cooperation between MS is required.

Not only do the findings confirm that infrastructure availability and source diversity are critical pieces of the EU policy agenda, but they also demonstrate that solidarity, and particularly strategic storage, should gain enormous traction as a valuable and underutilized alternative in response to the prospect of energy emergencies and on the path to an EU Energy Union.

The following sections address specific findings on each of the three main applications examined.

7.2 Contributions to the EU natural gas network resilience analysis

The developed model have been applied to examine the resilience of the EU natural gas network to HILP events, with scenarios that incorporate different levels of event uncertainties and increasing disruptions significance. The impact of such outages on natural gas prices, volumes, and survival time to crisis have been studied in three different application involving disruptions within the EU natural gas network and are summarized in the following sections.

7.2.1 The impact of a cold spell hitting the EU natural gas network

The first application stemmed from the oversupply in LNG imports in the EU with a focus on diversification of supply sources for gas network resilience. The EU natural gas network response to a real-world short-term unexpectedly intense cold weather threatening supply and triggering demand spikes with the help of such abundant volumes of LNG commodity available was investigated. Looking at supplying flows, the application unveils LNG and natural gas storage interdependence to improve resilience in the EU gas network.

To this end, firstly results suggest that oversupply of LNG as a single alternative means of delivering gas to the network during demand shocks is an inefficient approach cost-wise. EU gas network demand shocks cannot be efficiently counterbalance by LNG alone. As showed by the results, there is a 40% LNG cost rise in a scenario where natural gas hub price are set at 40% higher and LNG price is 20% lower than the market price, hence diffusion of LNG is found to be highly sensitive to the price of LNG.

Secondly, it was observed that the combination of LNG and storage play a unique and complementary role in providing system resilience to demand shocks in the EU gas infrastructure.

The findings indicate that not only does LNG plays a larger role when LNG prices approach those of low-cost US natural gas, but also that, when paired with storage, LNG may considerably contribute to reducing gas transport, LNG costs, and total cost within the EU gas network. The gas network experiences a 30% decrease in both LNG and transport costs when storage volume grows, which is only second to the reduction in total costs when commodity price changes are positive (+50%).

Finally, results have reinforced the view that storage reliability mitigates natural gas supply unexpected and sudden in the EU natural gas network. By stressing the importance of storage in conjunction with LNG when it comes to unexpected demand shocks, results shed a light on the insurance value storage plays in the EU natural gas network and how this component of the natural gas supply chain is vital for an efficient and effective functioning of the network especially when it comes to supply/demand emergencies hedging against supply risks. Storage is indeed an integral component of the natural gas network and a necessary backbone of EU security of supply.

7.2.2 Modeling solidarity among EU Member States during HILP scenario with supply disruption

The second application arose from the lack of studies in the literature mapping energy security and policy aspects, and in particular that of solidarity, into a modeling framework. The call for solidarity measures, to be put in place when it comes to energy security and HILP events at the EU level, has been forcefully emphasized by the EU Regulations over the past five years, culminating in the definition of a solidarity principle in EU Regulation 2017/1938. Given the findings of the first application and the crucial role of storage in the EU natural gas network, the second application discussed the benefits and value of a coordinated use of a non-market-based measure, such as strategic storage, within the EU natural gas system in case of HILP. In each MS that already possess a commercial storage has been added a strategic storage reserve. The reserve has been assumed to work the same way it is implemented in Italy, which is the only MS to have a strategic storage reserve system in place.

Three scenarios were constructed to simulate a dramatic disruption in natural gas supply of TAG pipeline in conjunction with natural gas demand peaks under different degrees of uncertainty and in two instances (i.e., with and without strategic storage in place), as follows: (1) Burian: 100% event probability under exceptional weather conditions (i.e., Burian cold spell), (2) Two disruptions: material failure probability under the same weather conditions as (1) with additional variations in production and transport volumes as well as commodity price, (3) Three disruptions: under the same weather conditions as (1) and (2) with three concurrent event probability (i.e., 100% event probability, material failure probability, and ground movement probability) as well as an additional variation in production volumes with respect to (2).

Results have shown that a non-market based measure in response to HILP involves lower costs than a market-based one: in the worst-case scenario analyzed in the application (3), when strategic storage is used the system experiences total cost reduction of up to +30% if compared to an instance where strategic storage is not utilized. Results indicate how a price-insensitive volume reserve helps cost-efficiently balancing the system and managing an emergency that invests commodity supply/demand volumes and prices.

Although strong cooperation and interconnection between MS is required, the concerted use of strategic storage has demonstrate to be a valid solidarity measure in counteracting the impact of supply disruptions and demand surges to lessen system costs and providing energy security. In scenarios with different disruption intensity, total system costs realized 13% and 28% cost reduction between instances, for scenario (2) and (3) respectively.

Lastly, similarly to the first application, results confirm that there is a complementarity between storage and LNG within the EU natural gas network in case of HILP when market fails, storage volume increasing when LNG costs experience the greatest decrease of all system costs (+60% and over). To this end not only source diversification is crucial, but also looking into overlooked emergency options, such as strategic storage, proves critical when it comes to respond to HILP. When everything else fails and LNG experiences delays in delivery (e.g., March 2013 and January

2017), Member States can count on a concerted strategic reserve that can inject volumes into the system.

7.2.3 Strategic storage as a solidarity measure among EU Regional Risk Groups

The third application originated from the realization that being the EU energy market and system increasingly interconnected and highly reliant on gas imports, any supply shocks could potentially greatly endanger the system with repercussion on a vast number of MS. In line with the last 30 years of EU regulations on natural gas security of supply and close regional cooperation when natural gas supply disruptions occur, this application is devoted to a more detailed analysis as to whether a solidarity measure, such as the coordinated use of strategic storage, could benefit EU Regional Risk Groups in case of supply sudden emergencies in mitigating the ripple effect of natural gas supply disruptions. For this application the geographical and temporal scope of the model has been increased compared to the previous application.

Four disruption scenarios were constructed, based on a *Reference* scenario (i.e., Burian weather condition and (*e1-e3)* event probability), each of which accounts for a total loss of different natural gas transit route to the EU affecting different MS in each regional Risk Group and in two instances (i.e., with and without strategic storage reserve), as follows: (1) Ukraine disruption: -100% gas from Ukraine, (2) Russia disruption: -100% gas from Russia, (3) Norway disruption: -100% gas from Norway, and (4) North Africa disruption: -100% gas from North Africa. In addition each scenario includes Burian week weather shock conditions and different event probabilities, affecting demand, survival time, natural gas supply mix, and network costs.

Results suggest that energy flexibility of a MS and its capacity to absorb a shock it is not solely determined by geographical proximity: 9 days was the average survival time limit for regional risk groups when no additional solidarity measures were in place. Hence additional factors, such as relative importance of gas in the energy mix, and any infrastructure limitation that might prevent connections to the gas networks of other countries, need to be taken into account when dealing with HILP events and Regional Risk Groups.

Results have reinforced the idea that HILP event impact is significantly lessen when solidarity is performed among Regional Risk Groups. Not only solidarity in the form of a coordinated use of strategic storage increases flexibility to support gas network during disruptions, with total system costs decreasing (-15%) and no demand curtailment during week 1 of the crisis. But it also balances the system preventing it from abruptly shutting down and moderating the emergency ripple effect within the EU, by doubling the emergency survival time of regional risk groups to two weeks. Hence, a concerted use of strategic storage, allowing for free allocation of additional and cheaper natural gas, has proved to be reliable and to insure against unexpected HILP events.

Finally, as seen in both the previous applications, not only are the availability of infrastructures and source diversification critical pieces of the puzzle, but solidarity, and especially a concerted use of strategic storage, gains considerable value as an underutilized alternative in response to HILP incidents. Results from this last application have confirmed that during supply/demand crisis the system is effectively balanced both in volume and costs by a strong interplay between LNG and strategic storage. Again the analysis confirmed that increasing storage volume withdrawals during a HILP event affect LNG costs (-70%) and volumes (+15%).

7.3 Limitations and future work

As the proposed two-stage stochastic LP cost minimization model on one hand looks at scenarios happening during a short-term specific real-world event, hence it has been designed with a very specific EU network configuration, that of February 2018; and on the other hand it examines a non-market based measure, that of strategic storage, where market conditions do not longer hold, hence it does not consider how the market could affect supply/demand dynamics.

In doing so, recognizing the importance of interdependencies within EU natural gas infrastructures with respect to evaluating the coordination of non-market based measures in case of HILP events, there are some assumptions that had been introduced with respect to both time and technical deliverability of natural gas considering different stages in the supply chain that limit the modeling of costs, volumes and deliverability hence the model should be enhanced to more accurately depict the European gas network by including additional aspects to broaden strategic planning. This would consist of augmenting the geographical and time granularity of the model, by adding technical data on the pipeline network and storages, as well as time deliverability and indicators of gas transmission. In addition, as far as storages are concerned, modeling pressure dynamics will be crucial to a deeper understanding of the response to emergencies of the natural gas network.

A more articulated costs description, both for storage and transmission costs as well as filling levels and storage performance curves would make results even more compelling as the model would be able to account for the immediate responsiveness of the system to shocking events with a lesser degree of approximation as natural gas availability and storage withdrawal speed highly depend on them. In addition, the introduction of indexes to account for policies at the national and international level incorporating in the model considerations on whether a MS is committed to cross-border cooperation on energy related issues (e.g. regional cooperation), as well as on the existence of energy security policies in MS (i.e., not having a codified energy security policy, which might mean that a member state might not be able to ensure energy security) are especially crucial aspects, since the external supply choice remains under MS' jurisdiction. Finally, the analysis could greatly benefit from the introduction of indirect costs, such as social costs and the macroeconomic activities of countries related to commodity price shocks, which are significant aspects when dealing with HILP and the estimation of its overall damages.

A more accurate description of the current network structure would need to consider additional data, technical limits and aspects, and should include:

Network related

- Existing and planned reverse flow and existing bottlenecks
- Velocity of natural gas in the pipelines in natural gas transmission
- Actual pipeline utilization rate
- Losses of natural gas in the transmission
- Investment decisions regarding capacity expansion
- Different contract prices and tariffs
- Behavior of players such as strategic storage stockholders, transit countries and demand countries

Storage related

- Storage operators' costs, including: operating the storage facility, purchasing gas, transporting gas to the storage and from the storage to the transmission pipeline, injection and withdrawal costs, capacity costs
- Investment in storage capacity and the marginal benefit of an additional unit of storage capacity
- Incorporating physical storage data such as storage type, volume in storage, filling/stock level, storage performance curves, cycle rate, average speed, deliverability
- Costs and benefits of alternative non-market based measures

Policy related

- Public stabilization funds or "antispeculative" gas reserve price
- Incentive price to account for solidarity and cross-border cooperation

Understanding what is the optimized cost competitive solution as well as the most efficient allocation of gas flows and capacities across Europe in case a HILP event disrupting supply occurs, using the existing capacities in strategic storage at best is a key component of constructing a self-standing system which could effectively help the EU in case of emergency, hence, away from the Italian pure strategic storage mechanism which has been the benchmark for the simulations in this work, the analysis of the mechanics and the impact of an ad hoc coordinated strategic natural gas reserve system should evaluate additional consideration on how to implement solidarity through strategic storage and how such a system could work could be explored in future works:

- In what scenarios/circumstances would this system be used?
- What counts as a strategic storage measure: underground storage only or a combination of underground storage, LNG, and/or other energy system measures such as voluntary demand reduction, supply diversification, flexible import contracts, interruptible contracts, swap contracts, flexible production, line-pack flexibility?
- What triggers its use? How is it activated?
- Is it to be managed nationally, Supra-Nationally or Privately?
- Who would be contributing to it in terms of stored volumes and costs?
- Who is in charge and accountable for it? Who ensures that its natural gas will be available when needed? How long would it take to deliver the gas where needed? How fast can it get there?
- How much gas would be stored? How to determine the amount? Who determines the quantity and with what criteria?
- How is it paid for? What are the costs of such a system and their temporal horizons?
- What are the policy implications to its implementation?

Additionally, to further estimate the value of strategic storage as solidarity security of supply measure for the EU and support the EU in its planning for a more “converging energy security supra-national society”, a full cost-benefit analysis of non-market based alternative options (e.g., enforced fuel switching or load shedding) with a larger range of shock scenarios and their occurrence probability deserves attention.

This work has concentrated on strategic gas storage because it is a readily available non-market measure to increase flexibility for the management of the HILP events related to natural gas supply disruption or extreme demand. However, it can assure natural gas demand reduction and flexibility to the gas grid and could be covered in future work.

In a first instance the integration of alternative sources in the natural gas infrastructure, whose generation should also align with the Paris Agreement decarbonization targets, such as synthetic gas, hydrogen, and biomethane, could increase the reliability of the network.

In particular, since 2016, biomethane production and trade within the EU grid have increased by 0.7% (on energy basis) [1]. Of the 729 biomethane plants injecting gas in to grid in 2020 -from 483 in 2018 with a 51% increase in number in two years and a total production of 2bcm per year, which represents 0.4% of the EU gas demand - Germany, UK, and France have the highest capacity as well as incentive schemes, 9800000 MWh since 2017, 3600000 MWh since 2011, and 1200000 MWh since 2018 respectively. However, when looking into biomethane a distinction has to be made between technical potential vs. actual grid-injectable availability. If European total biomethane technical production potential it is 1,010 TWh (95bcm in natural gas equivalent terms) per year by 2050, coming both from anaerobic digestion (62bcm) and regasification (33bcm) with few countries having the majority of woody and agricultural biomass potential (80%) (i.e., France, Germany, Spain, Sweden, Finland, Norway, Italy, Poland, UK, Romania); the actual injection into the grid is forecasted around 10bcm per year moving forward, which accounts for 10% of current available biomass conversion into biomethane. Limiting factors can be traced back to tight directive on what is considered sustainable biomass (i.e., Renewable Energy Directive II, 2018)), limited or cut in incentives as production is very sensitive to the level of support, declining in sources (i.e., landfill gas), and competition with alternative fuels in the level of support structure available [1,180,181].

If few aspects are still holding back the full potential of biomethane, primarily at this stage a clear and well-defined support structure and an agreement on what can be defined to be a renewable gas, momentum is building for the role of hydrogen, making demand for natural gas a crucial piece in the energy mix in a long-carbon future. With the EU Hydrogen Strategy, the EU targets to deliver one million tonnes of “green” renewable hydrogen (6000MWh) by 2024 and 10 million tonnes (40000MWh) by 2030, indicating hydrogen as an investment priority with a share or hydrogen in the energy mix of 13-14% by 2050 from 2% in 2019 (including the use of hydrogen as feedstock). Given the technology state of the art and the cost of production, reaching this target will require government-backed support schemes for large infrastructure development projects to progress, because it needs critical mass in investment to be driven pass the tipping point and create a large-scale infrastructure network [182].

Depending on the degree of decarbonization, the introduction of hydrogen in the energy mix will have repercussion on the share of natural gas in the mix, but still will deem natural gas network a needed asset. As of 2019, 33 bcm natural gas equivalent of hydrogen has been produced and the technology learning curve is going to bring down costs, which depending on the form of production are at: (1) 1.5 €/kg (38 €/MWh) for current "grey" (high carbon) hydrogen production; (2) 2 €/kg (50 €/MWh) for "blue" fossil-derived hydrogen with CCS; (3) 2.5-5.5 €/kg (65–135 €/MWh) for "green" renewable hydrogen. While "green" hydrogen it is seen as the final goal but until technology costs drop to be competitive with "grey" or "blue" hydrogen, priority in production is going to be given to the last two [183,184].

This process of hybridization (i.e., the development of 'hybrid' electric-gas energy system [185]), as implying a higher miscibility of the different vectors in the natural gas grid, would increase the network flexibility and reliability. To this end, network flexibility could also be achieved with the integration of synthetic gas through power-to-gas, either from hydrogen or methane, which could address renewable generation curtailment and improve the utilization of renewable assets,

In addition, on the demand side, an increase electrification, which is expected to be essential for decarbonizing sectors such as buildings and transport [43], would reduce the request of natural gas, which is likely to make the grid less exposed to HILP events. This realizes as long as the electricity grid, expected to run on a very high penetration of renewables, would have the ability to store the excess renewable energy sources.

Finally, the use of big data and information and communication technologies (ICT) has to be acknowledged as it could play a compelling role in forecasting HILP. In particular, when it comes to smart energy systems the Internet of Things (IoT) can be applied to state monitoring and anomaly detection could lead to a prompt maintenance program as well as interventions on the grid before a fault materializes. On the demand side, smart metering is just one example of how consumers' demand can be monitored, analyzed, and used for energy consumption predictions as well as management. Energy predictive efficiency is one of the benefits of the IoT, helping energy suppliers to predict energy consumption and hence meet demand. Additionally, it can result in lower demand peak and a more efficient utilization of renewable sources in the energy mix. Hence, given a timely, accurate and reliable collection of data, the IoT has a significant potential to help produce new and insightful information which could help prepare in advance for a crisis [186].

References

[1] Snam. Business Operating Data 2019.

[2] International Energy Agency (IEA). Medium-Term Gas Market Report. 2016.

[3] International Energy Agency (IEA). World Energy Outlook 2017. 2017.

[4] IHS. Eurasian Gas Export Outlook for May 2020 2020.

[5] IHS. Short-term European Outlook. 2017.

[6] Bartelet H, Mulder M. Natural Gas markets in the European Union: Testing Resilience. Econ Energy Environ Policy 2019;8.

[7] International Energy Agency (IEA). Global Gas Security Review 2017. n.d.

[8] European Parliament. Directive 98/30/EC of the European Parliament and of the Council of 22 June 1998 concerning common rules for the internal market in natural gas 1998.

[9] European Parliament C of the E. Directive 2003/55/EC of the European Parliament and of the Council of 26 June 2003 concerning common rules for the internal market in natural gas and repealing Directive 98/30/EC. Off J Eur Union 2003:57–78.

[10] European Parliament. Directive 2009/73/EC Of The European Parliament And Of The Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC 2009:94–136.

[11] Commission E. Regulation (EC) No 713/2009 - Establishing an Agency for the Cooperation of Energy Regulators. Off J Eur Union 2009;L211:1–14.

[12] European Commission. Regulation (EC) No 715/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the natural gas transmission networks and repealing Regulation (EC) No 1775/2005. Off J Eur Union 2009;L211:36–54.

[13] European Parliament. Regulation No 994/2010 of the European Parliament and of the Council of October 20, 2010 concerning measures to safeguard security of gas supply and repealing Council Directive 2004/67 2010.

[14] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL on the short term resilience of the European gas system Preparedness for a possible disruption of supplies from the East during the fall and winter of 2014/2015 2014;COM (2014).

[15] European Commission. Proposal for a regulation of the European Parliament and of the Council concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010. Off J Eur Union 2016:COM(52) Final.

[16] European Parliament. Briefing EU Legislation in Progress New rules on security of gas supply. Eur Parliam Res Serv 2016.

[17] Parliament E. P8_TA(2016)0406 EU strategy for liquefied natural gas and gas storage European Parliament resolution of 25 October 2016 on EU strategy for liquefied natural gas and gas storage (2016/2059(INI)) 2016.

[18] European Commission. Regulation (EU) 2017/1938 concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010. Off J Eur Union 2017;2017/1938. https://doi.org/http://eur-lex.europa.eu/pri/en/oj/dat/2003/l_285/l_28520031101en00330037.pdf.

[19] Boersma T. Energy Security and Natural Gas Markets in Europe. Lessons from the EU and the United States. Routledge. Routledge; 2015.

[20] Stern J. Security of European Natural Gas Supplies. The impact of import dependence and liberalization. 2002.

[21] Kopp S-DD. Politics, markets and EU gas supply security: Case studies of the UK and Germany. Springer; 2015. https://doi.org/10.1007/978-3-658-08324-3.

[22] Winzer C. Conceptualizing energy security. Energy Policy 2012;46:36–48. https://doi.org/10.1016/j.enpol.2012.02.067.

[23] Sovacool BK. An international assessment of energy security performance. Ecol Econ 2013;88:148–158.

[24] Keyaerts N. Economic principles for coordinated reactions to gas supply disruptions : first appraisal of the 2016 package on sustainable energy security. Florence Sch Regul Energy;

Policy Briefs; 2016. https://doi.org/10.2870/33038.

[25] Tagliapietra S, Zachmann G. Rethinking the security of the European Union's gas supply 2016.

[26] Buchan D, Keay M. Europe's Long Energy Journey: Towards an Energy Union? OUP Oxford; 2015.

[27] Flouri M, Karakosta C, Kladouchou C, Psarras J. How does a natural gas supply interruption affect the EU gas security? A Monte Carlo simulation. Renew Sustain Energy Rev 2015;44:785–96. https://doi.org/10.1016/j.rser.2014.12.029.

[28] Chyong CK, Hobbs BF. Strategic Eurasian natural gas market model for energy security and policy analysis : Formulation and application to South Stream. Energy Econ 2014:198–211.

[29] Eser C, Chokani N, Abhari R. Impact of Nord Stream 2 and LNG on gas trade and security of supply in the European gas network of 2030. Appl Energy 2019:816–830.

[30] Månsson A, Johansson B, Nilsson LJ. Assessing energy security: An overview of commonly used methodologies. Energy 2014;73:1–14. https://doi.org/10.1016/j.energy.2014.06.073.

[31] Rodríguez-Gómez N, Zaccarelli N, Bolado-Lavín R. European ability to cope with a gas crisis. Comparison between 2009 and 2014. Energy Policy 2016;97:461–74. https://doi.org/10.1016/j.enpol.2016.07.016.

[32] Praks P, Kopustinskas V, Masera M. Monte-Carlo-based reliability and vulnerability assessment of a natural gas transmission system due to random network component failures. Sustain Resilient Infrastruct 2017;2:97–107. https://doi.org/10.1080/23789689.2017.1294881.

[33] Vivoda V. Evaluating energy security in the Asia-Pacific region : A novel methodological approach. Energy Policy 2010;38:5258–5263.

[34] Giuli M. The energy security package: significant overhaul or business as usual? 2016.

[35] Yang Z, Zhang R, Zhang Z. An exploration of a strategic competition model for the European Union natural gas market. Energy Econ 2016;57:236–42.

[36] Baltensperger T, Füchslin RM, Krütli P, Lygeros J. European Union gas market

development. Energy Econ 2017;66:466–479.

[37] Smeers Y. Gas models and three difficult objectives. 2008.

[38] Hosseini S, Ivanov D, Dolgui A. Review of quantitative methods for supply chain resilience analysis. Transp Res Part E Logist Transp Rev 2019;125:285–307. https://doi.org/10.1016/j.tre.2019.03.001.

[39] Görlach B. What constitutes an optimal climate policy mix? Defining the concept of optimality, including political and legal framework conditions. CECILIA2050 WP1 Deliv 11 2013:1–38.

[40] Skea J, Chaudry M, Wang X. The role of gas infrastructure in promoting UK energy security. Energy Policy 2012;43:202–13. https://doi.org/10.1016/j.enpol.2011.12.057.

[41] Speirs J, Jalil Vega F, Cooper J, Gerber Machado P, Giarola S, Brandon N, et al. The flexibility of gas : what is it worth ? 2020.

[42] Speirs J, Dubey L, Balcombe P, Tariq N, Brandon N, Hawkes A. The best use of natural gas within Paris climate targets 2021.

[43] IEA. Net Zero by 2050: A Roadmap for the Global Energy Sector. Int Energy Agency 2021:224.

[44] Le Fevre C. Gas storage in Great Britain. 2013.

[45] European Commission. The Role of Gas Storage in Internal Market and in Ensuring Security of Supply. 2015.

[46] GIE. Storage Database 2018.

[47] EIA. The Basic of Underground Natural gas Storage 2015. https://www.eia.gov/naturalgas/storage/basics/.

[48] Energy UK. Defining Flexibility - 2018 2018.

[49] Ma J, Silva V, Belhomme R, Kirschen DS, Ochoa LF, Member S. Evaluating and Planning Flexibility in Sustainable Power Systems. IEEE Trans Sustain Energy 2013;4:200–9.

[50] Dickx L, Miriello C, Polo M. Balancing Systems and Flexibility Tools in European Gas

Markets. 2014.

[51] GIE GIE. The value of gas storage 2015.

[52] GIE. AGSI+ Transparency Platform. 2018-2020 n.d.

[53] Engie. WEC-GGC & Snam, Internal Workshop,12th April 2019.

[54] Zachmann G. Policies for ensuring sufficient gas storage levels 2017.

[55] Italian Parliament. Legislative Decree 164/2000 Attuazione della direttiva n. 98/30/CE recante norme comuni per il mercato interno del gas naturale, a norma dell'articolo 41 della legge 17 maggio 1999, n. 144. (GU n.142 del 20-6-2000) 2000.

[56] Italian Parliament. Legislative Decree 93/2011 Attuazione delle direttive 2009/72/CE, 2009/73/CE e 2008/92/CE relative a norme comuni per il mercato interno dell'energia elettrica, del gas naturale e ad una procedura comunitaria sulla trasparenza dei prezzi al consumatore fi 2011.

[57] Proedrou F. EU Energy Security in the Gas Sector: Evolving Dynamics, Policy Dilemmas and Prospects. Farnham:Ashgate; 2012.

[58] Haase N. European gas market liberalisation : Are regulatory regimes moving towards convergence ? 2008.

[59] Boersma T. The challenge of completing the EU internal market for natural gas. Swedish Inst Eur Policy Stud 2015:1–12.

[60] ACER. European Gas Target Model 2015:45.

[61] COUNCIL OF THE EUROPEAN UNION. COUNCIL DECISION of 28 March 1996 laying down a series of measures aimed at creating a more favourable context for the development of trans-European networks in the energy sector. Off J Eur Communities 1996.

[62] Aalto P, Korkmaz Temel D. European Energy Security: Natural Gas and the Integration Process. JCMS J Common Mark Stud 2014;52.

[63] European Commission. Council Directive 2004/67/EC of 26 April 2004 concerning measures to safeguard security of natural gas supply 2004.

[64] Aoun M-C, Rutten D. EU Security of Gas Supplies: Solidarity Runs Through the Pipeline. 2016.

[65] Zeniewski P, Bolado-lavin R. Preventive Action Plan and Emergency Plan Good Practices and emergency plans. 2012. https://doi.org/10.2790/43883.

[66] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL on the short term resilience of the European gas system Preparedness for a possible disruption of supplies from the East during the fall and winter of 2014/2015 2014;COM(2014).

[67] European Commission. Report on the implementation of Regulation (EU) 994/2010 and its contribution to solidarity and preparedness for gas disruptions in the EU 2014;SWD (2014):1–27.

[68] Watson G. Proposal for a regulation of the European Parliament and of the Council concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010. Off J Eur Union 2016.

[69] CONSOLIDATED VERSION OF THE TREATY ON THE FUNCTIONING OF THE EUROPEAN UNION. Off J Eur Union 2012.

[70] Chester L. Conceptualising energy security and making explicit its polysemic nature. Energy Policy 2010;38:887–95. https://doi.org/10.1016/j.enpol.2009.10.039.

[71] Ang BW, Choong WL, Ng TS. Energy security: Definitions, dimensions and indexes. Renew Sustain Energy Rev 2015;42:1077–93. https://doi.org/10.1016/j.rser.2014.10.064.

[72] Cherp A, Jewell J. The three perspectives on energy security: Intellectual history, disciplinary roots and the potential for integration. Curr Opin Environ Sustain 2011;3:202–12. https://doi.org/10.1016/j.cosust.2011.07.001.

[73] Cherp A, Jewell J. The concept of energy security: Beyond the four As. Energy Policy 2014;75:415–21. https://doi.org/10.1016/j.enpol.2014.09.005.

[74] Luft G, Korin A. Energy security. In the eyes of the beholder. In: Gal L, Anne K, editors. Energy Secur. challenges 21st century. A Ref. Handb. II, Praeger Security International; 2009, p. 1–17.

[75] Chang H-J. Institutional Change and Economic Development. United Nations University Press; 2007.

[76] Chester L. Does the polysemic nature of energy security make it a “wicked” problem? 2009.

[77] Yergin D. Energy Security in the 1990s. Foreign Aff 1988;67:110–32. https://doi.org/10.2307/20043677.

[78] IEA. The IEA natural gas security study. OECD/IEA; 1995.

[79] Sovacool BK. The Routledge Handbook of Energy Security: 2010.

[80] Baldwin DA. The concept of security. Rev Int Stud 1997;23:5–26. https://doi.org/10.5937/vojdelo1607068k.

[81] APERC. A quest for energy security in the 21. 2007.

[82] Krause LB, Nye JS. Reflections on the economics and politics of international economic organizations. Int Organ 1975;29:323–42. https://doi.org/10.1017/S0020818300017975.

[83] Johansson B. A broadened typology on energy and security. Energy 2013;53:199–205. https://doi.org/10.1016/j.energy.2013.03.012.

[84] Buzan B, Waever O, De Wilde J. Security: A New Framework for Analysis. Lynne Rienner Publishers; 1998.

[85] Sarica K, Tyner WE. Alternative policy impacts on US GHG emissions and energy security: A hybrid modeling approach. Energy Econ 2013;40:40–50. https://doi.org/10.1016/j.eneco.2013.06.003.

[86] Torabi SA, Baghersad M, Mansouri SA. Resilient supplier selection and order allocation under operational and disruption risks. Transp Res Part E Logist Transp Rev 2015;79:22–48. https://doi.org/10.1016/j.tre.2015.03.005.

[87] Morrissey K, Plater A, Dean M. The cost of electric power outages in the residential sector: A willingness to pay approach. Appl Energy 2018;212:141–50. https://doi.org/10.1016/j.apenergy.2017.12.007.

[88] Lehtonen M, Gunduz N, Kufeoglu S. On the Evaluation of Customers Interruption Costs due to Unexpected Power Outages. IEEE 59th Int. Sci. Conf. Power Electr. Eng., Riga: 2018, p.

8–11.

[89] Lochner S. Identification of congestion and valuation of transport infrastructures in the European natural gas market. Energy 2011;36:2483–2492.

[90] Giarola S, J.G. Crow D, Hawkes A. A framework for modelling investment decisions in gas infrastructures. Comput Aided Chem Eng 2016:259–264.

[91] Holz F, Hirschhausen C Von, Kemfert C. A strategic model of European gas supply (GASMOD). Energy Econ 2008;30:766–788.

[92] Egging R, Gabriel SA, Holz F, Zhuang J. A complementarity model for the European natural gas market. Energy Policy 2008;36:2385–2414.

[93] Lise W, Hobbs BF, Oostvoorn F Van. Natural gas corridors between the EU and its main suppliers : Simulation results with the dynamic GASTALE model. Energy Policy 2008;36:1890–1906.

[94] Boots MG, Rijkers FAM, Hobbs BF. Trading in the Downstream European Gas Market: A Successive Oligopoly Approach. Energy J 2004;25:73–102.

[95] Szikszai A, Monforti F. GEMFLOW : A time dependent model to assess responses to natural gas supply crises. Energy Policy 2011;39:5129–5136.

[96] Monforti F, Szikszai A. A MonteCarlo approach for assessing the adequacy of the European gas transmission system under supply crisis conditions. Energy Policy 2010;38:2486–2498.

[97] Lochner S, Bothe D. From Russia with Gas An analysis of the Nord Stream pipeline’s impact on the European Gas Transmission System with the Tiger-Model by From Russia With Gas An analysis of the Nord Stream pipeline’s impact on the European Gas Transmission 2007.

[98] Dieckhöner C, Lochner S, Lindenberger D. European natural gas infrastructure : The impact of market developments on gas flows and physical market integration. Appl Energy 2013;102:994–1003.

[99] Bettzuege MO, Lochner S, Dieckhoener C. Model-based Analysis of Infrastructure Projects and Market Integration in Europe with Special Focus on Security of Supply Scenarios 2010.

[100] Kopustinskas V, Bolado-lavin R, Masera M. Development of an evaluation tool to assess

correlated risks and regional vulnerabilities. 2012.

[101] Egging RG, Gabriel SA. Examining market power in the European natural gas market. Energy Policy 2006;34:2762–2778.

[102] Abada I, Gabriel S, Briat V., Massol. O. A Generalized Nash–Cournot Model for the Northwestern European Natural Gas Markets with a Fuel Substitution Demand Function: The GaMMES Model. Networks Spat Econ 2013;3:1–42.

[103] Chen Z, Zhang Y, JI T, Cai Z, Li L, Xu Z. Coordinated optimal dispatch and market equilibrium of integrated electric power and natural gas networks with P2G embedded. J Mod Power Syst Clean Energy 2018;6:495–508.

[104] Schulte S, Weiser F. Natural Gas Transits and Market Power: The Case of Turkey. Energy J 2019;40.

[105] Deane JP, Ciaráin M, Gallachóir BP. An integrated gas and electricity model of the EU energy system to examine supply interruptions. Appl Energy 2017;193:479–490.

[106] Devine MT, Russo M. Liquefied natural gas and gas storage valuation: Lessons from the integrated Irish and UK markets. Appl Energy 2019;238:1389–406. https://doi.org/10.1016/j.apenergy.2019.01.157.

[107] Chaudry M, Ekins P, Ramachandran K, Shakoor A, Skea J, Strbac G, et al. Building a Resilient UK Energy System: Working paper. : : London 2009.

[108] Richter PM, Holz F. All quiet on the eastern front? Disruption scenarios of Russian natural gas supply to Europe. Energy Policy 2015;80:177–89. https://doi.org/10.1016/j.enpol.2015.01.024.

[109] Bouwmeester MC, Oosterhaven J. Economic impacts of natural gas flow disruptions between Russia and the EU. Energy Policy 2017;106:288–97. https://doi.org/10.1016/j.enpol.2017.03.030.

[110] Allevi E, Boffino L, De Giuli ME, Oggioni G. Evaluating the impacts of the external supply risk in a natural gas supply chain: the case of the Italian market. J Glob Optim 2018;70:347–84. https://doi.org/10.1007/s10898-017-0584-z.

[111] Ponomarov SY, Holcomb MC. Understanding the concept of supply chain resilience. Int J

Logist Manag 2009;20:124–43.

[112] Khalili SM, Jolai F, Torabi SA. Integrated production–distribution planning in two-echelon systems: a resilience view. Int J Prod Res 2017;55:1040–64. https://doi.org/10.1080/00207543.2016.1213446.

[113] Mendez C, Cerda J, Grossmann IE, Harjunkoski I, Fahl M, Méndez CA, et al. State-of-the-art review of optimization methods for short-term scheduling of batch processes. Comput Chem Eng 2006;30:913–46. https://doi.org/10.1016/j.compchemeng.2006.02.008.

[114] Maggioni F, Potra FA, Bertocchi M. A scenario-based framework for supply planning under uncertainty: stochastic programming versus robust optimization approaches. Comput Manag Sci 2017;14:5–44. https://doi.org/10.1007/s10287-016-0272-3.

[115] Kondili E, Pantelides CC, Sargent WH. A general algorithm for short-term scheduling of batch operations-I. MILP formulation. Comput Chem Eng 1993;2:211–227.

[116] Shah Pantelides CC, Sargent WH. A general algorithm for short-term scheduling of bacth operations-II. Computational Issues. Comput Chem Eng 1993;2:229–244.

[117] Pantelides CC. Unified frameworks for optimal process planning and scheduling. New York Cache Publ 1994:253–274.

[118] Snyder L V., Atan Z, Peng P, Rong Y, Schmitt AJ, Sinsoysal B. OR/MS models for supply chain disruptions: A review. IIE Trans (Institute Ind Eng 2016;48:89–109. https://doi.org/10.1080/0740817X.2015.1067735.

[119] Namdar J, Li X, Sawhney R, Pradhan N. Supply chain resilience for single and multiple sourcing in the presence of disruption risks. Int J Prod Res 2018;56:2339–60. https://doi.org/10.1080/00207543.2017.1370149.

[120] Turnquist M, Vugrin E. Design for resilience in infrastructure distribution networks. Environmentalist 2013;33:104–20. https://doi.org/10.1007/s10669-012-9428-z.

[121] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL The European energy security strategy 2014;COM(2014). https://doi.org/10.4324/9781315455297-11.

[122] International Energy Agency (IEA). Oil and Natural Gas Logistics, ETSAP Technology

Brief 2011.

[123] ENTSO-G. ENTSO-G Transparency Platform 2019.

[124] IHS. Connect. European Gas Supply and Demand Tracker. LNG Waterborne Trade 2018.

[125] International Energy Agency (IEA). Energy Balances 2018.

[126] Eurostat. Eurostat database 2018.

[127] Department for Business E& IS (BEIS). Energy Trends: Gas 2019.

[128] Enagas. Natural Gas Demand 2019 2019.

[129] ICIS. Natural Gas Prices, Markets and Analysis 2018 2018.

[130] International Energy Agency (IEA). Natural Gas Gross Inland Delivery 01/02/2018 to 30/03/2018 2018.

[131] Agency for the Cooperation of Energy Regulators (ACER). ACER Market Monitoring Report 2017- Electricity and Gas Retail Markets Volume. 2018.

[132] Stern J. UK gas security: Time to get serious. Energy Policy 2004;32:1967–79. https://doi.org/10.1016/j.enpol.2004.03.015.

[133] European Gas Pipeline Incident Data Group (EGIG). 10th Report of the European Gas Pipeline Incident Data Group (period 1970 – 2016) 2018:50.

[134] El-Taha M. Theory of Probability: Basics and Fundamentals. In: Alhajj R, Rokne J, editors. Encycl. Soc. Netw. Anal. Min., New York, NY: Springer New York; 2018, p. 3076–92. https://doi.org/10.1007/978-1-4939-7131-2_170.

[135] Vianello C, Maschio G. Quantitative risk assessment of the Italian gas distribution network. J Loss Prev Process Ind 2014;32:5–17. https://doi.org/10.1016/j.jlp.2014.07.004.

[136] Bolado-lavin R, Mengolini A. Best practices and methodological guidelines for conducting gas risk assessments. 2012. https://doi.org/10.2790/44546.

[137] Cervigni G, Conti I, Glachant J-M, Tesio E, Volpato F. Towards an Efficient and Sustainable Tariff Methodology for the European Gas Transmission Network. 2019.

[138] Ameli H, Qadrdan M, Strbac G. Value of gas network infrastructure flexibility in supporting cost effective operation of power systems. Appl Energy 2017;202:571–80. https://doi.org/10.1016/j.apenergy.2017.05.132.

[139] Brown SPA, Yücel MK. Energy prices and aggregate economic activity: An interpretative survey. Q Rev Econ Financ 2002;42:193–208. https://doi.org/10.1016/S1062-9769(02)00138-2.

[140] Archanskaïa E, Creel JÔ, Hubert P. The nature of oil shocks and the global economy. Energy Policy 2012;42:509–20. https://doi.org/10.1016/j.enpol.2011.12.017.

[141] International Gas Union (IGU). 2019 World LNG Report. 2019.

[142] ENI. World Gas and Renewables Review-2018. Vol.2. 2018.

[143] CEER. How to Foster LNG Markets in Europe - CEER Report Liquefied Natural Gas Work Stream of Gas Working Group. 2019.

[144] Van Nuffel L, Natalie Janzow T, Koen Rademaekers T, Péter Kotek T, Borbala Toth R, Adrienn Selei R, et al. Study on gas market upgrading and modernisation - Regulatory framework for LNG terminals. 2020.

[145] Andersen S.S. SN. The EU’s Strategy Towards External Gas Suppliers and Their Responses: Norway, Russia, Algeria and LNG. Cham: Palgrave Macmillan, ; 2018.

[146] GLE. Lessons learnt from the February 2012 cold spell: LNG contribution to SoS 2012.

[147] Snam. Internal Memo to Corporate Strategy Department, 27th February 2018.

[148] Snam. Internal Memo to Corporate Strategy Department, 5th March 2018.

[149] IEA. European Union 2020: Energy Policy Review. Iea 2020.

[150] Ordoudis C, Delikaraoglou S, Kazempour J, Pinson P. Market-based coordination of integrated electricity and natural gas systems under uncertain supply. Eur J Oper Res 2020;287:1105–19. https://doi.org/10.1016/j.ejor.2020.05.007.

[151] European Parliament. Regulation (EU) 1938/2017 of the European Parliament and of the Council of 25 October 2017 concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010 2017.

[152] Hughes L. A generic framework for the description and analysis of energy security in an energy system. Energy Policy 2012;42:221–31. https://doi.org/10.1016/j.enpol.2011.11.079.

[153] Pirani S, Stern J, Yafimava K. The Russo-Ukrainian gas dispute of January 2009: a comprehensive assessment. vol. NG 27. 2009.

[154] Bros T. Reflection on the Baumgarten Gas Explosion : Markets are Working. Oxford Inst Energy Stud 2018.

[155] Sesini M, Giarola S, Hawkes AD. The impact of liquefied natural gas and storage on the EU natural gas infrastructure resilience. Energy 2020;209:118367. https://doi.org/10.1016/j.energy.2020.118367.

[156] Lustenberger P, Schumacher F, Spada M, Burgherr P, Stojadinovic B. Assessing the performance of the European natural gas network for selected supply disruption scenarios using open-source information. Energies 2019;12. https://doi.org/10.3390/en12244685.

[157] Hauser P, Heinrichs HU, Gillessen B, Müller T. Implications of diversification strategies in the European natural gas market for the German energy system. Energy 2018;151:442–54. https://doi.org/10.1016/j.energy.2018.03.065.

[158] Yu W, Song S, Li Y, Min Y, Huang W, Wen K, et al. Gas supply reliability assessment of natural gas transmission pipeline systems. Energy 2018;162:853–70. https://doi.org/10.1016/j.energy.2018.08.039.

[159] Fodstad M, Egging R, Midthun K, Tomasgard A. Stochastic modeling of natural gas infrastructure development in Europe under demand uncertainty. Energy J 2016;37:5–32. https://doi.org/10.5547/01956574.37.SI3.mfod.

[160] Lochner S, Dieckhöner C. Civil unrest in North Africa-Risks for natural gas supply? Energy Policy 2012;45:167–75. https://doi.org/10.1016/j.enpol.2012.02.009.

[161] Rqiq Y, Beyza J, Yusta JM, Bolado-Lavin R. Assessing the impact of investments in Cross-border pipelines on the security of gas supply in the EU. Energies 2020;13. https://doi.org/10.3390/en13112913.

[162] Lustenberger P, Kim W, Schumacher F, Spada M, Burgherr P, Hirschberg S, et al. Network analysis of the European natural gas infrastructure to quantify its performance in long-

duration pipeline shutdown scenarios. In: Barros A, van Gulijk C, Haugen S, Erik Vinnem J, Kongsvik T, editors. Saf. Reliab. - Safe Soc. a Chang. World Proc. ESREL 2018, June 17-21, 2018, Trondheim, Norw., Taylor & Francis; 2018.

[163] Gjorgiev B, Antenucci A, Volkanovski A, Sansavini G. An FTA Method for the Unavailability of Supply in Gas Networks Supported by Physical Models. IEEE Trans Reliab 2020;69:740–53. https://doi.org/10.1109/TR.2019.2895396.

[164] Dixit V, Verma P, Tiwari MK. Assessment of pre and post-disaster supply chain resilience based on network structural parameters with CVaR as a risk measure. Int J Prod Econ 2020;227:107655. https://doi.org/10.1016/j.ijpe.2020.107655.

[165] Hombach LE, Büsing C, Walther G. Robust and sustainable supply chains under market uncertainties and different risk attitudes – A case study of the German biodiesel market. Eur J Oper Res 2018;269:302–12. https://doi.org/https://doi.org/10.1016/j.ejor.2017.07.015.

[166] Saghaei M, Ghaderi H, Soleimani H. Design and optimization of biomass electricity supply chain with uncertainty in material quality, availability and market demand. Energy 2020;197:117165. https://doi.org/10.1016/j.energy.2020.117165.

[167] Ghelichi Z, Saidi-Mehrabad M, Pishvaee MS. A stochastic programming approach toward optimal design and planning of an integrated green biodiesel supply chain network under uncertainty: A case study. Energy 2018;156:661–87. https://doi.org/10.1016/j.energy.2018.05.103.

[168] Friuli Venezia Giulia. Catalogo dati eventi franosi 2020. http://irdat.regione.fvg.it/WebGIS/GISViewer.jsp?template=configs:ConfigMAAS/DissestiIdrogeologici.xml.

[169] AGCM. Allegato all'istruttoria nei confronti di eni per possibile abuso di posizione dominante nel mercato del trasporto internazionale di gas 2012.

[170] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions. The European Green Deal 2019;COM(2019).

[171] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions.

The European Green Deal. Annex 2019;COM (2019).

[172] ENTSO-G. Addendum to ENTSOG Union-wide Security of Supply Simulation Report 2020.

[173] ENTSO-G. ENTSOG Union-wide Security of Supply Simulation Report 2017.

[174] Hayashi M, Hughes L. The Fukushima nuclear accident and its effect on global energy security. Energy Policy 2013;59:102–11. https://doi.org/10.1016/j.enpol.2012.11.046.

[175] Dolgui A, Ivanov D, Sokolov B. Ripple effect in the supply chain: an analysis and recent literature. Int J Prod Res 2018;56:414–30. https://doi.org/10.1080/00207543.2017.1387680.

[176] Gorissen BL, Yanikoğlu I, den Hertog D. A practical guide to robust optimization. Omega (United Kingdom) 2015;53:124–37. https://doi.org/10.1016/j.omega.2014.12.006.

[177] Grossmann IE, Apap RM, Calfa BA, García-Herreros P, Zhang Q. Recent advances in mathematical programming techniques for the optimization of process systems under uncertainty. Comput Chem Eng 2016;91:3–14. https://doi.org/10.1016/j.compchemeng.2016.03.002.

[178] Schuller O, Reuter B, Hengstler J, Whitehouse, Zeitzen L. Greenhouse Gas (GHG) Intensity of Natural Gas Transport. 2017.

[179] IHS. Connect. European Gas Supply and Demand Tracker 2019.

[180] Wouter T, Peters D, van Tilburg J, Schimmel M, Berg T, Cihlar J, et al. Gas for Climate. The optimal role for gas in a net-zero emissions energy system. 2019.

[181] EBA/GIE. Biomethane Map 2020 2020:1.

[182] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions. A hydrogen strategy for a climate-neutral Europe 2020;COM (2020).

[183] Wouters C, Buseman M, van Tilburg J, Berg T, Cihlar J, Villar Lejarreta A, et al. Market state and trends in renewable and low-carbon gases in Europe. Gas for Climate report. 2020.

[184] Lambert M. EU Hydrogen Strategy - A case for urgent action towards implementation. Oxford Energy Comment 2020.

[185] Ministry ED, Resources N, December T. Integrated National Energy and Climate 2019:329.

[186] Ahmad T, Zhang D. Using the internet of things in smart energy systems and networks. Sustain Cities Soc 2021;68:102783. https://doi.org/10.1016/j.scs.2021.102783.

Appendices

Appendix A: Chapter 5 - Strategic storage and its coordination among EU Member States

Table A1 System costs breakdown in base scenario (€).

Cost (€)	***Baseline Instance***	***Solidarity Instance***
Total	6,484,720,300	5,558,016,200
Production	3,709,399,000	3,436,995,400
Import	4,919,989	4,847,078
LNG	1,072,201,400	617,812,884
Storage	104	104

Table A2 System costs breakdown in scenario "Two disruptions" with price and volumes parameter variations in the base (B) and solidarity (S) instances (€).

Cost (€)	***Pre-disruption***	**B**	**S**	**B**	**S**
Total	6,484,720,300	7,597,357,400	6,591,832,300	7,597,357,400	6,591,832,300
Production	3,709,399,000	3,707,009,500	3,436,472,500	3,707,009,500	3,436,472,500
Transport	4,919,989	4,893,815	4,518,769	4,893,815	4,518,769
LNG	1,072,201,400	1,075,456,200	621,091,880	1,075,456,200	621,091,880
Storage	104	104	104	104	104

Table A3 LNG and natural gas storage volumes usage in scenario “Three disruptions” (MWh).

	Baseline Instance	**Solidarity Instance**
Transport	1,658,737	1,516,299
Production	166,991,860	153,970,869
Storage	182,583,270	502,788,590
LNG	57,027,132	32,894,258

Appendix B: Chapter 6 - EU Regional Risk Groups and solidarity

Table B1 Natural gas commercial and strategic storage volumes usage in North Africa, Norway Russia, and Ukraine disruption scenarios (MWh).

North Africa		**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
Commercial	Austria	3,203,033	3,203,033	1,799,349	1,097,508	701,842	701,842	701,842
	Belgio	926,974	917,832	18,285	9,143			
	Bulgaria	308,872	282,417	141,208	141,208	141,208		
	Czech Republic	1,750,661	1,500,567	1,250,472	1,000,378	750,283	500,189	250,094
	Germany	10,845,090	7,864,968	7,864,968	7,864,968	4,884,843	2,973,124	2,973,124
	Denmark	489,284	194,424					
	Spain	477,327	477,327	477,327	477,327	477,327	477,327	
	France	7,118,155	5,199,035	3,279,914	2,353,926	2,353,926	1,919,121	1,919,121
	Croatia	342,533	252,462	162,391	162,391	72,320	72,320	
	Hungary	2,125,655	1,821,990	1,518,325	1,214,660	910,995	607,330	303,665
	Italy	11,188,710	7,412,511	3,636,311	3,636,311	3,636,311	3,636,311	
	Latvia	113,491	95,938	78,385	60,832	43,279	35,106	17,553

	Netherlands	4,462,798	3,528,870	2,594,941	1,661,012	727,083	727,083	
	Poland	422,186	422,186					
	Portugal	40,428	26,888	13,349	13,349	13,349	13,349	
	Romania	1,057,726	661,341	396,385	396,385	396,385	396,385	396,385
	Slovakia	2,012,228	1,626,027	1,626,027	1,239,826	853,625	467,424	386,201
Strategic	Austria	1,008,017	1,008,017	306,176	306,176	306,176	306,176	
	Belgium	23,345	23,345	23,345	23,345	23,345	383,039	16,144
	Bulgaria	121,391	121,391	121,391	91,043	54,626		
	Germany	10,008,780	7,028,658	4,048,532	2,980,125			
	Denmark	548,850	253,990					
	Spain	1,303,136	1,303,136	434,362	434,362	434,362		
	France	3,369,100	1,884,784	1,884,784				
	Croatia	275,782	177,425	177,425	90,071	90,071	58,546	58,546
	Italy	9,804,667	6,028,467	6,028,467	3,776,200	3,776,200	3,776,200	3,776,200
	Latvia	9,380	9,380	9,380	9,380	9,380		
	Netherlands	2,074,703	2,074,703	2,074,703	2,074,703	2,074,703	1,140,774	933,929
	Poland	1,472,527	717,857	717,857	717,857	717,857	717,857	717,857

	Portugal	112,111	112,111	112,111	40,809	27,269	13,730	13,539
	Romania	1,251,101	792,769	396,385	257,650			
	Slovakia	691,179	691,179	304,978	304,978	304,978	304,978	
Norway		**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
Commercial	Austria	3,203,033	2,501,191	2,105,525	1,403,683	701,842	701,842	701,842
	Belgio	926,974	917,832	908,689	570,822	561,680	561,680	
	Bulgaria	308,872	302,234	161,026	161,026	141,208		
	Czech Republic	1,750,661	1,500,567	1,250,472	1,000,378	750,283	500,189	250,094
	Germany	10,845,090	7,864,968	7,864,968	7,864,968	4,884,843	2,980,125	2,980,125
	Denmark	489,284	194,424					
	Spain	477,327	477,327	477,327				
	France	7,118,155	6,195,081	4,275,961	2,388,262	2,388,262	1,919,121	1,919,121
	Croatia	342,533	244,176	180,142	180,142	90,071	90,071	
	Hungary	2,125,655	1,821,990	1,518,325	1,214,660	910,995	607,330	303,665
	Italy	11,188,710	7,412,511	3,636,311	3,636,311	3,636,311	3,636,311	

	Latvia	113,491	95,938	78,385	60,832	43,279	35,106	17,553
	Netherlands	4,462,798	3,528,870	2,594,941	1,661,012	727,083	727,083	
	Poland	422,186	422,186					
	Portugal	40,428	26,888					
	Romania	1,057,726	326,904	326,904				
	Slovakia	2,012,228	1,626,027	1,626,027	1,239,826	853,625	467,424	386,201
Strategic	Austria	1,008,017	1,008,017	1,008,017	701,842			
	Belgium	392,181	383,039	383,039	210,671	210,671	210,671	
	Bulgaria	262,599	262,599	262,599	121,391			
	Germany	10,015,780	10,015,780	7,035,659	4,055,533	4,055,533	2,980,125	2,980,125
	Denmark	548,850	253,990	253,990	139,694		139,694	
	Spain	1,303,136	1,303,136	434,362	434,362	434,362	434,362	434,362
	France	5,288,220	5,288,220	3,369,100	3,369,100	1,919,121	1,919,121	
	Croatia	275,782	275,782	249,744	151,387	151,387	98,358	98,358
	Italy	9,804,667	6,028,467	3,776,200	3,776,200			
	Latvia	9,380	9,380	9,380	9,380	9,380		46,900
	Netherlands	2,074,703	2,074,703	2,074,703	2,074,703	2,074,703	1,140,774	1,140,774

	Poland	1,284,998	1,284,998	835,249	459,387	459,387		
	Portugal	112,111	98,571	40,618		27,079		
	Romania	1,189,154						
	Slovakia	691,179	691,179	304,978	304,978	304,978	304,978	304,978
Russia		**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
Commercial	Austria	3,203,033	2,501,191	1,799,349	1,403,683	701,842	701,842	701,842
	Belgium	926,974	27,428	18,285	18,285	18,285	18,285	9,143
	Bulgaria	308,872	167,664	167,664	167,664	141,208	141,208	141,208
	Czech Republic	1,750,661	1,500,567	1,250,472	1,000,378	750,283	500,189	250,094
	Germany	10,845,090	7,864,968	7,864,968	4,884,843	4,884,843	4,884,843	1,904,717
	Denmark	489,284	194,424					
	Spain	477,327	477,327					
	France	7,118,155	5,199,035	4,273,046	2,353,926	2,353,926	1,919,121	1,919,121
	Croatia	342,533	252,462	162,391	72,320	72,320	72,320	
	Hungary	2,125,655	1,821,990	1,518,325	1,214,660	910,995	607,330	303,665

	Italy	11,188,710	7,412,511	3,636,311	3,636,311	3,636,311	3,636,311	
	Latvia	113,491	95,938	78,385	60,832	52,659	35,106	17,553
	Netherlands	4,462,798	3,528,870	3,528,870	2,801,786	2,801,786	1,867,858	933,929
	Poland	422,186						
	Portugal	40,428	26,888	26,888	13,539			
	Romania	1,057,726	661,341	661,341	264,957	264,957	264,957	
	Slovakia	2,012,228	1,626,027	1,626,027	1,239,826	1,158,603	772,402	386,201
Strategic	Austria	1,008,017	1,008,017	1,008,017	1,008,017	1,008,017	1,008,017	306,176
	Belgium	392,181	392,181	392,181	383,039	373,896		
	Bulgaria	262,599	255,961	255,961	141,208	141,208	141,208	
	Germany	10,015,780	10,015,780	7,035,659	7,035,659	4,055,533	1,075,408	1,075,408
	Denmark	548,850	548,850	294,860	294,860	294,860	294,860	
	Spain	1,303,136	1,303,136	871,689				
	France	5,288,220	5,288,220	5,288,220	3,369,100	3,369,100	1,884,784	
	Croatia	275,782	275,782	185,711	185,711	185,711	90,071	90,071
	Italy	9,804,667	9,804,667	6,028,467	6,028,467	6,028,467	3,776,200	3,776,200
	Latvia	9,380	9,380	9,380	9,380			

	Netherlands	2,074,703	2,074,703	1,140,774	933,929			
	Poland	1,713,331	1,713,331	1,713,331	1,713,331	240,804	240,804	
	Portugal	112,111	98,571	98,381	27,079	13,539	13,539	
	Romania	854,716	792,769	396,385	396,385	218,012	218,012	218,012
	Slovakia	691,179	691,179	304,978	304,978			
Ukraine		**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
Commercial	Austria	3,203,033	2,501,191	1,799,349	1,403,683	701,842	701,842	701,842
	Belgium	926,974	917,832	16,144	16,144	16,144	16,144	16,144
	Bulgaria	308,872	167,664	161,026	161,026	141,208		
	Czech Republic	1,750,661	1,500,567	1,250,472	1,000,378	750,283	500,189	250,094
	Germany	10,845,094	7,864,968	7,864,968	7,864,968	4,884,843	2,973,124	2,973,124
	Denmark	489,284	194,424	194,424	194,424			
	Spain	477,327	477,327					
	France	7,118,155	5,199,035	5,199,035	3,279,914	2,813,641	2,813,641	1,890,567
	Croatia	342,533	244,176	216,007	196,716	98,358	98,358	98,358

	Hungary	2,125,655	1,821,990	1,518,325	1,214,660	910,995	607,330	303,665
	Italy	11,188,710	7,412,511	3,636,311	3,636,311	3,636,311	3,636,311	
	Latvia	113,491	95,938	87,765	70,212	52,659	35,106	17,553
	Netherlands	4,462,798	3,528,870	2,594,941	1,661,012	727,083	727,083	
	Poland	422,186						
	Portugal	40,428	26,888	26,888	13,349	13,349	13,349	
	Romania	1,057,726	787,870	380,076	380,076	380,076		
	Slovakia	2,012,228	1,626,027	1,626,027	1,239,826	853,625	467,424	386,201
Strategic	Austria	1,008,017	1,008,017	1,008,017	1,008,017	1,008,017	1,008,017	306,176
	Belgium	383,039	371,030	361,887	271,415	271,415	271,415	
	Bulgaria	262,599	262,599	262,599	121,391			
	Germany	10,008,780	10,008,780	7,028,658	4,048,532	4,048,532	2,980,125	
	Denmark	548,850	548,850	294,860				
	Spain	911,689	911,689	43,493	43,493	43,493	43,493	43,493
	France	5,288,220	5,288,220	3,369,100	3,369,100	1,919,121		
	Croatia	275,782	275,782	275,782	196,716	196,716	98,358	
	Italy	9,804,667	9,804,667	6,028,467	6,028,467	3,776,200	3,776,200	3,776,200

	Latvia	9,380	9,380					
	Netherlands	2,074,703	2,074,703	2,074,703	2,074,703	2,074,703	1,140,774	933,929
	Poland	1,713,331	1,472,527	1,472,527	1,104,395	1,104,395		
	Portugal	40,809	27,269	13,730		13,539		13,539
	Romania	1,251,101	1,251,101	843,306	305,846	168,215		
	Slovakia	691,179	691,179	304,978	304,978	304,978	304,978	

***Table B3** LNG import volumes in North Africa, Norway Russia, and Ukraine disruption scenarios (MWh).*

North Africa		**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
	Belgium	1,029,371	40,033	1,029,371	631,868	631,868		
	Spain	3,545,457	1,012,988	1,012,988	1,012,988	1,012,988	47,683	1,012,988
	France	1,103,480	38,151	38,151				
	Greece	175,844	175,844	175,844	175,844	175,844	175,844	175,844
	Italy	4,195,777	1,693,258	155,431	1,693,258	1,693,258	1,693,258	155,431
	Lithuania	220,783						
	Poland	1,636,141	1,167,045	1,636,141			1,368,580	
	Portugal	196,918	196,918	132,737	196,918	196,918	196,918	196,918

Norway		**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
	Belgium	1,029,371	1,029,371	664,121	1,029,371	1,029,371		1,029,371
	Spain	1,012,988	47,683	47,683	47,683	1,012,988		1,012,988
	France	1,106,718	34,913	1,106,718	1,106,718			
	Greece	175,844	175,844	175,844	175,844	175,844	175,844	175,844
	Italy	4,195,777	1,693,258	155,431				
	Lithuania	220,783	220,783	220,783	220,783	220,783	220,783	220,783
	Poland	1,636,141	1,167,045	1,636,141	1,636,141	1,636,141	1,368,580	
	Portugal	147,569	147,569					
Russia		**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
	Belgium	40,033	1,029,371	1,029,371	1,029,371	1,029,371	1,029,371	1,029,371
	Spain	1,012,988	3,239	44,444	1,012,988	1,012,988	1,012,988	1,012,988
	France	1,103,480	1,103,480				38,151	
	Greece	443,128	443,128	175,844	175,844	175,844	175,844	175,844
	Italy		4,195,777	4,195,777	4,195,777	1,693,258	155,431	

	Lithuania	334,062	334,062	334,062	220,783	220,783	220,783	220,783
	Poland	1,167,045	1,636,141	1,636,141	1,636,141		1,368,580	1,636,141
	Portugal	98,459						
Ukraine		**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
	Belgium	1,026,185	1,029,371	1,029,371	1,029,371	1,026,185	1,029,371	616,346
	Spain	1,028,032	1,013,199	1,012,988	1,028,032	1,028,032	1,012,988	497,668
	France	1,106,718	1,106,718	556,884	1,106,718	556,884	556,884	556,884
	Greece	443,128	443,128	443,128	443,128	175,844	175,844	175,844
	Italy	156,760	4,196,220	4,196,220	4,196,220			4,196,220
	Lithuania	220,783	220,783	220,783	220,783	220,783	220,783	165,587
	Netherlands	300,677	447,061	447,061	396,237	447,061		447,061
	Poland	1,188,598	1,657,694	1,657,694	1,657,694	1,657,694	1,657,694	1,657,694
	Portugal	98,459						