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Short Term Security Assessment Of Natural Gas Supply In European Union And Policy Insights

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Abstract

This paper assesses the security of natural gas supply in the European Union (EU) during the 2023/24 winter in the aftermath of the 2022 Russian gas disruption. We develop an optimization framework with a network model capturing intra- and inter-country constraints and incorporating recent EU measures to enhance supply security. Our findings underscore the significance of increased liquefied natural gas (LNG) imports and gas storages in keeping the annual demand reduction below 15% across most EU countries. This demonstrates the efficacy of the EU's 15% voluntary demand reduction target in avoiding involuntary demand reduction. Increased LNG imports largely substitute pipeline imports from Russia, especially in Finland, Greece, and Poland. Nevertheless, regions such as Central Europe, Denmark, and Sweden may face involuntary demand reduction, necessitating network capacity enhancements as a potential mitigation strategy.

Keywords: demand reduction, European Union, gas network, gas storage, security of supply

1. Introduction

With the declining domestic supply in the past decade, the European Union (EU) has become increasingly reliant on gas imports. Notably, Russian gas imports constituted nearly 40% of the gas supply between 2015 and 2021 (Bloomberg New Energy Finance, 2022a). The Russian invasion of Ukraine in February 2022 and the subsequent reduction of Russian gas supply through pipelines by 80% (Zachmann et al., 2023) created significant uncertainty about the gas supply security, elevating the average gas price in 2022 to 124 Euro/MWh—a 165% increase over the previous year.

Organizational and academic publications have analyzed the impact of Russian gas disruption on gas supply security during the 2022/23 winter. The European Network of Transmission System Operators for Gas (ENTSOG) (ENTSOG, 2022a) highlights that while the efficient use of gas network capacities enhances the overall supply security, a cold winter exposes the Baltic countries and Finland to significant demand reduction. Similarly, (Mannhardt et al., 2023) reveal that selfish behavior under Russian gas disruption exacerbates the energy scarcity in Eastern European countries. Zhou et al. analyze the historical supply and demand structure in the EU and provide policy recommendations to address the national supply-demand gaps arising from Russian gas disruption. (Ruhnau et al., 2023) study the energy crisis in 2022 from an economic perspective, concluding that market prices effectively incentivize gas savings and should not be diluted by subsidies aimed at cushioning hardship.

The combination of price-driven demand response and mild winter weather led to a record 13% drop in gas demand in the EU in 2022 (International Energy Agency, 2023). This left the EU with an above-average storage level of 56% at the end of the 2022/23 winter (Gas Infrastructure Europe, 2023a). However, the absence of Russian gas may create a supply-demand gap in 2023 and renew intense price volatility. To prepare for the winter 2023/24, the EU adopted three measures: (1) setting a storage target of 90% by October 2023 (European Council, 2023a); (2) reintroducing a voluntary target for member states to reduce their annual gas demand by 15% (European Council, 2023b); and (3) developing new liquified natural gas (LNG) terminals, increasing the overall regasification capacity to half of the EU demand (Gas Infrastructure Europe, 2023b).

However, network capacity enhancements are essential to ensure that all EU countries can benefit from LNG (European Commission, 2022). Indeed, intra- and inter-country congestions have been identified as potential risks to supply security in an early assessment of Russian gas supply disruption (ENTSOG, 2022b).This paper investigates gas supply security in the EU during the winter 2023/24, accounting for recent policies and infrastructure developments. We use a network model with a subnational resolution, as opposed to a national resolution of prior studies (Mannhardt et al., 2023; Zhou et al., 2022), to consider both intra- and inter-country network constraints. Our objectives are twofold: (1) identify vulnerable regions and quantify the anticipated demand reduction due to network congestions; (2) examine how LNG imports, demand level, storage requirements, and network capacities influence demand reduction? Our findings offer policy insights for enhancing the short-term security of gas supply in the EU.

2. Gas network modeling

We model the European gas network using publicly available data. The SciGRID_gas dataset (Diettrich et al., 2021) is adapted to reflect recent pipeline and LNG terminal developments (ENTSOG, 2023a). The spatial scope is limited to EU countries because gas market and infrastructure policies are predominantly stipulated within the EU. Cyprus, Ireland, and Malta are excluded as they lack pipelines connections to Continental Europe, and Switzerland is included as a major transit in Central Europe (ENTSOG, 2023a). Extra-EU connections of the gas network are modeled as supply nodes. Fig. 1 illustrates the locations of gas suppliers, demands, and storages on the modeled gas network.

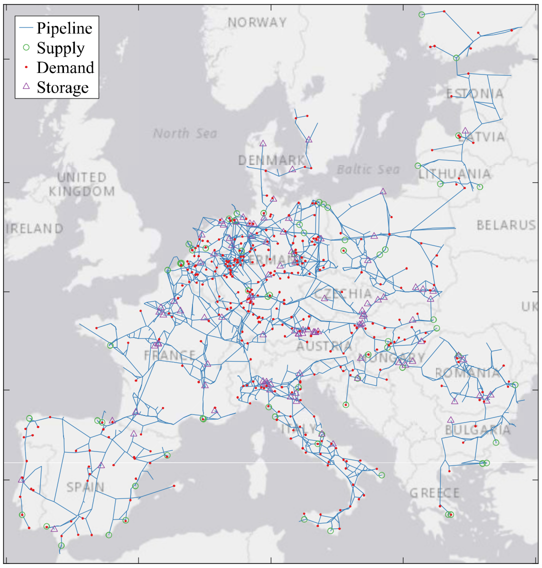

Fig. 1. Modeled European gas network.

The horizon of the analysis spans from June 2023 to May 2024, allowing to capture the seasonal structure of gas supply and demand over a year. In line with ENTSOG supply outlook studies (ENTSOG, 2023b, 2023c), our analysis uses a monthly resolution, justified by the ample European gas storage capacity, which mitigates the relevance of intra-month variations.

We employ optimization to determine gas network operations, ensuring the most efficient use of available resources and assuming perfect collaboration across the EU. This assumption, though optimistic, aligns with ongoing harmonization efforts across the EU (European Commission, 2023a). The optimization problem (1) seeks to minimize the cost of gas supply (f^{s}) and the cost of demand reduction (f^{d}) subject to technical constraints and policy considerations.

$$\begin{aligned} &\min f = f^{\mathrm{s}} + f^{\mathrm{d}} \\ &\text{s.t. } (2), (4), (6), (7), (8), (9). \end{aligned} \tag{1}$$

2.1. Supply modeling

Gas suppliers include domestic producers, pipeline imports, and LNG imports. Domestic production capacity is estimated by extrapolating the declining production of individual producers between 2017 and 2022 (Eurostat, 2023a). Pipeline imports from outside the EU are capped at maximum inflows as they have been stable since the war's outbreak (ENTSOG, 2023d). Wartime pipeline imports from Russia are limited to Hungary and Slovakia via Ukraine, Bulgaria via Turkey, and Lithuania via Belarus, according to ongoing EU inflows (ENTSOG, 2023d). The LNG imports are constrained by the regasification capacity of LNG terminals (ENTSOG, 2023d) and the available LNG quantity for import to the EU. We model the latter constraint as an annual import cap (Institute for Energy Economics and Financial Analysis, 2023), distributed to individual months proportional to actual LNG imports in the years 2019 to 2021 (Gas Infrastructure Europe, 2023b). The supply constraints are formulated as

$$\underline{\phi}_{it}^{\mathrm{s}} \leq \phi_{it}^{\mathrm{s}} \leq \overline{\phi}_{it}^{\mathrm{s}} \; \forall i \in \mathcal{S}, t \in \mathcal{T}, \; \sum_{i \in \mathcal{S}^{\mathrm{LNG}}} \phi_{it}^{\mathrm{s}} \leq \bar{\phi}_{t}^{\mathrm{LNG}} \; \forall t \in \mathcal{T}, \tag{2}$$

where ϕ_{it}^{s} is the decision variable for supply quantity. $\mathcal{S}$ and $\mathcal{S}^{\mathrm{LNG}}$ are the sets of all suppliers and of LNG suppliers, respectively. $\mathcal{T}$ is the set of 12 months. The total cost of gas supply is

$$f^{\mathrm{s}} = \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{S}} C_{it}^{\mathrm{s}} \phi_{it}^{\mathrm{s}}, \tag{3}$$

where C_{it}^{s} is the specific cost of gas supply and follows the historical seasonality of European gas prices (Bloomberg New Energy Finance, 2022b).

2.2. Demand modeling

We model gas demand related to residential, commercial, industrial, and power generation uses. For each use and country, we retrieve the annual gas demand and monthly profile from (Eurostat, 2023b) and (Zhou et al., 2022), respectively. The demands in each country are disaggregated to a maximum of 16 regions at NUTS 1 level (Eurostat, 2023c) according to SciGRID_gas (Diettrich et al., 2021). The served gas demand, ϕ_{it}^{d}, is a decision variable bounded by the expected demand, $\bar{\phi}_{it}^{\mathrm{d}}$:

$$0 \leq \phi_{it}^{\mathrm{d}} \leq \bar{\phi}_{it}^{\mathrm{d}} \; \forall i \in \mathcal{D}, t \in \mathcal{T}, \tag{4}$$

where $\mathcal{D}$ is the set of all demands. The total cost of demand reduction is

$$f^{\mathrm{d}} = \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{D}} C_{i}^{\mathrm{d}} \left(\bar{\phi}_{it}^{\mathrm{d}} - \phi_{it}^{\mathrm{d}} \right), \tag{5}$$

where C_{i}^{d} is the specific cost of demand reduction. The specific costs are arranged to prioritize voluntary demand reductions up to a share of 15%, matching the European Council's voluntary demand reduction target (European Council, 2023b). We assign the highest demand reduction costs to residential and commercial uses to mirror the EU regulation of protecting vulnerable consumers (European Commission, 2023b) and the lowest demand reduction cost to power generation use due to existing substitutes, e.g. coal power generators (Euronews, 2022). Acknowledging the intricacy of monetizing demand reduction (Mannhardt et al., 2023), we note that these specific costs do not influence the overall quantity of demand reduction because demand reduction is the last resort.

2.3. Storage modeling

European storages (Gas Infrastructure Europe, 2023a) are modeled with their injection rate ($\overline{\phi}_{n}^{\mathrm{st}}$), withdrawal rate ($\underline{\phi}_{n}^{\mathrm{st}}$), working gas capacity ($\overline{m}_{n}^{\mathrm{st}}$), and injection efficiency (η_{n}^{st}). The initial storage levels ($\widetilde{m}_{n}^{\mathrm{st}}$) are set to the actual levels at the beginning of June 2023. To meet winter preparedness standards set by the EU regulation, the storage levels at the end of October 2023 must be at least 90% of working gas capacity ($\underline{m}_{i5}^{\mathrm{st}}$) (European Council, 2023a), a criterion surpassed by the realized storage level of 99% (Gas Infrastructure Europe, 2023a). Furthermore, the storage levels at the end of May 2024 should respect a specified minimum ($\underline{m}_{i12}^{\mathrm{st}}$) to sustain supply security in the subsequent years. These considerations can be mathematically expressed as

$$\begin{aligned} &\underline{\phi}_{i}^{\mathrm{st}} \leq \phi_{it}^{\mathrm{st}} \leq \overline{\phi}_{i}^{\mathrm{st}}, \; 0 \leq m_{it}^{\mathrm{st}} \leq \overline{m}_{i}^{\mathrm{st}} \\ &m_{it}^{\mathrm{st}} - m_{i(t-1)}^{\mathrm{st}} \leq \Delta t \eta_{i}^{\mathrm{st}} \phi_{it}^{\mathrm{st}}, \; \phi_{it}^{\mathrm{st}}, m_{it}^{\mathrm{st}} - m_{i(t-1)}^{\mathrm{st}} \leq \Delta t \phi_{it}^{\mathrm{st}} \quad \forall i \in \mathcal{U}, t \in \mathcal{T}, \\ &m_{i0}^{\mathrm{st}} = \widetilde{m}_{i}^{\mathrm{st}}, \; m_{i5}^{\mathrm{st}} \geq \underline{m}_{i5}^{\mathrm{st}}, \; m_{i12}^{\mathrm{st}} \geq \underline{m}_{i12}^{\mathrm{st}} \end{aligned} \tag{6}$$

where $\mathcal{U}$ is the set of all storages, and Δt is the duration of one month.

2.4. Pipeline flow constraints

Pipeline flows (ϕ_{mnt}) are bounded by constraints related to diameter, maximum pressure drop, and nominal pipeline capacity (Diettrich et al., 2021) as

$$\underline{\phi}_{mn} \leq \phi_{mnt} \leq \overline{\phi}_{mn} \; \forall (m,n) \in \mathcal{P}, t \in \mathcal{T}, \quad (7)$$

where $\underline{\phi}_{mn}$ and $\overline{\phi}_{mn}$ are lower and upper flow bounds for the pipeline connecting nodes m and n. $\mathcal{P}$ is the set of network pipelines. Cross-border pipeline flows are additionally subject to the firm technical capacities specified in the ENTSOG system development map (ENTSOG, 2023a) as

$$\underline{\phi}_{ab} \leq \sum_{(m,n)\in\mathcal{P}(a,b)} \phi_{mnt} \leq \overline{\phi}_{ab} \; \forall (a,b) \in \mathcal{C}, t \in \mathcal{T}, \quad (8)$$

where $\mathcal{P}(a,b)$ is the set of pipelines between countries a and b, and $\mathcal{C}$ is the set of adjacent countries.

2.5. Nodal flow balance

We enforce flow balance as

$$\sum_{i\in\mathcal{S}(n)} \phi_{it}^{\mathrm{s}} - \sum_{i\in\mathcal{D}(n)} \phi_{it}^{\mathrm{d}} - \sum_{i\in\mathcal{U}(n)} \phi_{it}^{\mathrm{st}} = \sum_{m\in\mathcal{P}(n)} \phi_{nmt} \;\; \forall n \in \mathcal{N}, t \in \mathcal{T}, \quad (9)$$

where $\mathcal{S}(n)$, $\mathcal{D}(n)$, $\mathcal{U}(n)$, and $\mathcal{P}(n)$ are the sets of suppliers, demands, storages, and pipelines connected to node n.

3. Results and discussion

Section 3.1 calibrates and verifies the gas network model using historical data. Due to the uncertainty of future gas supply and demand, Section 3.2 details temporal and spatial results for an expected future, i.e., the baseline scenario, while Section 3.3 investigates supply and demand variations and the potential measures to enhance supply security.

Table 1 lists the parameter values in the baseline scenario and the ranges investigated in the scenario analysis. The baseline LNG import cap corresponds to the LNG demand forecasts for 2023 and 2024 (Institute for Energy Economics and Financial Analysis, 2023; The Energy Institute, 2023), while variations capture the uncertainty of LNG availability for the EU. The baseline annual gas demand corresponds the year 2020, while extreme demand levels reflect the combined uncertainty of weather conditions and consumer behavior, drawing from minimum and maximum demands for each sector and each country in the years 2010-2023 (Eurostat, 2023b). The baseline scenario sets a minimum 60% storage level at the end of May 2024, exceeding the historical average but justified by the above-average level at the end of May 2023 (Gas Infrastructure Europe, 2023a). This storage requirement is varied to reflect the trade-offs of supply security between the period from June 2023 to May 2024 and the subsequent years. Finally, enhancing cross-border capacities over baseline values (ENTSOG, 2023a) represents the possibility of partially relieving network congestions in a short period, as demonstrated by contractual adjustments and infrastructure expansions in 2023 (ENTSOG, 2023c, 2023e).

Table 1. Parameter values for the baseline scenario and scenario analysis.

Parameter	Baseline value	Investigated range
Annual LNG import cap (bcm)	162.8	[0.0, 220.0]
Annual gas demand (bcm)	362.0	[296.8, 399.3]
Minimum storage level at the end of May 2024 (%)	60	[40, 70]
Congested cross-border capacities (%)	100	[100, 140]

3.1. Model calibration and verification

Running the optimization model (1) with prewar data for supply, demand, and infrastructure reveals demand reduction caused by network congestions, suggesting the underestimation of certain pipeline flow bounds in SciGRID_gas (Diettrich et al., 2021). To address this, we design a calibration procedure, which involves formulating an optimization problem minimizing the increase in individual pipe flow bounds while ensuring zero demand reduction for the prewar conditions. The calibration results in a relative increase of pipeline flow bounds below 16% for 99% of the pipelines, indicating a limited impact on most pipelines.

We verify the model by simulating the period between June 2020 and May 2021, while enforcing actual initial and final storage levels and using the prewar data for supply, demand, and infrastructure. Model results indicate that the monthly supply balance matches the actual supply from domestic production, pipeline imports, and LNG imports (International Energy Agency, 2021). In addition, the storage level, as depicted in Fig. 2, follows the actual seasonal trend, verifying model accuracy with respect to the quantity and timing of storage utilization.

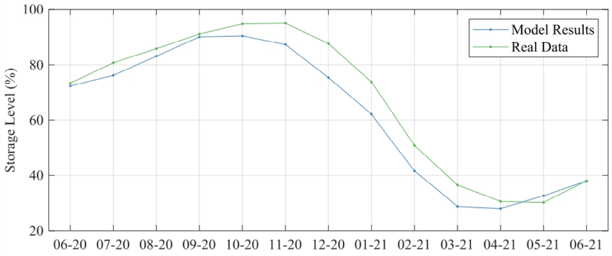

Fig. 2. Monthly evolution of aggregated EU storage level between June 2020 and June 2021.

3.2. Baseline scenario

To account for estimation uncertainties in pipeline flow bounds, a Monte Carlo simulation is conducted by drawing samples from uniform distributions over the uncertainty ranges specified in the SciGRID_gas dataset (Diettrich et al., 2021). For each sample, we calibrate the resulting pipeline flow bounds according to the procedure outlined in Section 3.1 to mitigate the underestimation of pipeline flow bounds. and run the optimization model (1) to obtain the monthly operational results.

The distribution of the aggregate demand reduction over the year at the EU level stabilizes with 200 samples and ranges between 27.4 and 33.0 bcm, with 95% confidence accounting for uncertainties in pipeline flow bounds. The confidence interval corresponds to 7.6% - 9.1% of the expected demand, well below the 15% voluntary demand reduction target. Nevertheless, the temporal heterogeneity of demand results in 3.1 bcm of involuntary demand reduction during winter, as depicted in Fig. 3.

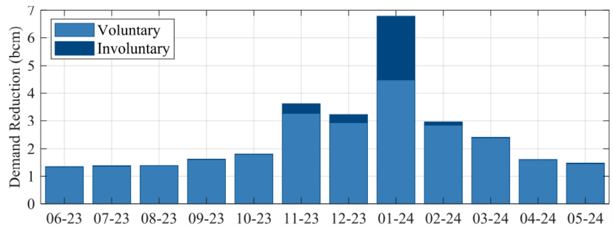

Fig. 3. Monthly EU demand reduction obtained from averaging Monte Carlo results.

Moreover, the demand reduction exhibits spatial heterogeneity. As illustrated in Fig. 4, the demand reduction below 1% of the expected demand for countries well-connected to import nodes (i.e., Belgium, Greece, Portugal, Spain) and for countries with abundant domestic production (i.e., Netherlands, Romania). In contrast, 14%-20% demand reduction occurs in Austria, Denmark, Germany, Italy, Latvia, and Sweden—countries with relatively high historical dependence on Russian gas (Zhou et al., 2022). Notably, newly installed LNG terminals reduce demand reduction below 5.1% in Finland, Greece, and Poland; whereas Germany and Italy, despite having LNG terminals, face higher demand reduction due to network congestions.

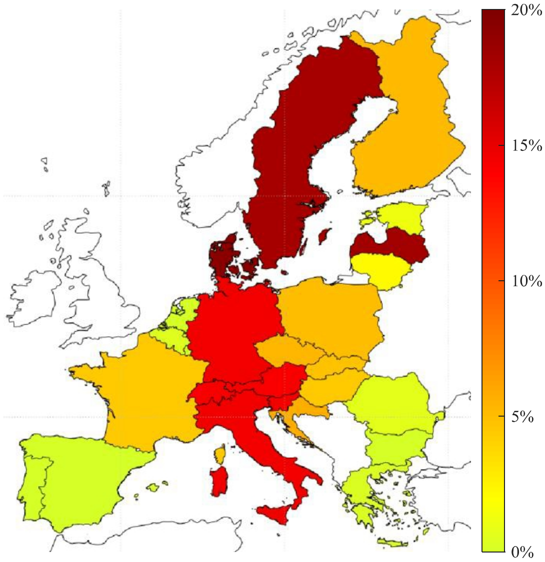

Fig. 4. Relative demand reduction in European countries obtained from averaging Monte Carlo results.

We quantify congestion as the sensitivity of the objective function to pipeline flow bounds and cross-border capacities. The congestion level is derived by computing the dual variables of the corresponding constraints and aggregating them over the year. This metric, illustrated in Fig. 5, represents the economic gain from incremental capacity enhancements. Pipeline congestions are observed within Germany and Italy and between Germany and its neighbors. Additionally, cross-border congestions restrict supply to Central European countries, including congested capacities from Spain to France, from France to Switzerland and Germany, and from East European countries toward Austria and Germany.

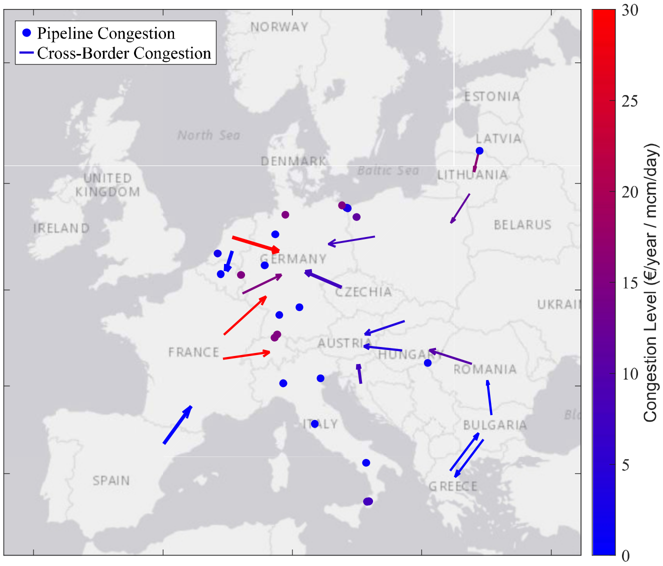

Fig. 5. Pipeline and cross-border congestion levels obtained from averaging Monte Carlo results.

3.3. Scenario analysis

The left panel in Fig. 6 shows that increased LNG import beyond the prewar level partially mitigates demand reduction. However, the LNG contribution to EU demand is restricted by network congestions, resulting in residual demand reduction despite sufficient LNG availability. As expected, higher demands and more stringent storage requirements lead to higher demand reduction across all LNG availabilities. In the high-demand scenario, residual demand reduction ranges from 9.3% to 14.9% depending on the final storage level. It is expected that the higher demand will coincide with higher storage withdrawal, as observed during the cold 2020/21 winter (Gas Infrastructure Europe, 2023a), potentially endangering supply security in subsequent years.

The right panel in Fig. 6 investigates the role of the gas network in supply security. Enhancing congested cross-border capacities increases the contribution of LNG imports from Western Europe and pipeline imports from the Caspian area in supplying the demand in Central Europe. Consequently, a 40% capacity enhancement mitigates residual demand reduction by up to 22%, corresponding to 1.8% of the expected demand. Nevertheless, enhanced cross-border capacities cannot compensate for insufficient gas supply, as instantiated by the insensitivity of demand reduction to cross-border capacities when LNG imports are capped at prewar levels. When the annual demand is below 300 bcm, an LNG supply of 120 bcm suffices to eliminate demand reduction, obviating the need for cross-border capacity enhancements.

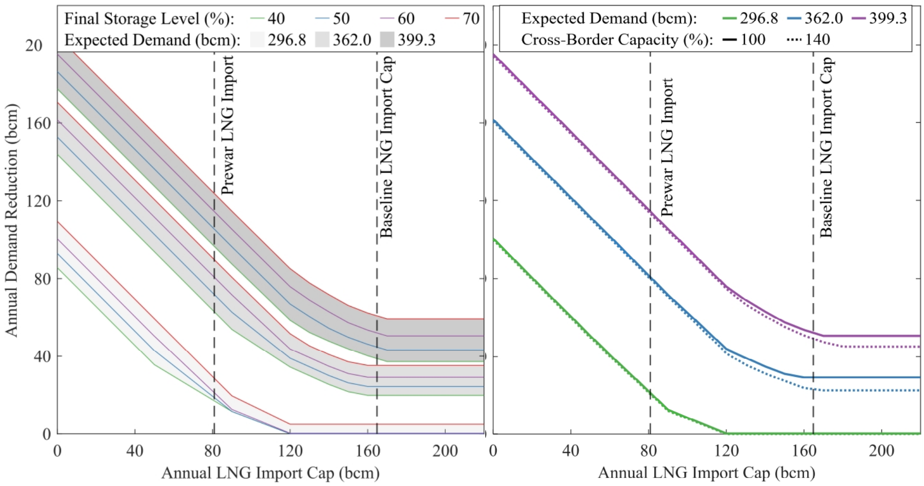

Fig. 6. Dependence of demand reduction on LNG import, gas demand, final storage level, and cross-border capacities.

4. Conclusions

We develop an optimization-based framework to assess the security of natural gas supply in the EU between June 2023 and May 2024, accounting for technical constraints and policy considerations. The results support the following policy insights:

1. The baseline scenario indicates an annual demand reduction of 8.2% at the EU level, with most countries experiencing reductions below 15%. Therefore, the 15% voluntary demand reduction target of the European Council (European Council, 2023b) can largely avoid involuntary demand reduction through measures aligned with the EU's long-term climate policy, namely, energy efficiency measures, accelerated electrification of heating, accelerated renewables deployment, and encouraging consumption reduction (International Energy Agency, 2022).
2. Increased LNG imports largely substitute pipeline imports from Russia, especially in Finland, Greece, and Poland. However, the LNG contribution is limited by intra- and inter-country network congestions, exposing regions such as Central Europe, Denmark, and Sweden to involuntary demand reduction. To address this short-term urgency, the focus should shift from excessive LNG terminal development (Economics and Analysis, 2023) to a more effective mitigation strategy—enhancing network capacities

that connect Central Europe to Western European LNG imports and Southeastern European pipeline imports.

3. European gas storage levels reached a record high before the winter 2023/24. This favorable circumstance can effectively limit the aggregate annual demand reduction to 9.3% in the event of a cold winter, while maintaining a 40% storage level at the end of May 2024. However, higher storage withdrawals, while beneficial in the short term, endanger supply security in subsequent years and cannot bridge the fundamental gap between supply and demand.
4. A perfect collaboration across the EU, as assumed in this paper, keeps demand reductions in individual countries below 20%. As selfish behavior exacerbates the energy scarcity for countries without domestic supply or direct access to imports (Mannhardt et al., 2023), it is paramount for vulnerable countries to secure joint supply and storage agreements (European Commission, 2023a; Keystone-SDA/swissinfo.ch/dos, 2022).

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