



What can the EU do to address the high natural gas prices?

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ABSTRACT

Natural gas prices worldwide increased on the back of the COVID economic recovery in 2021. European prices skyrocketed when the dominant external supplier, Gazprom, started to withhold supplies in Q4 2021. This analysis uses market modelling to assess and compare the effectiveness of various measures to mitigate the gas – and by extension energy – price crisis in the short and longer term. First, the realization of the 5th PCI package adopted by the European Commission in November 2021 would significantly reduce EU prices, especially in the Eastern Member States that tend to be more dependent on the single external supplier. At the same time, the billions of euros that would be poured in risk becoming stranded assets in the long-term with tightening climate regulations. Secondly, uniform voluntary demand response has significant potential to reduce prices, especially in the Eastern Member States. Thirdly, the introduction of European strategic gas reserves can bring temporary price relief but is not a cost-efficient solution. However, security of supply considerations can outweigh the negative economic outcomes.

1. Introduction

As a result of the economic recovery following the COVID pandemic, global demand for natural gas increased significantly in 2021, while several geopolitical, environmental, and economic factors reduced the supply. The upheaval and uncertainty caused by the Russian Invasion of Ukraine on 24 February 2022 have intensified debate about the need for regulatory change related to European gas infrastructure and markets. The war in Europe has again put the security of supply concerns into the spotlight, both in terms of affordability of the commodity for household consumers given the outstanding high prices in the EU and also the risk of insufficient physical availability due to lack of own production, storage stocks and constraints of the import diversification options. The unforeseen events like a pandemic or a war highlight the vulnerability of the EU's energy system and the need to better understand the risks and drivers of price volatility.

Our paper uses market modelling to examine the potential impact of various policy actions on the current gas price landscape in the EU including:

- demand reduction
- optimization of current transit routes

- realization of the 5th PCI (Project of Common Interest) list
- European level strategic storages

We do not assess supply disruption scenarios but concentrate on the market factors.

The paper begins with an overview of the factors feeding into the unprecedented EU gas price spike, followed by a review of the related literature, and an explanation of our methodological approach. Next, the modelling results are presented before concluding with a discussion of general lessons and policy conclusions from this modelling exercise.

2. Background and literature review

Over the last few years there has been unprecedented volatility in natural gas prices. First, in March 2018, prices jumped to 70 €/MWh across European gas exchanges from the usual 20–25€/MWh range that characterized the EU wholesale gas markets for years (Fig. 1). This was caused by a confluence of supply and demand factors - an unscheduled drop in Norwegian offshore gas production, above average (though not extreme) winter demand, shortfall of storage capacity in the UK, and the sudden need for Ukrainian traders to reschedule their portfolios¹ (Kotek et al., 2018). While the drop in global energy demand from COVID-19

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¹ Gazprom withdrew from its gas supply agreement with Ukraine on 1 March 2018 following the initial Stockholm court of arbitration ruling in December 2017.

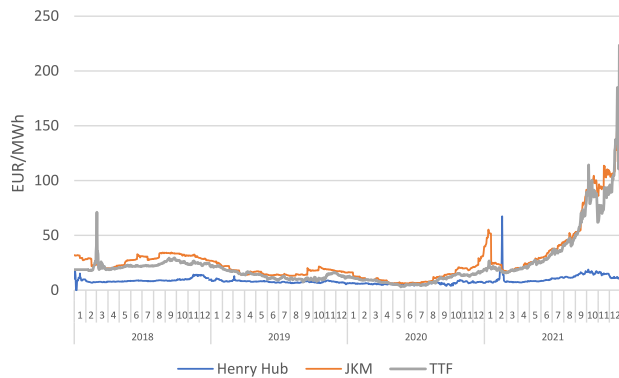


Fig. 1. International gas price markers. Henry Hub indicates the US gas markets, JKM the Asian gas markets and TTF the European Data source: EIA, Investing.com, EEX.

restrictions led to negative oil prices in the US in July 2020, a shock of this scale did not occur in the EU natural gas market, where demand fell only 3–5% year on year (ACER, 2021). It was rather the oversupply of global gas markets that precipitated a huge increase in European storage stocks at a historically low price of 5 €/MWh. Since March 2021 the TTF² price has risen steadily above the pre-COVID 2019 levels. By September 2021, extremely high prices brought the European Green Deal decarbonization back onto the political agenda, which some people blamed, while the liberalization agenda and advocacy of market pricing over long-term contracts also came under attack (Bloomberg, 2021).

In its October 2021 electricity market overview, the European Union Agency for the Cooperation of Energy Regulators (ACER) concluded that natural gas prices, not renewables, are responsible for the high electricity prices (ACER, 2021). There have been numerous studies of the high EU natural gas prices throughout 2021, mostly citing a tight global LNG market (IEA, 2021 and OIES, 2021). Also, indigenous EU production is in a state of broad decline, covering only 20% in 2021 compared to 35% in 2011. The rest is supplied by import pipelines from Russia (30–35%), Norway (20–25%), and Algeria (5–7%), as well as shipped as LNG (8–19%) from various sources like Qatar, Nigeria, USA, Russia, Algeria, Norway, etc. (illustrated in Fig. 2).

Fig. 3 shows how Europe's gas supply sourcing changed from 2020,

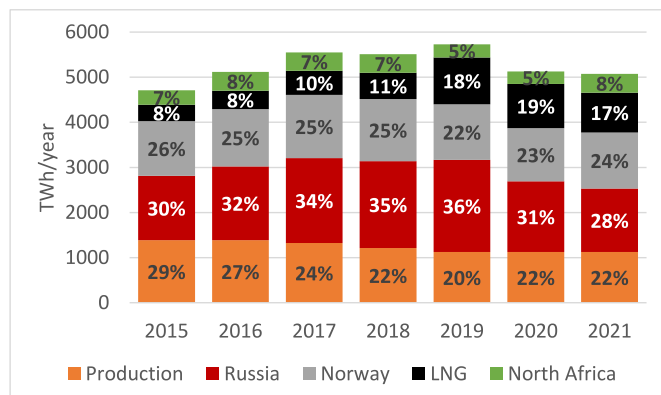


Fig. 2. The main supply of European natural gas consumption Data source: Authors' estimate based on ENTSOG, ALSI and Eurostat.

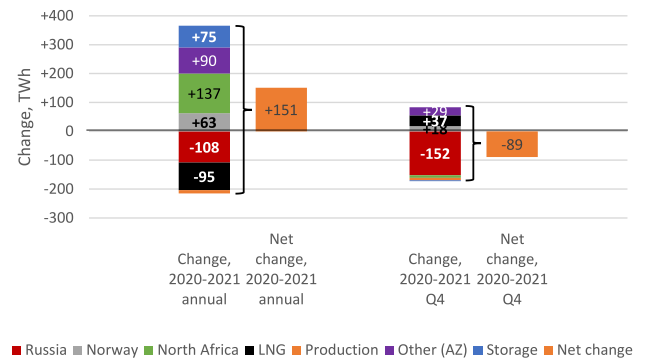


Fig. 3. Change of EU 27 supply structure from 2020 to 2021 Data source: ENTSOG and GIE data.

when natural gas prices were 20 €/MWh, to 2021, under a sustained price spike. Russian and LNG supply fell significantly even though net supply increased overall (151 TWh). However, the net change in Q4 year-to-year was negative (–81 TWh), when Norwegian supply and storage could not cover the gap in Russian supplies. The average EU gas storage filling rate in 2021 was 75%. Gazprom-owned storages in Germany, the Netherlands and Austria all remained far below normal fill levels.³

Fig. 4 illustrates the difference between Russian supplies in 2020 and 2021 and the change in the monthly European gas wholesale prices (TTF). As prices rise, Russia is not delivering above its long-term contracted levels on the Yamal pipeline in Poland and via Ukraine.

The tight EU market and high prices suit Russian economic interests for higher profits, especially considering the revised pricing formula indexing Russian long-term contracts to TTF spot prices, a change driven by liberalization of the wholesale energy markets in Europe and strongly supported by the regulatory push by the European Commission over recent years. For the past decade, hub-based market prices were below the price of oil-indexed long-term contracts, but now the situation has flipped. In an oversupplied market, Russia had to adjust its pricing formula to defend its market share and remain competitive. However, by December 2021 Russia clearly had more leverage over European prices.

The question is: how to bring the supply-demand balance back to an

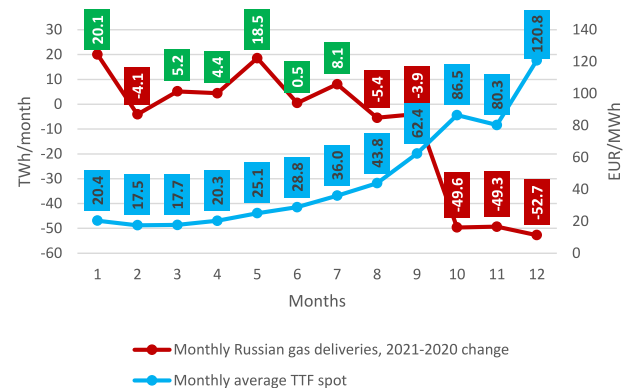


Fig. 4. Change of Russian deliveries from 2020 to 2021 and TTF spot price Data source: ENTSOG and GIE data.

² TTF (Title Transfer Facility) is a virtual trading point for natural gas in the Netherlands and serves as a leading benchmark price in Europe.

³ AGSI + data on EU 27 1 October 2021 compared to 82–96% in previous years.

equilibrium with somewhat lower prices in Europe? There are some ideas on how the situation could be mitigated in the short-, mid-and long term. For a thorough review see [Mišfk \(2022\)](#) and [McWilliams et al. \(2022a, 2022b\)](#). The following section investigates those possible measures that the EU has been outlining in its strategies and policy documents.

Following the previous gas crisis in 2009, the EU focused its strategy on diversifying supplies to the EU via infrastructure development, connecting the markets and adding reverse flows. The impact assessment of the TEN-E ([Akkermans et al., 2020](#)) acknowledged the importance of the newly built projects between 2013 and 2020 for their market integration and security of supply importance. The revision of the TEN-E regulation in Dec 2021 however suggested excluding the gas projects from those that are eligible for EU financing due to the decarbonization considerations ([European Commission, 2020b](#)).

The Fit for 55 package of July 2021 already envisages EU natural gas demand to drop 30% (approximately 1000 TWh) by 2030 due to energy efficiency measures and decarbonized gases such as biogas, biomethane and hydrogen ([European Commission, 2021b](#)). Under declining demand circumstances the decision to avoid building additional gas infrastructure was generally agreed to be a logical move, given that security of supply considerations⁴ were met by the additional infrastructure that reached final investment decision or was built between 2006 and 2021.

In October 2021 the EU published a Toolbox of measures to help the Member States mitigate the energy price shock and protect the most vulnerable household consumers without harming the market ([European Commission, 2021c](#)). Most recently, the March 2022 REPowerEU communication accelerates the phaseout of Russian fossil gas to 2027 ([European Commission, 2022a](#)).

In July 2022 the European Commission proposed a uniform 15% reduction target for each EU Member State intending to prepare for the upcoming winter, addressing the threat of limited gas supplies by Russia but also as a measure to mitigate the high gas prices by demand response ([European Commission, 2022c](#)).

Only a few EU Member States have introduced rules for mandatory strategic gas reserves, such as Hungary, Denmark and Spain, while most prefer market-based solutions ([ACER, 2022b](#)). But this changed in October 2021, when Spain led a joint statement with France, Greece, Romania and the Czech Republic, suggesting a European centralized strategic gas reserve platform.

Then in March 2022, the European Commission proposed new rules to keep gas storage levels up, including an obligation to fill 80% by November 2022 and a 100% discount from the capacity-based transmission tariffs at storage entry and exit points. All other forms of compensation remain under the authority of Member States considering the state-aid regulation ([European Commission, 2022b](#)).

In the context of Russian diversification strategies, different gas import and infrastructure scenarios, including the use of the Ukrainian system and the commissioning of the Nord Stream 2, were widely analysed. [Mitrova et al. \(2016\)](#) examined several gas import scenarios, concluding that the European gas mix is fairly robust and will maintain a significant share of natural gas from Russia in all scenarios. [Paltsev \(2014\)](#) and [Vatansever \(2017\)](#) also find that the Ukrainian route is not necessary if Nord Stream 2 and TurkStream are constructed while acknowledging that the cessation of Ukrainian transit will push up EU prices. [Takácsné Tóth et al. \(2020\)](#) model the welfare gains of different Russian pipeline routes and pricing strategies, finding that Russia will lose more if it stops supplying via the Ukrainian route before Nord Stream 2. This finding is supported by [Eser et al. \(2019\)](#), who conclude that only 40% of Ukrainian transit can be re-routed via Nord Stream. Furthermore, [Henderson and Sharples \(2018\)](#) assert that Europe's

⁴ The security of supply considerations have to be reconsidered Europe-wide after Russia invaded Ukraine on 24 February 2022, however, this is not the focus of our paper.

growing gas import demand cannot be satisfied without the Ukrainian system, even if Nord Stream 2 and Turk Stream are built. [Hauser \(2021\)](#) asserts that both Nord Stream 2 and Ukraine transit are needed to ensure a cost-effective supply for the European gas market.

In historical context Per Högselius argued that the increasing dependency on “red gas” was discussed in Europe and Germany from the beginning of the first deliveries in 1968, but the political perception of the threat was more related to potential abuse of market power of Russia by e.g. overflowing Europe with natural gas and thereby threaten the domestic (coal industry) than by considering a “use of gas as a weapon”. Therefore, Western European countries especially considered the building of additional infrastructure that would allow for a diversified supply and the improvement of the interconnectivity of the network between the Member States as a good and effective tool to mitigate the Russian risk ([Högselius, 2021](#)). The gas infrastructure building has been on the European level supported by prioritizing certain missing links in Europe and providing accelerated licensing and financial grants for selected projects based on the trans-European infrastructure regulation (TEN-E), which labelled the key priority projects to be implemented as Projects of Common Interest (PCI) from 2013 every second year ([European Commission, 2020a](#)).

Although the European market we see is a well-functioning interconnected one, there are still some bottlenecks and in times of scarce supply decoupling of major markets may occur.

The effect of PCI and PECE⁵ projects received less attention in academic modelling literature. [Kotek et al. \(2019\)](#) assessed the socio-economic benefits from the 3rd PCI list using three different models, concluding that there is no need for more gas pipelines or LNG terminals owing to the European Green Deal decarbonization agenda. [Selei and Takácsné Tóth \(2022\)](#) continued the analysis for the 4th PCI list, finding that although the whole list does not perform well as a package, the net benefit of PCIs with final investment decision turns out to be positive in high price environment. Using the concept of Catalytic Power Europe, [Prontera and Plenta \(2020\)](#) analyse the gas interconnector and LNG PCI projects that are under development in the V4 region and illustrate how the European Commission has emerged as a facilitator and has helped the implementation of projects with an extensive regional impact that otherwise would be very difficult to realise.

[Sesini et al. \(2021\)](#) and [\(2022\)](#) apply a scenario-based modelling approach to show that coordinated strategic storage increases system resilience and acquires significant value in mitigating high prices. Others maintain that strategic storage is too costly and will not relieve high prices in the short term. They suggest a European solidarity mechanism with harmonized gas storage requirements setting a minimum commercial stock level ([Egenhofer and Kustova, 2021](#)). [Bai and Dahl \(2018\)](#) assess the strategic petroleum reserves in the US market, pointing out that the costs of energy reserves include not only the pure energy costs but also maintenance and capital expenditures of the facilities. They argued that these costs need to be recovered from taxpayers or end consumers.

We can conclude that the analysed measures in this paper have already been examined - although to different extent - in the previous literature ([Mišfk, 2022](#)). The novelty and actuality of our paper are that using market modelling approach we analyse how successfully these measures can be used to mitigate the extremely high prices on the European markets in a comparable manner.

3. Methodology

The following section provides a modelling-based analysis of the possible measures outlined above using REKK's European Gas Market

⁵ PECE is the Energy Community label for Project of Energy Community Interest.

Model (EGMM).

Modelling is an appropriate tool for analysing the effects of possible measures to address high prices. Compared to electricity market models, there are considerably fewer mathematical models of European gas markets. A gas market model analysing the policy measures to the high prices should incorporate the crucial elements of the European gas markets, such as (i) infrastructure constraints of pipeline, storage and LNG facilities (ii) contractual constraints of long-term supply contracts such as take-or-pay obligations, price formulae, already contracted delivery routes of gas (iii) regulatory constraints such as minimum storage obligations, transportation tariffs, (iv) global LNG markets considering the gas demand in Asia as well as the potential supply from LNG liquefaction plants (v) sectoral demand of building heating, industry and power and heat generation as well as unique elasticities. Even though our modelling approach covers all these aspects of the European gas market, we must point out some caveats.

Our model is a competitive model, it assumes that market participants are price-takers hence the strategic response of main gas suppliers to Europe is not endogenously modelled, rather we exogenously set the pricing and volume behaviour of these countries. However, we remedy this shortcoming by setting prices and consequently the volume of gas sold to Europe to deliver the maximum profit to the main exporters – this way the modelling mimics the optimal marketing strategy of suppliers.

The EGMM is a dynamic, multi-market equilibrium model that simulates the operation of the wholesale natural gas market across the whole of Europe. It includes a supply-demand representation of European countries, including gas storage and transportation linkages. Large external markets, including Russia, Turkey, Libya, Algeria and LNG exporters are represented exogenously with market prices, long-term supply contracts and physical connections to Europe. The timeframe of the model covers 12 consecutive months starting in April. Market participants have perfect foresight over this period and dynamic connections between months are introduced by the operation of gas storages and take-or-play constraints of long-term contracts.

The model operates with four “players”: (i) Consumers defined by a linear downward-sloping monthly demand function. Different sectoral consumptions (power and heat, industry and building heating) are considered per country (ii) Local producers of natural gas are represented by linear short-run cost functions, with upper and lower limits on monthly production and a separate upper constraint on yearly output (iii) Importers of gas long-term take-or-pay (TOP) contracts are sourced from gas exporters in outside markets (Russia, Norway, Algeria) and several LNG exporting countries. Each contract specifies a price, a delivery route, and a minimum and maximum delivered quantity per month and per year as well as a penalty on TOP (iv) Traders move gas between markets using cross-border pipelines and LNG shipments considering price differences, and between time periods using storages.

Pipeline and LNG regasification infrastructure facilitates the trade movements between markets. Storage sites offer inter-temporal arbitrage options for traders. As in reality, operators of infrastructure are not strategic actors in the model, i.e. do not seek to maximize their profits or congestion rents, usage tariff is set as a parameter based on the latest historically available tariff.

Decision variables in the model are connected to the players listed above. The volume of production of local gas sources is set by producers maximizing their profits on gas extraction. The total volume of gas delivered to Europe from the main suppliers by importers of gas is calculated by maximizing the profit of importers. Spot trade between European markets and LNG, as well as the use of storages (injection to and withdrawal from), is defined by maximizing the profits of gas traders. Consumption is a function of other market participants’ decision variables. Market equilibrium determines a state where the total welfare of the consumers, local producers, importers and traders is at a maximum. The competitive nature of the European gas markets may be questioned, as the major supplier to Europe may have market power and can affect wholesale prices. The model considers the pricing behaviour

of major suppliers as exogenous parameters, i.e. for each model run, a pre-defined price level for Norwegian, Russian and other imports is set. Norway and Algeria are considered to follow a price-taker strategy on the European markets, while Russia engages in profit maximisation based on its limited market power. LNG supply is defined as the function of Asian gas demand and price and acts as a cap on Russian market power.

In the current (war) situation, Russian marketing strategy may follow other logic than profit maximisation (e.g. “punishing” European gas consumers by constraining or completely stopping flows and deliberately discarding potential revenues), but this issue is beyond the scope of our analysis.

Given the input data, the model calculates a dynamic competitive market equilibrium for the modelled countries, where all arbitrage opportunities are exhausted to the extent that storage facilities, transportation, infrastructure, and contractual conditions permit. As a result, the competitive equilibrium yields an efficient, welfare-maximizing outcome. A detailed description of the model can be found in Kiss et al. (2016), mathematical formulation of the model is presented in Appendix.

EGMM pipeline, storage and LNG infrastructure data are from Gas Infrastructure Europe⁶ and GIIGNL (GIIGNL, 2020). Infrastructure tariffs are collected from the national regulatory authorities and from the terminal operator websites. Long-term contracts are based on Cedigas, GIIGNL and publicly available sources. Demand and production volumes are taken from the PRIMES EUCO 3232.5 scenario (E3M Modelling, 2021).⁷ The main input parameters are listed in Table 1.

To analyse the impact of a measure we always compare the results of a reference model run to a scenario and measure the difference in the outputs. To avoid bias of combined impacts we use an incremental approach and change only one main parameter at a time.

The Reference case simulates the post-COVID recovery of a “perfect storm”: high Asian demand, a tight LNG market (only 1050 TWh/yr is reaching EU the 27 terminals), and no transit flows for spot deliveries via Ukraine, with an assumed 400 bcm/yr (4071 TWh/yr) aggregated EU 27 demand.

The Reference scenario was calibrated to illustrate the 2021 European gas market demand and supply structure, capacity/use of infrastructure, and price environment. To better reflect the high price environment in the last quarter, the Ukrainian transit system was not used for additional spot volumes from Russia. We assume that Nord Stream 2 is not commissioned, while Turkish Stream and Balkan Stream operate up to Hungary. The alternative routes (Nord Stream 1, Turk Stream 1–2, Blue Stream and Yamal) are utilised to meet the long-term contracted gas obligations. See the main assumptions and the change in the reference case and the scenarios summarized in Table 1.

The scenarios selected show the possible way out of the high price crisis. In the autumn of 2021, Russian communication put a strong emphasis on the need for additional infrastructure and the need to speed up the licensing process of the Nord Stream 2 pipeline to allow additional Russian flows to reach Germany. According to the Russian narrative, the additional route would eliminate any transit risk and could bring substantial price relief to Europe. This is simulated by Scenario 1A: Nord Stream 2 is commissioned and utilised at full capacity, while transit via Ukraine, LNG, storage and demand remain the same as in the Reference case.

On the other hand, the existing gas transmission infrastructure in Ukraine has been under-utilised and the renewal of the long-term transit contract from 01.01.2020. envisaged a 65 bcm/year transit to 2025 as a compromise negotiated by Gazprom and Naftogaz. This contracted

⁶ www.gie.eu.

⁷ EUCO3232.5 is a policy scenario using the PRIMES model designed to achieve a 32% share of renewable energy in gross final energy consumption and a 32.5% energy efficiency target in the EU up to 2030.

Table 1

Main input parameters of demand, production, pipeline and storage infrastructure, TWh/yr.

	Demand	Local production	Pipeline in	Pipeline out	LNG in	Storage withdrawal	Storage working gas volume
	TWh/yr	TWh/yr	TWh/yr	TWh/yr	TWh/yr	TWh/yr	TWh/yr
AL	1	1	15	0	0	0	0
AM	27	0	66	0	0	0	0
AT	86	8	783	806	0	273	62
AZ	133	393	169	438	0	0	0
BA	2	0	7	0	0	0	0
BE	201	0	951	742	174	62	9
BG	29	1	498	433	0	13	6
BY	202	2	438	1007	0	116	15
CH	36	0	372	331	0	0	0
CY	4	13	0	0	15	0	0
CZ	88	2	902	919	0	257	41
DE	922	44	2497	1728	0	2694	291
DK	32	22	61	398	0	71	10
EE	5	0	169	118	0	0	0
ES	330	1	356	134	697	78	32
FI	26	0	107	26	0	0	0
FR	423	2	779	254	457	915	133
GE	28	0	489	392	0	0	0
GR	65	3	239	259	75	0	0
HR	31	13	48	8	30	22	6
HU	116	13	383	193	0	322	68
IE	61	14	141	0	0	0	0
IT	744	49	1346	300	177	1192	204
LT	27	0	143	25	45	0	0
LU	7	0	32	0	0	0	0
LV	10	0	182	89	0	115	24
MD	10	0	34	0	0	0	0
MK	4	0	7	0	0	0	0
MT	4	0	0	0	17	0	0
NL	387	197	634	666	140	1019	130
PL	213	49	684	390	58	210	36
PT	53	0	53	29	73	31	4
RO	131	114	490	293	0	127	34
RS	27	4	196	75	0	18	5
SE	15	0	365	0	0	4	0
SI	11	0	54	27	0	0	0
SK	50	1	1395	918	0	175	36
TR	507	5	1229	346	391	416	62
UA	320	192	3407	1510	0	1018	333
UK	619	363	1021	379	563	531	16
Total modelled	5986	1505	20744	13233	2911	9679	1556
Total EU27	4071	545	13293	8755	1957	7580	1124

Table 2

Main characteristics of the modelled scenarios.

Scenario	Demand in Europe	Infrastructure	Russian use of UA transit route	LNG supply to Europe	Storage use
Reference	2019 (last pre- Covid year, 4071 TWh/yr for EU27)	As of October 1, 2021	NO	Scarce (calibrated to 2021 Q1, 1050 TWh/yr)	Commercial, optimised by the model
1.A Nord Stream 2	Reference	Nord Stream 2	Reference	Reference	Reference
1.B Ukrainian transit	Reference	Reference	YES	Reference	Reference
2. DEMAND RESPONSE	–15% for each EU MS (3400 TWh/yr for EU27)	Reference	Reference	Reference	Reference
3. STORAGE	Reference	Reference	Reference	Reference	Strategic storage stocks released
4. PCI	Reference	5th PCI list gas projects	Reference	Reference	Reference

capacity has not been utilised in 2021. Scenario 1B allows for utilization of the Ukrainian transit system up to full capacity, while LNG supply and demand remain the same as in the Reference case and Nord Stream 2 is not commissioned.

European countries may ease the effects of high prices by consuming less gas and thus lowering the gas price. This may stem either from fuel switching in the power sector, demand reduction in industrial production due to high energy prices or savings in building sector heating. To model this, we use a simplified assumption for the Demand Response

Scenario, namely a uniform 15% reduction in demand in each modelled country due to high prices in the Reference case, with all else remaining the same as the Reference. A similar approach has been communicated in July 2022 by the European Commission calling for a voluntary 15% uniform demand reduction for each Member State as a counter-measure to the energy crisis (European Commission, 2022b).

Furthermore, countries with access to storage facilities may opt to build up strategic stocks for the coming winter. Strategic stocks are reserves formed by governments to increase the security of supply in

highly import-dependent countries. This means that stocks are not built by traders to earn seasonal arbitrage but built up by governments or TSOs as requested by laws and regulations. These stocks can only be released in a state of emergency. A similar system of strategic stocks is operating in the oil market to ease price hikes since the 1973 oil crisis. Although some countries have strategic reserves, no such coordinated strategic stocks exist at the European level. The idea of creating such reserves popped up in October 2021 pushed by Spain, France, Greece, Romania and the Czech Republic. Storage Scenario 3 measures the price impact of building up and releasing various levels of strategic stocks, spanning 5–10–15–20% of total European storage capacity. The gas reserves enter and exit at low market prices to alleviate the high price environment. All other parameters are the same as in the Reference case.

In the PCI scenario, we measure the effect of better interconnectivity of European gas markets by constructing additional infrastructure. Scenario 4 estimates the effect of commissioning the 5th PCI list in the high-price environment. For this scenario, all projects on the 5th PCI list (European Commission, 2021a) are added to the infrastructure and their price effect and benefits are evaluated against their investment cost. All other parameters are the same as in the Reference case.

4. Results and discussion

4.1. Reference scenario

Fig. 5 shows the average annual wholesale gas price in modelled countries. Under the Reference Scenario conditions in 2022 modelled European gas prices decouple, forming three distinct price zones:

- Western Europe - where LNG cargoes set the price (~40 EUR/MWh);
- Central and Eastern Europe – where scarcity results in the highest prices (~50–55 EUR/MWh);
- South-East Europe – where new deliveries on the Balkan route results in the lowest prices (30–35 EUR/MWh).

The reason for this decoupling of price regions is the change in flow directions. The increased LNG flows face internal bottlenecks in the European pipeline system when trying to supply gas from the West to the East substituting the traditional direction. Most pressing are the bottlenecks between the UK and mainland Europe, leaving part of the UK LNG regasification terminals underutilized. The other crucial bottleneck is between France and Germany and the Netherlands to Germany. In fact, our modelling results have been supported by the latest evidence of price developments in Europe: the decoupling of major European hubs along the price zones identified above. ACER reported for years on the increasing price convergence as the success of the market integration efforts of European regulation, but in 2022 the pattern changed, and the reasons cited by ACER are exactly the increased LNG inflows and the capacity constraints that we also modelled here (ACER, 2022a).

4.2. The effect of Nord Stream 2 and the Ukrainian transit

Scenarios 1A and 1B tested the impact of additional spot deliveries from Russia, including Nord Stream 2, which is now operational but awaiting German regulatory approval.⁸ Compared to the current base case, additional deliveries via the Nord Stream 2 significantly dampen the prices in Europe as depicted on the left of Fig. 6. Similar and even slightly better results are possible utilizing the Ukrainian trunk system, as depicted on the right side of Fig. 6. Both alternative routes return to the traditional East to West shipments, which relieves the bottlenecks

⁸ <https://www.euractiv.com/section/energy/news/germany-has-four-months-to-certify-nord-stream-2-pipeline/> After the Russian invasion of Ukraine, Germany suspended the licensing of Nord Stream 2 and the company went bankrupt.

mostly also when the Nord Stream 2 route is assumed, as the evacuation transport route has already been put in place on the internal German, the Czech and Slovak system in the last few years. In case of the use of the Ukrainian system, it is no surprise that the bottlenecks fully disappear, and price relief is brought to the most severely impacted countries among them Ukraine itself.

Therefore, it can be concluded that it is not Nord Stream 2 but additional Russian deliveries through any route that would alleviate gas prices in Europe. The main problem of these scenarios is that it is not the decision of the EU or any of its Member States to ship more Russian gas on any possible routes.⁹ Russia can withhold volumes above the contracted minimum to keep EU prices high or sell to higher-priced Asian markets up to the available pipeline and LNG capacities.¹⁰

4.3. The effect of demand decrease

Fig. 7 shows the impact of a 15% fall in demand under Scenario 2. It would reduce prices in Central and Eastern Europe by 11 €/MWh on average. This may involve high gas prices triggering switching to coal in the power sector and heat pumps in households. For comparison, the COVID pandemic resulted in approximately a 3–5% demand decrease in annual natural gas consumption. To reach this 15% reduction will require huge efforts in all sectors and probably also government interventions to mitigate the effects on vulnerable consumers or strategic industrial segments.

Fig. 7 shows that a uniform 15% demand decrease across all the EU27 has the main impact on the gas price decrease of the countries of Central and Eastern Europe. The demand reduction of France, Spain, Greece and other countries with LNG terminals would help to boost liquidity on the wholesale level and could dampen the overall EU gas price level. It must be noted that the demand decrease in this scenario is exogenously set, which is capturing well the idea of the Commission's proposal that member states should voluntarily put in place measures to reach this 15% target (European Commission, 2022b). Would governments in the less impacted countries implement costly demand reduction measures to decrease the gas dependence of their building or industry sector that would certainly have positive spillover effects on the Central Eastern part of the EU. For this reason, it is difficult to understand why Hungary (as the EU Member State most positively impacted by such a coordinated demand reduction with −9.3 €/MWh) has voted against the Commission's proposal in the Council.¹¹ Still, the proposal was accepted despite Hungarian opposition.

4.4. The effect of strategic storage

In 2021 there are not too many strategic storage stocks in Europe, as it is a rather costly way of providing security of supply. Altogether there are 8 TWh working gas storage labelled as strategic reserves in facilities of Hungary, Denmark, Italy and Spain.

To quantify the effect of using the existing strategic storages, those 8 TWhs are released in a month (January) at 20 €/MWh.¹² At the same time, we assume that national regulations do not put restrictions on the free movement of gas at EU-EU or EU-third country nodes.

⁹ The only tool in the hands of the EU and its Member States that it can decide on not allowing the use of a route – like Germany stopped the licencing process of Nord Stream 2. Alternatively, the EU could decide to ban Russian gas imports as a political reaction, which could not be agreed on so far (August 2022).

¹⁰ <https://www.bloomberg.com/news/articles/2021-10-06/russia-ready-to-help-stabilize-global-energy-markets-putin-says>.

¹¹ Hungary Rejects EU's Proposal To Reduce Gas Consumption, Calls The Move 'unjustifiable' 27. July 2022 <https://www.republicworld.com/world-news/europe/hungary-rejects-eus-proposal-to-reduce-gas-consumption-calls-the-move-unjustifiable-articleshow.html>.

¹² Price paid for gas stored in 2020.

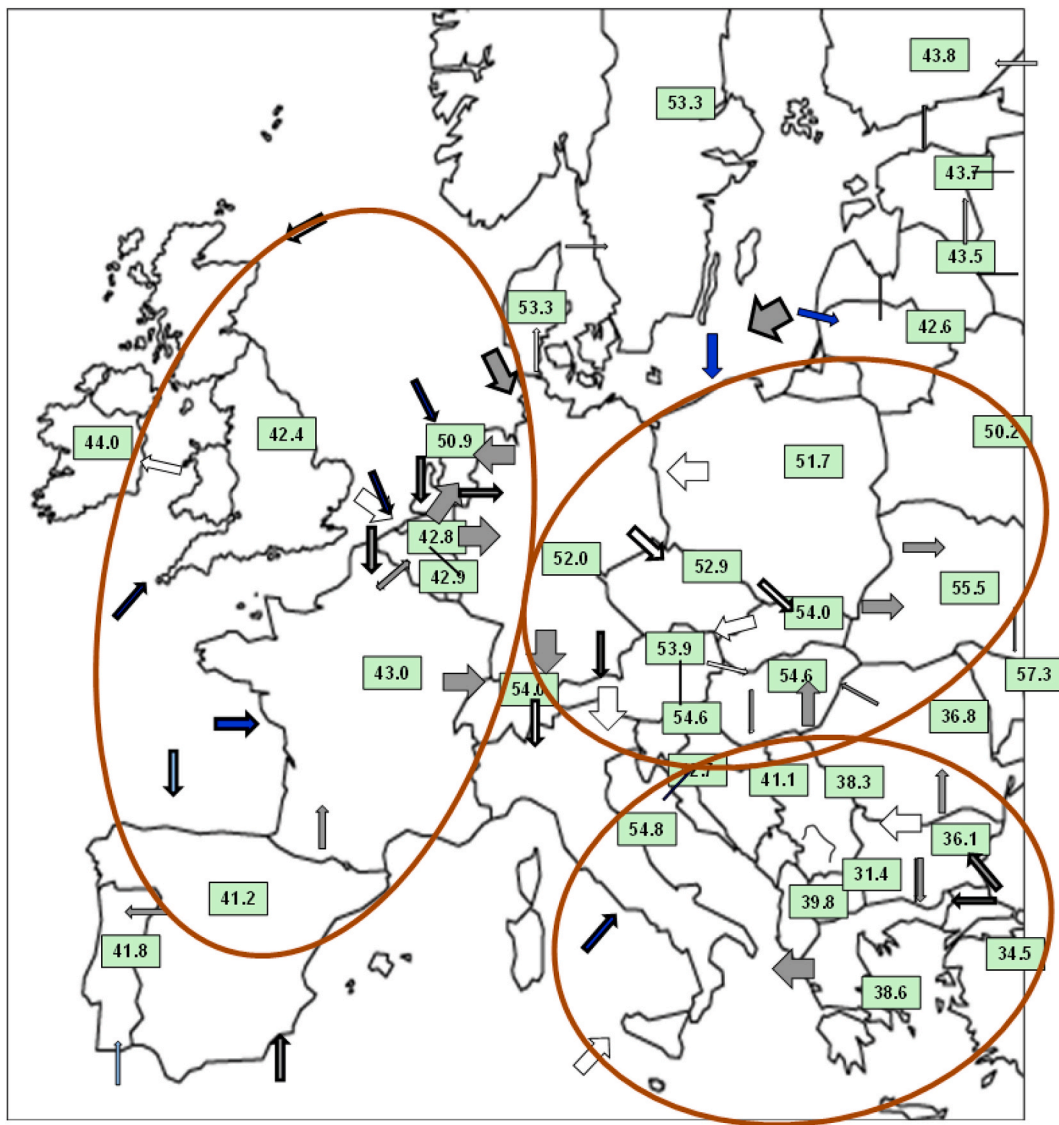


Fig. 5. Modelled yearly average wholesale natural gas prices (€/MWh) and price regions in the reference scenario

Green boxes depict the average annual wholesale gas price in modelled countries. Grey arrows indicate congested pipeline flows, where the pipeline was used at 90% capacity for at least 3 months. Blue arrows indicate LNG flows, where the terminal was used at 90% capacity for at least 3 months. The size of the arrow is proportional to the total volume of flows.

Source: EGMM modelling.

Fig. 8 shows that Ukraine would absorb a significant part of the additional gas, with other Eastern European countries also benefiting from lower prices, Hungary would be the main beneficiary of such a measure as it is highly dependent on Russian gas, is landlocked and has already developed the strategic gas reserves, that were filled with stocks when gas prices were around 20 €/MWh. In fact, the Hungarian strategic stocks were indeed partly released in the autumn of 2021 when prices were already climbing high (around 50–60 €/MWh). At that time the sentiment was that high market prices are temporary consequences of demand increase due to the economies' post Covid recovery and the market will balance in a few months ((ACER, 2022a,b). The problem with this measure is that it can only be applied once in a storage cycle, and only short-term price shocks can be mitigated. It is also difficult to see what the right time is to release the stocks: in Hungary, the strategic reserves had to be refilled with gas at prices at the level of above 200 €/MWh during the summer of 2022.

Despite these concerns listed in the Hungarian example above we simulated the proposed measure to set up a joint EU strategic stock, and observe the effect for different strategic stock obligation percentages (5–

10–15–20%) of total European storage capacities. As before, this storage capacity is released in one month at a price of 20 €/MWh. It is important to note that at the high price environment of 2022 it is unrealistic to procure stocks at this low price. Furthermore, putting additional storage obligation at the market when it is tight, does curb prices further up. Therefore, such a measure could only be executed when prices are low and supply is abundant. Thus, the following scenario is more a theoretical analysis to show whether it is worth to build up strategic stocks when prices are low in order to prevent in the future such a crisis we experience now (see Table 2).

Fig. 9 shows that the European strategic storage obligation helps the Eastern region with the highest prices tremendously. Intuitively, the higher the percentage of strategic storage, the more the price effect: 5% strategic storage results in an average EU27 price decrease of 6 €/MWh, and 20% triggers a 26 €/MWh average drop in EU prices. The weighted average monthly (January) European wholesale gas price in the reference scenario, before strategic storage stocks are released is 50.2 €/MWh. These numbers can be found in Table 3.

The next step is to calculate the net benefit of strategic storage

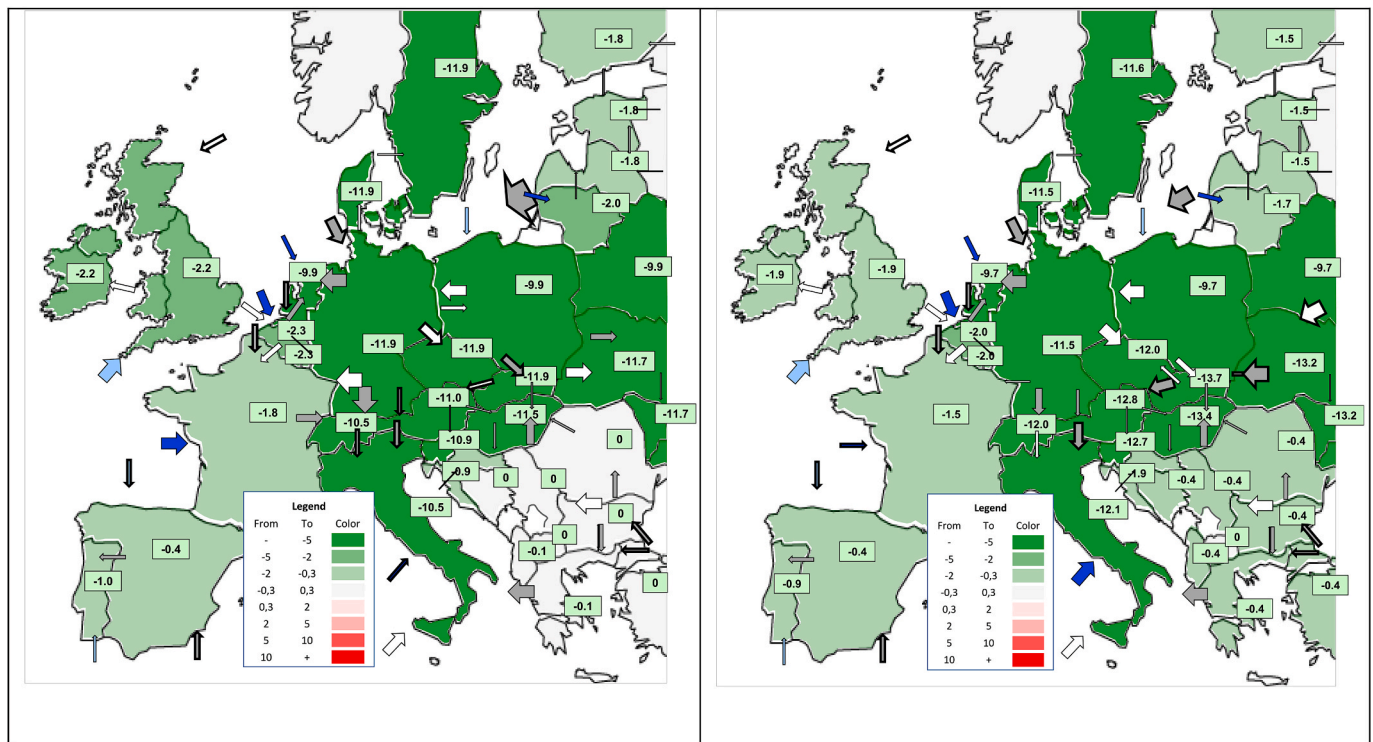


Fig. 6. Yearly average price change due to commissioning of NS2 (left) and due to using Ukrainian transit route €/MWh. Green boxes depict the average annual wholesale gas price change in modelled countries compared to the reference scenario. Grey arrows indicate congested pipeline flows, where the pipeline was used at 90% capacity for at least 3 months. Blue arrows indicate LNG flows, where the terminal was used at 90% capacity for at least 3 months. The size of the arrow is proportional to the total volume of flows. Source: EGMM modelling.

quantified as the decrease in consumer expenditure multiplied by the probability of the high price environment minus the costs. Column A shows the total volumes withdrawn from strategic stock; Column B the price effect on European markets; Column C the total cost of the gas injected into strategic stocks; Column D the cost of storage fees (1 EUR/MWh, $D = 1 \cdot B$); Column E the overall benefits, quantified as the decrease in the total cost of gas for EU27 consumers; Columns F-G-H the value of storage, according to releasing the strategic stocks in 1, 2 or 3 years. Storage withdrawal in 1-2-3 years means that the strategic stocks built are released in the first, second or third year. Most importantly, this is the difference between the benefits and costs of strategic storage.¹³

The modelled outcomes indicate that benefits are strongly positive if stocks are used within a year, but if no price hikes occur within two years, in the long run, it is too costly to keep the stocks with such a low probability of the high price shock. Furthermore, this modelling assumed market players are buying low and selling high. In the 2022 market situation, this was impossible as gas prices were extremely high. Meanwhile, the security of supply value automatically increases with a higher risk to supply disruption.

4.5. The effect of PCI projects

The 5th PCI list published in late 2021 (European Commission, 2021a,b,c) includes 20 natural gas projects shown in Annex 1.

The modelling includes all gas projects with cross-border effects,¹⁴ first one at a time, then all together. This allows us to assess the welfare effect on consumers, producers, traders and infrastructure operators. The yearly net welfare changes are based on the benefits and the

annualized cost of infrastructure commissioning compared to the Reference scenario. The annualized costs of the PCI projects were calculated based on the TYNDP 2020 of ENTSO-G (ENTSOG, 2020).

Table 5 shows that most of the gas projects perform well in terms of utilization.¹⁵ In contrary, the IGB project meant to supply Bulgaria from Greece, a top EU priority for more than a decade, does not perform well. This is because the Balkan Stream pipeline, meant to deliver Russian gas from TurkStream 2 to Bulgaria, Serbia and Hungary, can accommodate Azeri gas or LNG when Russian flows are lower.¹⁶ The same logic applies to the IBS (connecting Bulgaria and Serbia) pipeline. The extension of the Hungarian-Slovakian interconnector is also underutilized with flow direction changes and new sources finding shorter routes to markets.

Polish LNG terminal performs well as a gateway to the Eastern Member States in need of additional gas volumes. Cyprus LNG is underutilized since LNG does not compete with Cyprus' offshore production.

The projects offering new sources and diversification perform well, including BRUA, Poseidon, EastMed, and the Baltic Pipe. Storage sites in Bulgaria, Romania, Greece and Latvia are utilised for system flexibility in the absence of liquid markets, but benefits tend to be lower since the market does not pay for the flexibility or security of supply. Furthermore, consumer benefits are counteracted by the losses of long-term contract holders earning less money. This leads to the negative socioeconomic net present value of storage projects, though further considerations are necessary.

The benefit/cost ratio is highest for the Polish LNG terminal, followed by the Croatian-Slovenian Interconnector, the Baltic pipe, and the

¹⁵ It must be noted that in case of bidirectional projects the utilization of the main direction is reported.

¹⁶ Assuming third-party access rules and congestion management standard practices apply to all pipelines.

¹³ $F = E - C - D$; $G = E \cdot 1/2 - C \cdot 2 \cdot D$; $H = E \cdot 1/3 - C \cdot 3 \cdot D$.

¹⁴ Three PCIs (6.8.2, 7.3.4, 8.3.1) without cross-border effects are left out.

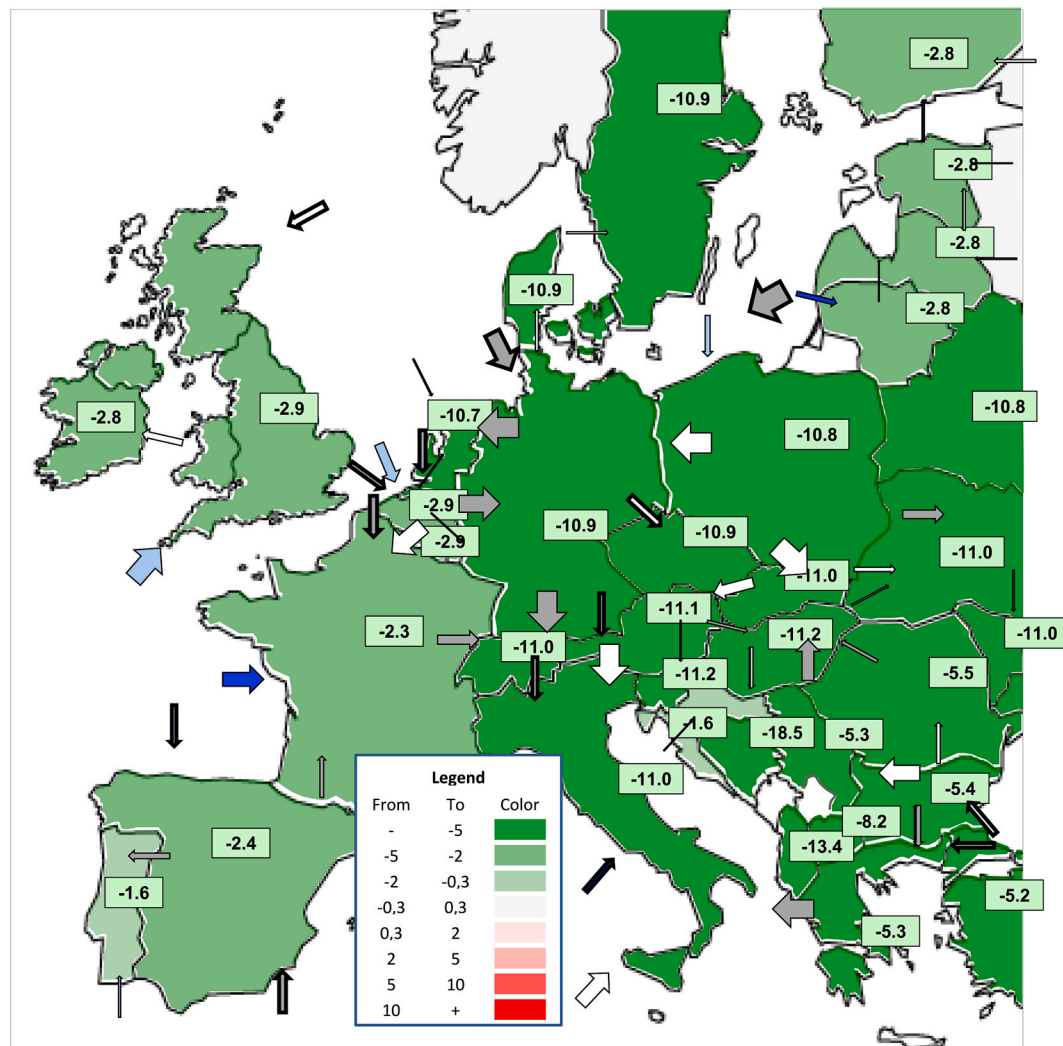


Fig. 7. The yearly average price effect of a 15% demand decrease compared to the reference scenario (€/MWh)

Green boxes depict the average annual wholesale gas price change in modelled countries compared to the reference scenario. Grey arrows indicate congested pipeline flows, where the pipeline was used at 90% capacity for at least 3 months. Blue arrows indicate LNG flows, where the terminal was used at 90% capacity for at least 3 months. The size of the arrow is proportional to the total volume of flows.

Source: EGMM modelling.

second phase of the BRUA pipeline.

Realization of the full 5th PCI list would result in a B/C ratio of 1.5, meaning long-term benefits outweigh costs in the current high price environment, mitigating high gas prices and bringing convergence in the single market. The high gas price environment has a tremendous impact on the social economic value of the gas infrastructure projects: would the high price environment stay with us, the projects show positive results and can mitigate price differences within the EU. However, if due to these high prices and the geopolitical circumstances Europe phases out gas before the end of the 25-year project lifetime, any new project will become a stranded asset.

4.6. Comparison of modelled measures

The modelled scenarios are worth to be compared along with the change in weighted average European wholesale prices whereby the bigger markets will have more of an effect.

Another useful indicator is the consumption weighted standard deviation, measuring EU27 market integration, calculated as:

$$SD_w = \sqrt{\frac{\sum_{i=1}^{EU27} Consumption_i (Price - \overline{price})^2}{\sum_{i=1}^{EU27} Consumption_i}}$$

Table 6 provides the weighted average price and standard deviation across scenarios. This shows that from the scenarios representing European responses (scenarios 2–6) the demand decrease scenario results in the lowest average gas price (down by 16.2% compared to the reference) followed by the PCI infrastructure development scenario. Strategic storage has a more limited price effect on yearly average prices and is stronger within the year, meaning that its impact is very short-term, only 1–2 months following the release of the stocks (see Table 4). While more Russian gas delivered on Nord Stream 2 or via Ukraine has a significant price effect, they cannot be influenced by EU policy, we can look at them as possible “peace scenarios”, would Russian supply return to pre-war levels. PCI projects have the biggest effect on price convergence, as they directly address the congestions of the pipeline system and add more LNG supply entry point to Germany (weighted standard deviation decreases from 5.76 to 1.7 €/MWh). Price convergence can also be increased by the Nord Stream 2 and Ukrainian transit scenarios and lower demand, but not really by the storage scenarios.



The current EU gas price crisis is rooted in strong Asian demand related to the economic recovery from the 2020 COVID crisis. The current situation is somewhat different compared with past Asian gas price spikes since European gas prices are more exposed to global prices with the decline in domestic EU production.

It remains to be seen what lessons will be taken from the current crisis for risk management, contract pricing and flexibilities on every level of natural gas trading: from end users to utilities, midstream traders and the governments and wholesale companies directly negotiating long-term contracts with the producers.

vulnerability to global shocks and the market power of its biggest supplier. In this respect, regulation should allow Member States to protect vulnerable EU consumers (household heating) following European Commission guidance to temporarily relieve prices through fiscal policy and targeted energy efficiency.

If high prices are sustained in the midterm, it could strengthen the mistrust of the commodity and speed up switching from gas in all sectors. Phasing out gas-fired power plants that provide flexibility to the electricity system might temporarily be substituted by coal-fired generation as clean dark spreads become positive and clean spark spreads negative.¹⁷ In the long run, the decarbonization agenda will lead to more innovative new solutions doing away with coal.

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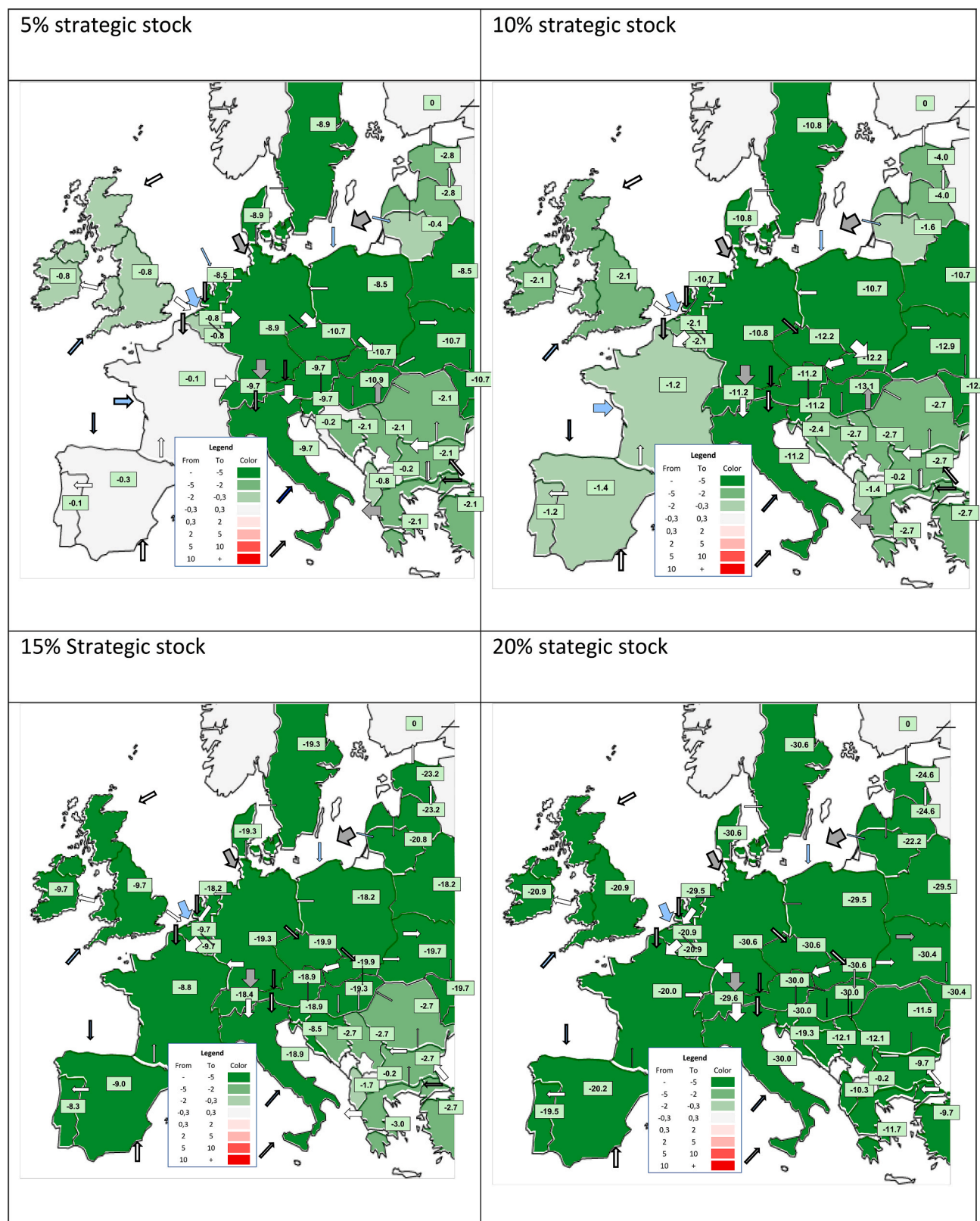


Fig. 9. The yearly average price effect of the common European strategic stock – 5-10-15-20% of the EU storage stock

Green boxes depict the average annual wholesale gas price change in modelled countries compared to the reference scenario. Grey arrows indicate congested pipeline flows, where the pipeline was used at 90% capacity for at least 3 months. Blue arrows indicate LNG flows, where the terminal was used at 90% capacity for at least 3 months. The size of the arrow is proportional to the total volume of flows.

Source: EGMM modelling.

Table 3
Market effect of different levels of strategic storage.

	Strategic stocks volume withdrawn	Commercial storage	Total storage withdrawal	Price effect in the month when stocks were released
	TWh/yr	TWh/yr	TWh/yr	EUR/MWh
Current strategic stock	8	497	505	−2.49
5% strategic stock	41	491	532	−6.15
10% strategic stock	72	485	558	−7.74
15% strategic stock	103	481	585	−15.16
20% strategic stock	134	475	609	−26.02

It is not the lack of natural gas reserves that drives scarcity but the unwillingness of banks to finance new fossil projects due to climate considerations. This attitude towards natural gas might change to ease global scarcity and support a smooth transition from coal to gas in Asia. However, Europe should concentrate on reducing natural gas demand through energy efficiency and renewable investment to re-establish an

equilibrium in light of depleted domestic production, even though the long-term demand adjustments will not impact short-term pricing.

Strategic storage stock holding can mitigate high prices but only for a short period. Commercial storage operation works in that direction too. It is not socio-economically viable to keep high strategic stocks coordinated by the EU to mitigate market risks. However, consideration should be given to the increased security of supply risk due to the war in Ukraine, and the increased risk of the Russian supply cuts. The strategic storage stocks - if seriously considered politically - would be best placed in the Central Eastern European region as the vulnerability of the central region (Germany, Czech Republic, Slovakia, Hungary, Italy) is clearly visible from the modelling results.

The current volatility of European gas prices can affect the decarbonization agenda both in positive and negative ways. On the one hand, high gas prices can support switching and speed up the decarbonization agenda. There is already a strong push to use the post-COVID recovery funds for energy efficiency and fuel switching in the heating system. On the other hand, the partial or complete cessation of Russian gas supplies can result in regionally decoupled gas prices, gas to coal switch in the power sector, even with LNG deliveries returning to Europe. Near-term congestion might trigger gas infrastructure PCI investments that become stranded assets in the long run. Therefore the EU should better focus on demand adjustment and switching gas to renewables instead of infrastructure investments in fossil fuels.

Table 4
Evaluating the effects of strategic storage.

Storage obligation	A	B	C	D	E	F	G	H
	Strategic stocks withdrawal	Price effect	Cost (energy, 20EUR/MWh)	Cost (storage fees)	Benefit	Value of storage if withdrawal occurs in		
	TWh/yr	EUR/MWh	MEUR	MEUR	MEUR	1 year	2 years	3 years
						MEUR	MEUR	MEUR
current	8	−2,49	167	8	94	−81	−136	−160
5% strategic stock	41	−6,15	822	41	1201	339	−303	−544
10% strategic stock	72	−7,74	1444	72	1694	177	−742	−1096
15% strategic stock	103	−15,16	2067	103	4093	1923	−227	−1012
20% strategic stock	134	−26,02	2680	134	7885	5071	994	−454

Table 5
Modelled utilization and welfare effects of PCI projects.

PCI number	Short name	Utilization modelled as a standalone project	Modelled benefits	Annualized investment cost	Net benefits	Benefit/Cost ratio
		%	MEUR	MEUR	MEUR	
5.19	MT-IT	67%	114	22	92	5.2
6.2.13	SK-HU	0%	0	11	−11	0.0
6.8.1	IGB	3%	10	15	−6	0.6
6.8.2	—	—	—	—	—	—
6.8.3	IBS	39%	−1	5	−6	0.1
6.20.2	Storage BG	23%	1	14	−14	0.0
6.20.3	Storage GR	100%	10	20	−10	0.5
6.20.4	Storage RO 1	66%	0	6	−5	0.1
6.20.7	Storage RO 2	62%	0	9	−8	0.1
6.24.4	BRUA phase 2	77%	161	29	132	5.6
6.26.1	HR-SI	26%	114	5	109	23.4
6.27	LNG PL	100%	455	13	442	36.2
7.3	EastMed	23%	307	333	−26	0.9
7.3.3	Poseidon	36%	459	218	241	2.1
7.3.4	—	—	—	—	—	—
7.5	LNG CY	0%	0	17	−17	0.0
8.2.1	LT-LV	47%	1	2	−1	0.4
8.2.4	LV storage	84%	0	6	−6	0.0
8.3.1	—	—	—	—	—	—
8.3.2	Baltic pipe	56%	813	46	767	17.7
	All PCI projects	—	978	769	392	1.5

Table 6

Weighted yearly average prices and standard deviation for the EU27.

	REF	1A	1B	2	3a	3b	3c	3d	3e	4
		NS2	UA transit	Demand decrease	Strategic storage					PCI 5th list
					current	5%	10%	15%	20%	
EU27 weighted average price, EUR/MWh	49.81	42.29	42.03	41.76	49.7	49.4	49.2	48.4	47.3	44.8
Price change compared to REF (%)		−15.1%	−15.6%	−16.2%	−0.2%	−0.8%	−1.2%	−2.8%	−5.0%	−10.1%
Weighted standard deviation, EUR/MWh	5.76	2.34	1.97	3.01	5.6	5.4	5.3	5.2	5.1	1.7
Relative weighted standard deviation, %	12%	6%	5%	7	11%	11%	11%	11%	11%	4%

CRedit authorship contribution statement

Péter Kotek: Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Software. **Adrienn Selei:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Software. **Borbála Takácsné Tóth:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Balázs Felsmann:** Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Annex 1 Natural gas projects of the 5th PCI list

Priority Corridor	PCI number	PCI description	Short name
NSI West Gas	5.19	Connection of Malta to the European gas network — pipeline interconnection with Italy at Gela	MT-IT
NSI East Gas	6.2.13	Development and enhancement of transmission capacity of Slovak-Hungarian interconnector	SK-HU
	6.8.1	Interconnection Greece — Bulgaria [currently known as "IGB"] between Komotini (EL) and Stara Zagora (BG) and compressor station at Kipi (EL)	IGB
	6.8.2	Rehabilitation, modernization and expansion of the Bulgarian transmission system	–
	6.8.3	Gas interconnection Bulgaria — Serbia [currently known as "IBS"]	IBS
	6.20.2	Chiren UGS expansion (BG)	Storage BG
	6.20.3	South Kavala UGS facility and metering and regulating station (EL)	Storage GR
	6.20.4	Depomures storage in Romania	Storage RO
	6.20.7	Bilciuresti underground gas storage	1 Storage RO
	6.24.4	ROHU/BRUA –2nd phase, including: Expansion of the transmission capacity in Romania from Recas to Horia towards Hungary up to 4.4 bcm/a and expansion of the compressor stations in Podisor, Bibesti and Jupa - Black Sea shore — Podișor (RO) pipeline for taking over the Black sea gas - Romanian-Hungarian reverse flow: Hungarian section 2nd stage compressor station at Csanádpalota (HU)	BRUA phase 2
	6.26.1	Cluster Croatia — Slovenia at Rogatec, including: - Interconnection Croatia — Slovenia (Lučko — Zabok - Rogatec) - Compressor station Kidričevo, 2nd phase of upgrade (SI) - Upgrade of Rogatec interconnection	HR-SI
	6.27	LNG Gdansk (PL)	LNG PL
SGC	7.3	7.3.1 Pipeline from the East Mediterranean gas reserves to Greece mainland via Cyprus and Crete [currently known as "EastMed Pipeline"], with metering and regulating station at Megalopoli	Eastmed
	7.3.3	Offshore gas pipeline connecting Greece and Italy [currently known as "Poseidon Pipeline"]	Poseidon
	7.3.4	Reinforcement of internal transmission capacities in Italy, including reinforcement of the South-North internal transmission capacities [currently known as "Adriatic Line"] and reinforcement of internal transmission capacities in Apulia region [Matagiola - Massafra pipeline]	–
	7.5	Development of gas infrastructure in Cyprus [currently known as "Cyprus Gas2EU"]	LNG CY
BEMIP Gas	8.2.1	Enhancement of Latvia — Lithuania interconnection	LT-LV
	8.2.4	Enhancement of Inčukalns Underground Gas Storage (LV)	LV storage
	8.3.1	Reinforcement of Nybro — Poland/Denmark Interconnection	–
	8.3.2	Poland–Denmark interconnection	Baltic pipe

Annex 2. Capacity of natural gas pipeline interconnectors, GWh/day

Table 7

Capacity of natural gas pipeline interconnectors, GWh/day

Pipeline interconnector capacity							
	GWh/day		GWh/day		GWh/day		GWh/day
AT-DE	548	DE-CH	318	HU-RO	52	RS-BA	18
AT-HU	153	DE-CZ	2072	HU-RS	142	RS-HU	188
AT-IT	1149	DE-DK	167	HU-SK	51	RU-AZ	464
AT-SI	113	DE-FR	620	HU-UA	207	RU-BY	1201
AT-SK	247	DE-LU	38	IR-AM	63	RU-DE	1792
AZ-GE	1200	DE-NL	503	IR-TR	291	RU-EE	214
BE-DE	290	DE-PL	234	IT-AT	193	RU-FI	220
BE-FR	620	DK-DE	91	IT-CH	441	RU-GE	140
BE-LU	49	DZ-ES	732	IT-GR	158	RU-LV	179
BE-NL	271	DZ-IT	1150	IT-SI	28	RU-TR	1313
BE-UK	803	EE-FI	72	LT-LV	68	RU-UA	7620
BG-GR	117	EE-LV	252	LV-EE	178	SI-HR	54
BG-MK	20	ES-FR	224	LV-LT	65	SI-IT	21
BG-RO	177	ES-PT	144	LY-IT	440	SK-AT	1570
BG-RS	395	FI-EE	72	NL-BE	795	SK-CZ	400
BG-TR	477	FR-BE	270	NL-DE	536	SK-HU	127
BY-LT	325	FR-CH	260	NL-UK	494	SK-UA	416
BY-PL	1476	FR-ES	165	NO-BE	488	TR-BG	567
BY-UA	956	GE-AM	119	NO-DE	1240	TR-GR	380
CH-DE	173	GE-TR	954	NO-FR	570	UA-HU	517
CH-FR	100	GR-AL	40	NO-NL	964	UA-MD	94
CH-IT	635	GR-BG	47	NO-UK	1499	UA-PL	136
CZ-DE	1242	GR-IT	291	PL-DE	932	UA-RO	1114
CZ-PL	28	GR-TR	331	PL-UA	136	UA-SK	2278
CZ-SK	1247	HR-HU	14	PT-ES	80	UK-BE	652
DE-AT	383	HR-SI	8	RO-BG	751	UK-IE	387
DE-BE	401	HU-HR	78	RO-HU	53		

Annex 3 Detailed mathematical description of EGMM model

Indices

- Seasons: $s = 1, \dots, S (= 12)$ months, most likely aligned with the gas storage year.
- Markets: $m = 1, \dots, M$. Third countries (e.g. Russia) are not treated as markets.
- Non-default demand sectors: $d = 1, \dots, D$. (Consumption in the default demand sector in each market is a derived variable to ensure that the physical energy balance is always fulfilled. Each market has exactly one default demand sector and any nonnegative number of non-default demand sectors.)
- Producers: $p = 1, \dots, P$. Local production only.
- Pipelines and LNG connections: $f = 1, \dots, F$. Each direction has a separate index.
- Storages: $g = 1, \dots, G$.
- Take-or-pay forward contracts: $c = 1, \dots, C$. Import from third countries or transit through the region.
- Flow-limit combinations: $k = 1, \dots, K$.

“Pointers”

$\Delta_{md} = 1$ if non-default demand sector d is in market m , 0 otherwise. $\Pi_{mp} = 1$ if producer p is in market m , 0 otherwise. $\Gamma_{mg} = 1$ if storage g is in market m , 0 otherwise. $\Phi_{mf} = 1$ if the direction of connection f is into market m , -1 if it is out of market m , and 0 otherwise. Ψ_{kf} is the weight of the flow on connection f in flow-limit combination k (typically either 0 or 1). $\Upsilon_k = 0$ if the flow-limit concerns the physical flow, and $\Upsilon_k = 1$ if the limit is on spot-traded quantities only. $0 \leq \Omega_{fc}^s \leq 1$ is the fraction of the TOP contract c that flows through connection f in season s (exogenous input parameter, sums to 1 across parallel routes).

Decision variables and associated constraints

- Consumption in the non-default demand sectors: $q_d^s [S \times D]$
 - Minimum/maximum consumption (may be different from 0/the horizontal intercept of the sectoral demand function): kq_d^s, Kq_d^s .
- Production: $e_p^s [S \times P]$
 - Production capacity: ke_p^s, Ke_p^s .

- Spot trade in the default direction: $t_f^s [S \times F]$
 - Spot trade restriction (if any): Kt_f^s .
- Backhaul trade: $b_f^s [S \times F]$
 - Backhaul capacity: Kb_f^s .
- Forward delivery: $d_c^s [S \times C]$ (up to the TOP monthly minimum), $D_c^s [S \times C]$ (from the TOP monthly minimum to the TOP monthly maximum)
 - TOP monthly min/max: Kd_c^s, KD_c^s . Upper limit on “cheap” and costly TOP deliveries.
- Injection: $i_g^s [S \times G]$
 - Injection capacity: Ki_g^s
- Withdrawal: $w_g^s [S \times G]$
 - Withdrawal capacity: Kw_g^s

Parameters

- Vertical intercept and absolute slope of the linear demand functions in the default demand sectors: $A_m^s, B_m^s > 0$.
- Vertical intercept and absolute slope of the linear demand functions in the non-default demand sectors: $\alpha_d^s, \gamma_d^s > 0$.
- Production costs: $ce_p^s \leq Ce_p^s$. Marginal costs at zero production and the maximum production level. If equality holds, marginal production costs are constant, otherwise they are linearly increasing from ce_p^s to Ce_p^s . Production costs also include a constant entry fee into the transmission system.
- Combined entry-exit fees in the default flow direction for spot trade: Ct_f^s .
- Combined entry-exit fees in the default flow direction for long-term contracts: Cc_f^s .
- Combined entry-exit fees for backhaul deliveries: Cb_f^s .
- Exit fee towards the gas distribution system where the default sector's consumption occurs: CQ_m^s .
- Exit fee towards the gas distribution system where the non-default sector's consumption occurs: CQ_d^s .
- Spot import/export prices: Pt_f^s . The price (cost) paid for spot imports, or received for exports. Counts with third countries only, zero on all internal borders! E.g. $Pt_{RU \rightarrow UA} > 0$ (import cost), $Pt_{SK \rightarrow AT} = 0$, $Pt_{GR \rightarrow TR} < 0$ (export benefit).
- Long-term import prices: Pd_c^s, PD_c^s
- Injection charges: Ci_g^s
- Withdrawal charges: Cw_g^s
- Maximum yearly production level (might be less than the sum of the months): Ke_p .
- Physical flow capacity: Kx_f^s, Kx_f^s . Minimum and maximum pipeline flow.
- Flow-limit combination upper constraints: Kc_k^s .
- Maximum backhaul ratio: Rb_f^s . (Maximum fraction of contractual deliveries on a pipeline that can be exploited by virtual reverse flow.)
- Working gas capacity: Kg_g
- Gas inventories: $0 \leq I_g^0, I_g^s \leq Kg_g$ (starting and minimum end-of-month)
- TOP yearly min/max: kd_c, KD_c . Lower and upper limit on the sum of all forward deliveries.

Derived variables

Physical flow

$$x_f^s = t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s)$$

Consumption in the default demand sector

$$Q_m^s = -\sum_d \Delta_{md} \cdot q_d^s + \sum_p \Pi_{mp} \cdot e_p^s + \sum_f \Phi_{mf} \cdot [x_f^s] + \sum_g \Gamma_{mg} \cdot (w_g^s - i_g^s)$$

or:

$$Q_m^s = -\sum_d \Delta_{md} \cdot q_d^s + \sum_p \Pi_{mp} \cdot e_p^s + \sum_f \Phi_{mf} \cdot \left[t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] + \sum_g \Gamma_{mg} \cdot (w_g^s - i_g^s)$$

Prices in the default demand sector

$$P_m^s(Q_m^s) = A_m^s - B_m^s \cdot Q_m^s$$

(linear inverse demand function).

Prices in the non-default demand sectors

$$P_d^s(q_d^s) = \alpha_d^s - \gamma_d^s \cdot q_d^s$$

(linear inverse demand function).

Production costs

$$C_p^s(e_p^s) = \frac{C e_p^s - c e_p^s}{2 \cdot K e_p^s} (e_p^s)^2 + c e_p^s \cdot e_p^s$$

(linear marginal costs).

Objective function

Welfare is given by gross consumer surplus minus the costs (and benefits) of consumption, production, storage and trade (including imports and exports with outside countries, which is where the benefits may arise):

$$\begin{aligned} W = \sum_s \beta^s & \left\{ \sum_m \left[\int_0^{Q_m^s} P_m^s(Q) dQ - C Q_m^s \cdot Q_m^s \right] \right. \\ & + \sum_d \left[\int_0^{q_d^s} p_d^s(q) dq - C q_d^s \cdot q_d^s \right] \\ & - \sum_p C_p^s(e_p^s) \\ & - \sum_g C i_g^s \cdot i_g^s - \sum_g C w_g^s \cdot w_g^s \\ & - \sum_f C c_f^s \cdot \left[\sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] - \sum_f C t_f^s \cdot t_f^s - \sum_f C b_f^s \cdot b_f^s \\ & \left. - \sum_f P t_f^s \cdot (t_f^s - b_f^s) - \sum_c P d_c^s \cdot d_c^s - \sum_c P D_c^s \cdot D_c^s \right\} \end{aligned}$$

β denotes the monthly discount factor.¹⁸ Substituting the inverse demand and cost functions:

$$\begin{aligned} W = \sum_s \beta^s & \left\{ \sum_m \left[(A_m^s - C Q_m^s) \cdot Q_m^s - \frac{B_m^s}{2} (Q_m^s)^2 \right] \right. \\ & + \sum_d \left[(\alpha_d^s - C q_d^s) \cdot q_d^s - \frac{\gamma_d^s}{2} (q_d^s)^2 \right] \\ & - \sum_p \left[\frac{C e_p^s - c e_p^s}{2 \cdot K e_p^s} (e_p^s)^2 + c e_p^s \cdot e_p^s \right] \\ & - \sum_g C i_g^s \cdot i_g^s - \sum_g C w_g^s \cdot w_g^s \\ & - \sum_f C c_f^s \cdot \left[\sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] - \sum_f C t_f^s \cdot t_f^s - \sum_f C b_f^s \cdot b_f^s \\ & \left. - \sum_f P t_f^s \cdot (t_f^s - b_f^s) - \sum_c P d_c^s \cdot d_c^s - \sum_c P D_c^s \cdot D_c^s \right\} \end{aligned}$$

¹⁸ Therefore $\beta^{12} = \frac{1}{1+r}$ where r is the yearly interest rate used for discounting.

Constraints (other than on the decision variables)

Consumption

Nonnegative consumption in the default demand sectors:

$$-\sum_d \Delta_{md} \cdot q_d^s + \sum_p \Pi_{mp} \cdot e_p^s + \sum_f \Phi_{mf} \cdot \left[t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] + \sum_g \Gamma_{mg} \cdot (w_g^s - i_g^s) \geq 0$$

Production

Upper yearly production limit:

$$\sum_s e_p^s \leq K e_p$$

Transportation

Lower pipeline capacity:

$$t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \geq k x_f^s \quad \forall s$$

Upper pipeline capacity:

$$t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \leq K x_f^s \quad \forall s$$

Combined flow-limits:

$$\sum_f \Psi_{kf} \cdot \left[t_f^s - b_f^s \right] + (1 - \Upsilon_k) \cdot \sum_f \Psi_{kf} \cdot \left[\sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] \leq K c_k^s \quad \forall s$$

Maximum virtual reverse flow as a fraction of contractual deliveries:

$$R b_f^s \cdot \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) - b_f^s \geq 0 \quad \forall s$$

Contracts

TOP yearly limits:

$$\sum_s d_c^s + \sum_s D_c^s \geq k d_c$$

$$\sum_s d_c^s + \sum_s D_c^s \leq K D_c$$

Storages

Minimum end-of-month storage levels (might often be zero; also takes care of end-of-year reloading):

$$I_g^0 + \sum_1^{\bar{s}} i_g^s - \sum_1^{\bar{s}} w_g^s \geq \bar{I}_g^s \quad \forall \bar{s} \in \{1, \dots, S\}$$

No overloaded storage in any month:

$$I_g^0 + \sum_1^{\bar{s}} i_g^s - \sum_1^{\bar{s}} w_g^s \leq K g_g \quad \forall \bar{s} \in \{1, \dots, S\}$$

The Lagrangian

$$\begin{aligned}
L = & \sum_s \beta^s \left\{ \sum_m \left[(A_m^s - CQ_m^s) \cdot Q_m^s - \frac{B_m^s}{2} (Q_m^s)^2 \right] \right. \\
& + \sum_d \left[(\alpha_d^s - Cq_d^s) \cdot q_d^s - \frac{\gamma_d^s}{2} (q_d^s)^2 \right] \\
& - \sum_p \left[\frac{Ce_p^s - ce_p^s}{2 \cdot Ke_p^s} (e_p^s)^2 + ce_p^s \cdot e_p^s \right] \\
& - \sum_g Ci_g^s \cdot i_g^s - \sum_g Cw_g^s \cdot w_g^s \\
& - \sum_f Cc_f^s \cdot \left[\sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] - \sum_f Ct_f^s \cdot t_f^s - \sum_f Cb_f^s \cdot b_f^s \\
& \left. - \sum_f Pt_f^s \cdot (t_f^s - b_f^s) - \sum_c Pd_c^s \cdot d_c^s - \sum_c PD_c^s \cdot D_c^s \right\} \\
& + \sum_s \sum_m \delta_m^s \left(- \sum_d \Delta_{md} \cdot q_d^s + \sum_p \Pi_{mp} \cdot e_p^s + \sum_f \Phi_{mf} \cdot \left[t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] \right) \\
& + \sum_g \Gamma_{mg} \cdot (w_g^s - i_g^s) \\
& + \sum_p \varepsilon_p \left(Ke_p - \sum_s e_p^s \right) \\
& + \sum_s \sum_f \phi_f^s \left(t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) - kx_f^s \right) \\
& + \sum_s \sum_f \varphi_f^s \left\{ Kx_f^s - t_f^s + b_f^s - \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right\} \\
& + \sum_s \sum_k \kappa_k^s \left\{ Kc_k^s - \sum_f \Psi_{kf} \cdot (t_f^s - b_f^s) - (1 - \Upsilon_k) \cdot \sum_f \Psi_{kf} \cdot \left[\sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] \right\} \\
& + \sum_c \tau_c \left(\sum_s d_c^s + \sum_s D_c^s - kd_c \right) \\
& + \sum_c \theta_c \left(KD_c - \sum_s d_c^s - \sum_s D_c^s \right) \\
& + \sum_s \sum_f \rho_f^s \left[Rb_f^s \cdot \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) - b_f^s \right] \\
& + \sum_g \sum_{\bar{s}=1}^{\bar{S}} \mu_g^{\bar{s}} \left(I_g^0 + \sum_1^{\bar{s}} i_g^{\bar{s}} - \sum_1^{\bar{s}} w_g^{\bar{s}} - I_g^{\bar{s}} \right) \\
& + \sum_g \sum_{\bar{s}=1}^{\bar{S}} L_g^{\bar{s}} \left(Kg_g - I_g^0 - \sum_1^{\bar{s}} i_g^{\bar{s}} + \sum_1^{\bar{s}} w_g^{\bar{s}} \right)
\end{aligned}$$

Lower and upper constraints on the decision variables are not explicitly included in the Lagrangian, but are taken into account in the MLCP solution algorithm.

First derivatives of the Lagrangian with respect to decision variables

$$\frac{\partial L}{\partial q_d^s} = \beta^s \left[- \sum_m \Delta_{md} \cdot (A_m^s - CQ_m^s) + \sum_m \Delta_{md} \cdot B_m^s \cdot Q_m^s + (\alpha_d^s - Cq_d^s) - \gamma_d^s \cdot q_d^s \right] - \sum_m \delta_m^s \cdot \Delta_{md}$$

$$\frac{\partial L}{\partial e_p^s} = \beta^s \left[\sum_m \Pi_{mp} \cdot (A_m^s - CQ_m^s) - \sum_m \Pi_{mp} \cdot B_m^s \cdot Q_m^s - \frac{Ce_p^s - ce_p^s}{Ke_p^s} e_p^s - ce_p^s \right] + \sum_m \delta_m^s \Pi_{mp} - \varepsilon_p$$

$$\frac{\partial L}{\partial t_f^s} = \beta^s \left[\sum_m \Phi_{mf} \cdot (A_m^s - CQ_m^s) - \sum_m \Phi_{mf} \cdot B_m^s \cdot Q_m^s - Ct_f^s - Pt_f^s \right] + \sum_m \delta_m^s \cdot \Phi_{mf} + \phi_f^s - \varphi_f^s - \sum_k \Psi_{kf} \cdot \kappa_k^s$$

$$\frac{\partial L}{\partial b_f^s} = \beta^s \left[- \sum_m \Phi_{mf} \cdot (A_m^s - CQ_m^s) + \sum_m \Phi_{mf} \cdot B_m^s \cdot Q_m^s - Cb_f^s + Pt_f^s \right] - \sum_m \delta_m^s \cdot \Phi_{mf} - \phi_f^s + \varphi_f^s + \sum_k \Psi_{kf} \cdot \kappa_k^s - \rho_f^s$$

$$\begin{aligned} \frac{\partial L}{\partial d_c^s} = & \beta^s \left[\sum_m \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) \cdot (A_m^s - CQ_m^s) - \sum_m \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) \cdot B_m^s \cdot Q_m^s - \sum_f Cc_f^s \cdot \Omega_{fc}^s - Pd_c^s \right] \\ & + \sum_m \delta_m^s \cdot \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) + \sum_f \phi_f^s \cdot \Omega_{fc}^s - \sum_f \varphi_f^s \cdot \Omega_{fc}^s \\ & - \sum_k (1 - \Upsilon_k) \cdot \kappa_k^s \cdot \left(\sum_f \Psi_{kf} \cdot \Omega_{fc}^s \right) + \tau_c - \theta_c + \sum_f \rho_f^s \cdot Rb_f^s \cdot \Omega_{fc}^s \end{aligned}$$

$$\begin{aligned} \frac{\partial L}{\partial D_c^s} = & \beta^s \left[\sum_m \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) \cdot (A_m^s - CQ_m^s) - \sum_m \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) \cdot B_m^s \cdot Q_m^s - \sum_f Cc_f^s \cdot \Omega_{fc}^s - PD_c^s \right] \\ & + \sum_m \delta_m^s \cdot \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) + \sum_f \phi_f^s \cdot \Omega_{fc}^s - \sum_f \varphi_f^s \cdot \Omega_{fc}^s \\ & - \sum_k (1 - \Upsilon_k) \cdot \kappa_k^s \cdot \left(\sum_f \Psi_{kf} \cdot \Omega_{fc}^s \right) + \tau_c - \theta_c + \sum_f \rho_f^s \cdot Rb_f^s \cdot \Omega_{fc}^s \end{aligned}$$

$$\frac{\partial L}{\partial i_g^s} = \beta^s \left[- \sum_m \Gamma_{mg} \cdot (A_m^s - CQ_m^s) + \sum_m \Gamma_{mg} \cdot B_m^s \cdot Q_m^s - Ci_g^s \right] - \sum_m \delta_m^s \cdot \Gamma_{mg} + \sum_{\bar{s}=s}^S \mu_{\bar{g}}^{\bar{s}} - \sum_{\bar{s}=s}^S \nu_{\bar{g}}^{\bar{s}}$$

$$\frac{\partial L}{\partial w_g^s} = \beta^s \left[\sum_m \Gamma_{mg} \cdot (A_m^s - CQ_m^s) - \sum_m \Gamma_{mg} \cdot B_m^s \cdot Q_m^s - Cw_g^s \right] + \sum_m \delta_m^s \cdot \Gamma_{mg} - \sum_{\bar{s}=s}^S \mu_{\bar{g}}^{\bar{s}} + \sum_{\bar{s}=s}^S \nu_{\bar{g}}^{\bar{s}}$$

Complementarity conditions in the MLCP

The first set of brackets on the left hand side contains linear combinations of the variables, while the second set contains constants (as in: $Ax + b \geq 0, x \geq 0, (\perp)$).

$$\begin{aligned} & \left\{ \beta^s \cdot \gamma_d^s \cdot q_d^s - \beta^s \cdot \sum_m \Delta_{md} \cdot B_m^s \cdot Q_m^s + \sum_m \delta_m^s \cdot \Delta_{md} \right\} \\ & + \left\{ \beta^s \cdot Cq_d^s - \beta^s \cdot \alpha_d^s + \beta^s \cdot \sum_m \Delta_{md} \cdot (A_m^s - CQ_m^s) \right\} \geq 0 \quad q_d^s \geq kq_d^s \quad (\perp) \\ & \left\{ \beta^s \cdot \sum_m \Pi_{mp} \cdot B_m^s \cdot Q_m^s + \beta^s \cdot \frac{Ce_p^s - ce_p^s}{Ke_p^s} \cdot e_p^s - \sum_m \delta_m^s \Pi_{mp} + \varepsilon_p \right\} + \left\{ \beta^s \cdot ce_p^s - \beta^s \cdot \sum_m \Pi_{mp} \cdot (A_m^s - CQ_m^s) \right\} \geq 0 \quad e_p^s \geq ke_p^s \quad (\perp) \\ & \left\{ \beta^s \cdot \sum_m \Phi_{mf} \cdot B_m^s \cdot Q_m^s - \sum_m \delta_m^s \cdot \Phi_{mf} - \phi_f^s + \varphi_f^s + \sum_k \Psi_{kf} \cdot \kappa_k^s \right\} \\ & + \left\{ \beta^s \cdot Ct_f^s + \beta^s \cdot Pt_f^s - \beta^s \cdot \sum_m \Phi_{mf} \cdot (A_m^s - CQ_m^s) \right\} \geq 0 \quad t_f^s \geq 0 \quad (\perp) \\ & \left\{ - \beta^s \cdot \sum_m \Phi_{mf} \cdot B_m^s \cdot Q_m^s + \sum_m \delta_m^s \cdot \Phi_{mf} + \phi_f^s - \varphi_f^s - \sum_k \Psi_{kf} \cdot \kappa_k^s + \rho_f^s \right\} \\ & + \left\{ \beta^s \cdot Cb_f^s - \beta^s \cdot Pt_f^s + \beta^s \cdot \sum_m \Phi_{mf} \cdot (A_m^s - CQ_m^s) \right\} \geq 0 \quad b_f^s \geq 0 \quad (\perp) \end{aligned}$$

$$\begin{aligned}
& \left\{ \beta^s \cdot \sum_m \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) \cdot B_m^s \cdot Q_m^s - \sum_m \delta_m^s \cdot \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) - \sum_f \phi_f^s \cdot \Omega_{fc}^s + \sum_f \varphi_f^s \cdot \Omega_{fc}^s \right. \\
& \quad \left. + \sum_k (1 - \Upsilon_k) \cdot \kappa_k^s \cdot \left(\sum_f \Psi_{kf} \cdot \Omega_{fc}^s \right) - \tau_c + \theta_c - \sum_f \rho_f^s \cdot R b_f^s \cdot \Omega_{fc}^s \right\} \\
& \quad + \left\{ -\beta^s \cdot \sum_m \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) \cdot (A_m^s - C Q_m^s) + \beta^s \cdot \sum_f C c_f^s \cdot \Omega_{fc}^s + \beta^s \cdot P d_c^s \right\} \geq 0 \\
& \quad d_c^s \geq 0 \quad (\perp)
\end{aligned}$$

$$\begin{aligned}
& \left\{ \beta^s \cdot \sum_m \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) \cdot B_m^s \cdot Q_m^s - \sum_m \delta_m^s \cdot \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) - \sum_f \phi_f^s \cdot \Omega_{fc}^s + \sum_f \varphi_f^s \cdot \Omega_{fc}^s \right. \\
& \quad \left. + \sum_k (1 - \Upsilon_k) \cdot \kappa_k^s \cdot \left(\sum_f \Psi_{kf} \cdot \Omega_{fc}^s \right) - \tau_c + \theta_c - \sum_f \rho_f^s \cdot R b_f^s \cdot \Omega_{fc}^s \right\} \\
& \quad + \left\{ -\beta^s \cdot \sum_m \left(\sum_f \Phi_{mf} \cdot \Omega_{fc}^s \right) \cdot (A_m^s - C Q_m^s) + \beta^s \cdot \sum_f C c_f^s \cdot \Omega_{fc}^s + \beta^s \cdot P D_c^s \right\} \geq 0 \\
& \quad D_c^s \geq 0 \quad (\perp)
\end{aligned}$$

$$\begin{aligned}
& \left\{ -\beta^s \cdot \sum_m \Gamma_{mg} \cdot B_m^s \cdot Q_m^s + \sum_m \delta_m^s \cdot \Gamma_{mg} - \sum_{\bar{s}=s}^S \mu_g^{\bar{s}} + \sum_{\bar{s}=s}^S \nu_g^{\bar{s}} \right\} \\
& \quad + \left\{ \beta^s \cdot C i_g^s + \beta^s \cdot \sum_m \Gamma_{mg} \cdot (A_m^s - C Q_m^s) \right\} \geq 0 \quad i_g^s \geq 0 \quad (\perp)
\end{aligned}$$

$$\begin{aligned}
& \left\{ \beta^s \cdot \sum_m \Gamma_{mg} \cdot B_m^s \cdot Q_m^s - \sum_m \delta_m^s \cdot \Gamma_{mg} + \sum_{\bar{s}=s}^S \mu_g^{\bar{s}} - \sum_{\bar{s}=s}^S \nu_g^{\bar{s}} \right\} \\
& \quad + \left\{ \beta^s \cdot C w_g^s - \beta^s \cdot \sum_m \Gamma_{mg} \cdot (A_m^s - C Q_m^s) \right\} \geq 0 \quad w_g^s \geq 0 \quad (\perp)
\end{aligned}$$

$$\begin{aligned}
& \left\{ -\sum_d \Delta_{md} \cdot q_d^s + \sum_p \Pi_{mp} \cdot e_p^s + \sum_f \Phi_{mf} \cdot \left[t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] + \sum_g \Gamma_{mg} \cdot (w_g^s - i_g^s) \right\} \\
& \quad \geq 0 \quad \delta_m^s \geq 0 \quad (\perp)
\end{aligned}$$

$$\left\{ -\sum_s e_p^s \right\} + \{K e_p\} \geq 0 \quad e_p \geq 0 \quad (\perp)$$

$$\left\{ t_f^s - b_f^s + \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right\} + \{ -k x_f^s \} \geq 0 \quad \phi_f^s \geq 0 \quad (\perp)$$

$$\left\{ -t_f^s + b_f^s - \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right\} + \{K x_f^s\} \geq 0 \quad \varphi_f^s \geq 0 \quad (\perp)$$

$$\left\{ -\sum_f \Psi_{kf} \cdot (t_f^s - b_f^s) - (1 - \Upsilon_k) \cdot \sum_f \Psi_{kf} \cdot \left[\sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) \right] \right\} + \{K c_k^s\} \geq 0 \quad \kappa_k^s \geq 0 \quad (\perp)$$

$$\left\{ \sum_s d_c^s + \sum_s D_c^s \right\} + \{ -k d_c \} \geq 0 \quad \tau_c \geq 0 \quad (\perp)$$

$$\left\{ -\sum_s d_c^s - \sum_s D_c^s \right\} + \{K D_c\} \geq 0 \quad \theta_c \geq 0 \quad (\perp)$$

$$\left\{ R b_f^s \cdot \sum_c \Omega_{fc}^s \cdot (d_c^s + D_c^s) - b_f^s \right\} \geq 0 \quad \rho_f^s \geq 0 \quad (\perp)$$

$$\left\{ \sum_1^{\bar{s}} i_g^s - \sum_1^{\bar{s}} w_g^s \right\} + \{I_g^0 - I_g^{\bar{s}}\} \geq 0 \quad \mu_g^{\bar{s}} \geq 0 \quad (\perp)$$

$$\left\{ -\sum_1^{\bar{s}} i_g^s + \sum_1^{\bar{s}} w_g^s \right\} + \{K g_g - I_g^0\} \geq 0 \quad \nu_g^{\bar{s}} \geq 0 \quad (\perp)$$

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