

Nord Stream 2: A prelude to war

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ABSTRACT

To understand the impact of keeping Nord Stream 2 off the map, we model the European natural gas market from the point of view of supply security. Focusing on the network aspects, we propose a novel framework to measure supply security, combining a linear programming approach with a risk assessment technique, expected shortfall (ES) borrowed from finance, particularly suited to measure extreme risk, such as the risk of failing pipelines.

Shifting Russian gas exports from Ukraine to Nord Stream 2 increases risks for South-Eastern Europe, and the Trans-Anatolian and Trans-Adriatic Pipelines can only partially alleviate these changes.

1. Introduction

The leaders of the European Union have just agreed on another sanction package, drastically reducing oil imports from Russia for its invasion of its sovereign neighbour, Ukraine. This move aims to stop financing war and reduce the risk of abrupt, politically motivated supply drops. The agreement was difficult due to Europe's high reliance on Russian energy sources and differences in substitutability across the member states of the European Union.

The substitutability issue seems to stem from three causes. Firstly, some Central European countries (Austria, Czech Republic, Slovakia, Hungary) are landlocked; secondly, past efforts to diversify supply sources have been abandoned in favour of other projects, such as Nabucco in favour of Nord Stream, or diverted, such as the Southern Gas Corridor eventually going to Italy via the Trans-Adriatic Pipeline. At last, current network transmission capacities are inadequate to transport new sources to every part of the continent. In this paper, we deal with the latter issue.

Most of Europe's gas demand is transmitted via an extensive pipeline network. The high fixed costs imply tight transmission capacities and that the dropping out of any of the pipelines or hubs can immediately lead to congestion and eventual shortages at the receiving end.

One would think that such a fundamental infrastructure is somehow fault-proof, but this is certainly not the case. The risks caused

by *source* or *facility-dependence* include strikes by Norwegian platform workers [1–3], the bombing of an on-shore section of a pipeline in Algeria [4] causing long-term concerns of similar attacks, the shutting down of the Arun liquefaction plant in Indonesia for several months due to political instability [5], the 2017 Baumgarten incident [6], an explosion that led to a state of emergency in Italy [7,8] and the general political and commercial risks of trading with rogue countries. For *transit-dependence*, Stern [9] had already warned about Russian transits via Ukraine, and the 2009 January crisis affected 18 countries, causing unprecedented outages [10]. The 2021 closures of the Brotherhood and Yamal pipelines may already have contributed to the current energy crisis, ultimately caused by the Russian invasion of Ukraine and the ensuing sanctions and responses. In the absence of data for the post-war trades, we focus on the preceding network developments and their effects on supply security.

Ours is not the first paper to study supply security (or security of supply, SOS) and transport security in particular. Already before the 2009 Russia–Ukraine gas dispute, Weisser [11] put out a manifesto warning of the risk of limited sourcing and a possible shock comparable to the Oil Crisis, calling for action. Despite efforts to increase connectivity and regulate the market, the interest in the *supply security* of natural gas to various markets remains [12–15]. These studies take many different aspects into account. Cabalu [12] considers gas supply

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interruptions, volatile gas prices, transportation and distribution bottlenecks and a growing reliance on long-distance imports, exploring the vulnerability of certain Asian countries. Stern [9] distinguishes between source-, transit- and facility-dependence as the primary sources of risks in an import-dependent country. None of these papers addresses the issue of war explicitly. Only Vainio [16] – in her research completed at the NATO Energy Security Centre of Excellence – mentions that the green transition to renewable energy sources may cause a major loss of income for Russia and that Russia “may behave aggressively in the markets to maintain their dominant player position”. Su et al. [17] also mention that “renewable energy is capable of accommodating new powers in the international political system” – we add: and demoting others.

Our approach follows Scotti and Vedres [18] and Praks et al. [19] in focusing on the network rather than just the availability of sources. The effect of disruptions is scrutinised using the simplified pipeline network model [20] and an intuitive model to determine the optimal flows assuming rational payoff-maximising agents. We examine the exposure of different countries to transport disruptions and – not unlike ENTSG [21] – the effect of network developments thereon: beyond a baseline scenario, considering a closing of the Ukrainian corridor, the completion of Nord Stream 2 as well as combined scenarios. These are currently the most neuralgic points in the European network development scene, see, e.g. [22–25]. We include the Trans-Anatolian and Trans-Adriatic Pipelines (TANAP and TAP) in the analysis. The more recent TurkStream and Balkan Stream are not yet present in our data set. At last, we consider seasonal differences corresponding to a (negative) supply shock in the winter and a positive demand shock in the summer, when full storage can help temporary shortages.

While several indicators have been introduced for supply security for natural gas and energy in general [26–28], our approach and indicator are new. Acknowledging VaR’s inability to capture ‘tail risk’ [29], we use *expected shortfall* as it is a spectral risk measure, therefore theoretically more suitable [30,31]. It also bears the recommendation of the Basel Committee [32] and is generally becoming more popular to study risk.

The structure of the paper is as follows. First, we introduce our model, elucidating its limitations. Next, we discuss the data collected and finally present and discuss the main findings.

2. Model

In the absence of disruptions, calculating the gas supply of a country or region is a simple optimisation task, where gas is purchased from the available sources taking prices, transportation costs and capacity constraints into account. First, this optimisation problem is formally described along with the assumptions made and an example in Section 2.5. Then our notion of supply security is explained, clarifying the winter and summer setups. We end the section with an example.

2.1. Optimal flows

First, we determine optimal gas flows in the network following Cserssik et al. [20].

Consider the following optimisation problem:

$$\begin{aligned} \min_{x \in \mathbb{R}^L} \{cx + p(d + Ax)\} \quad \text{such that} \\ 0 \leq x \leq q, \text{ and} \\ -d \leq Ax \leq s, \end{aligned} \quad (2.1)$$

where, N and L are the sets of nodes and (directed) pipelines; $x \in \mathbb{R}_+^L$ is the flow vector, $q \in \mathbb{R}_+^L$ is the vector of transmission capacities, $c \in \mathbb{R}_+^L$ is the cost of transferring a unit gas over pipeline $\ell \in L$, d, s , and $p \in \mathbb{R}_+^N$ are the demand, supply, and price vectors, respectively, and $A \in \{-1, 0, 1\}^{N \times L}$ is the incidence matrix such that $A_{ij} = 1$ and $A_{ij} = -1$ if pipeline j starts/ends in node i .

In this problem, we minimise the total transportation and sourcing costs while observing supply, demand and transmission capacity constraints. The price vector shows, for the producers, the price of supplied gas and, for the consumers, the cost of reducing demand: an alternative energy source or the loss due to gas shortage. Consumers taking gas out of the network *reduce* such substitution costs.

More specifically, the term, Ax , shows the net in- or outflow of a node. If a component of Ax is negative, it means that the corresponding node has a net inflow. The inflow cannot be larger than the demand of a node hence $-d \leq Ax$. For producers, the demand is zero (the corresponding components of Ax are non-negative), so they can only have an outflow. Supply cannot exceed the production capacity, hence $Ax \leq s$. For consumers, supply is zero. The components of $d + Ax$ that correspond to suppliers are the same as Ax since their demand is zero. Thus, for suppliers, $p(d + Ax)$ represents the total cost of production — the unit cost is multiplied by the outflow. Consumers have an inflow; thus, the corresponding components of $d + Ax$ show how much demand is unsatisfied, which is multiplied by the alternative cost. Note that the pd term is a constant; hence it can be omitted from the optimisation. We chose to include it in the objective function to make the linear program more transparent.

2.2. Modelling assumptions

We consider an *idealised network*. In this network, countries/regions are points, and all demand or supply occurs at this node. We ignore national networks and rule out the possibility of multiple national hubs. Since our focus is on failing pipelines, the first simplification is crucial, and our results must be studied with its limitations in mind. It is safe to assume that in healthy networks, no national bottlenecks restrict gas flows, but there may be scenarios where national networks are unprepared for unusual flow directions.

We do not explicitly model *storage* or the seasonal variation of demand. We do, however, study the effect of disruptions in two extreme cases: when storage is full or depleted (end of summer and winter scenario setups, respectively). In the first case, the temporary supply shock can be spread over a more extended time period, while in winter, the healthy part of the network must accommodate what seems like a demand shock. We plan to elaborate on the role of storage in a further study.

When we calculate the optimal flow for each region, Ax gives the inflow into or outtake from the network. Naturally, we cannot have both. Most countries are, however, both producers and consumers: we take their *net positions*. There is a hidden assumption here: local production is used to satisfy local demand despite cheaper sources available in the network. We argue that the limited gas resources of importing countries would not be exported for strategic reasons.

Prices are fixed and are the same for each consumer. To study an oligopolistic competition over a network with transmission capacity constraints is a difficult open problem and certainly beyond the scope of this paper.

The cost of substitution – the “price” for consumers – is assumed to be fixed, high, and uniform. This assumption is consistent with demand being inelastic in the short run. The calculations are naturally sensitive to a picked value. Moreover, as a referee pointed out, minor differences in pipeline length may lead to drastic discrimination among consumers during shortages. Adding real substitution curves for each region could produce more accurate numerical results. On the other hand, in a thorough sensitivity analysis, Sziklai et al. [24] found the results surprisingly robust. Another referee drew our attention to the interaction between different energy sources. Renewables, including photovoltaic energy [33] can be used to produce electricity, which, in turn, can be used to produce hydrogen. Hydrogen can then be mixed with natural gas in the pipeline networks, effectively adding to the local gas production [34,35]

We assume that *pipelines are bidirectional* and have the same transfer capacity in both directions and are therefore represented by a pair of connections with the same transmission capacities. In reality, most pipelines have been designed to carry gas in one direction and reversing the flow is either not possible (in the short run) or only with substantially reduced capacities. Optimal solutions have pipelines used in only one direction: the non-negligible transmission costs rule out optimal flows with, for example, a shared bidirectional operation. It is reasonable to assume that the calculated flows match pipeline directions and that network disruptions affect the flow direction mostly in interconnectors that are designed to have reversible flows.

Gas quality is assumed to be uniform. This simplification would be difficult to remove.

This simple optimisation problem helps us to find the optimal flows. This optimal flow is not necessarily the same as the one we see in actual transfer data: we do not take price fluctuations, temporary disruptions due to, for example, planned maintenance, or a strategic diversification of sources into account. Also, it does not generally tell us the source and route of the gas and, thereby, the payoff for the individual consumers. Obtaining these payoffs is nontrivial when different supply paths — with different generalised prices — intersect. We assume that incoming gas flows mix at each node, and the price outflows are the weighted average of the prices, where weights correspond to the different volumes of the flows. Since circular flows are eliminated to reduce costs, the optimal flows constitute a directed acyclic graph, and so this calculation is well-defined.

2.3. Supply security

Out of the many factors that affect supply security, our focus lies on the aspects related to the physical network: on disruptions that put one of the pipelines out of use, including political risks, natural disasters, technical failures but also sabotage and terrorism. EGI [36] documented 1411 pipeline-related incidents in the 50-years between 1970 and 2020. The listed incidents include primary failures (corrosion, construction or material, external effects such as constructions affecting the pipeline, etc.) with a decreasing probability currently at 0.126 per 1000 km-yrs. We must add the incidents targeting pumping stations or other additional infrastructure, not to mention the incidents that are due to sabotage or terrorism or the strategic closure of pipelines by operators. To evaluate such risks, we turn to models used in finance and the study and the design of electric power grids.

The so-called $N - 1$ contingency analysis evaluates the effects of an incident where one of the links drops out (double incidents have a negligible probability) and is a standard approach for electric networks to avoid cascading failures [37]. For natural gas networks, the closure of a pipeline increases congestion and may lead to shortages but does not directly affect the operation of other connections.

For the network nodes, that is, the countries, the effects may prove to be more drastic. In the optimal flow, supply is redirected to the remaining routes, increasing congestion along the affected pipelines, and some countries may find themselves without available gas sources. While a disruption increases the overall cost of supplying the network, players may be hardly or severely affected depending upon their connectedness. In rare cases, a player may even benefit from the change (see Section 2.5 for a detailed example).

We assume that each pipeline may fail with the same probability. Each failure is a state of the world with corresponding country payoffs, so that the latter can be seen as random variables. Our method can be generalised to accommodate pipeline-specific risks.

We evaluate these scenarios using a *risk measure* [38,39]. While risk is interpreted in many ways, we want to answer the question: how much must one eventually pay for the energy supply realising the possibility of pipeline failures? Risk aversion implies that we must go beyond a simple expected value, and we follow Artzner et al. [40] to find that a suitable risk measure must be coherent. Artzner et al.

[40] also discuss several risk indicators used in practice, including the popular value-at-risk (VaR) and conclude that only tail conditional expectation — nowadays known as expected shortfall (ES) — is a suitable risk measure. Danielsson et al. [41] go as far as claiming “Value-at-Risk can destabilise an economy and induce crashes when they would not otherwise occur” as “it does not measure the distribution or extent of risk in the tail, but only provides an estimate of a particular point in the distribution”. In light of the financial crisis, these concerns seem to have been well-founded [42].

Formally, the risk of a random payoff equals the (possibly negative) amount of cash that needs to be added to it to make it acceptable and is calculated as a weighted average of payoffs. We express the conservatism of the players by assigning higher weights to more critical scenarios. In other words, we use spectral risk measures [30]. Specifically, we employ the α -expected shortfall with $\alpha = 10\%$, calculated as the expected value of the worst 10% of scenarios; in our case, this refers to inspecting the disruptions that affect the player least favourably. The expected shortfall, unlike VaR, handles tail risk well, so it is more suitable to model stressed situations [43,44].

2.4. Seasonality

The European natural gas network exhibits a natural seasonality. As the gas is used for heating, among other services, consumption is higher in the winter than in the summer. Transmission capacities are often insufficient to cater to winter demands: storage is filled during the summer, and then, in the winter, the supply is supplemented from the storage. Note that storage is also used as a reserve to reduce the impact of incidents. We model this difference using the following two setups:

Winter Reserves are depleted, so any gas shortage must be immediately supplied from the network or from an alternative energy source.

Summer Gas shortages are compensated from the reserves, but these must be refilled, essentially converting a major supply shock into a smaller demand shock. For simplicity, we assume that refilling increases demand by 1/3 of the shortage but with a fixed network. The alternative source is only used if this increased demand cannot be met.

Our setups can be seen as simplifications of the three cases [21] considers: (i) a high demand winter, (ii) 2 weeks of exceptionally high demand, and (iii) a peak day of exceptionally high demand. The last case has relevance for the national networks, while the first two correspond to our winter and summer setups. On the other hand, our model is not driven by the exceptional nature of the demand (or supply) but rather a partial network failure and its consequences.

2.5. Example

Consider the example presented in Fig. 1 (left). We have five nodes and six pipelines connecting them — each represented by a pair of pipelines, one in each direction. Two of these nodes are producers, supplying at most 6 units of gas, $p_1 = 300$, $p_2 = 400$, and two are consumers, utilising 4 each. Node 3 has a balanced production/consumption pattern, and each node has an alternative energy source at $p_i = 600$.

The pipelines all have the same capacity $q = 3$. We assume that transportation costs are negligible but positive, $C_{ij} = \varepsilon > 0$ so that they do not enter the calculations but act as tie-breakers in favour of shorter routes. Formally,

$$d = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 4 \\ 4 \end{pmatrix}, s = \begin{pmatrix} 6 \\ 6 \\ 0 \\ 0 \\ 0 \end{pmatrix}, p = \begin{pmatrix} 300 \\ 400 \\ 600 \\ 600 \\ 600 \end{pmatrix}, \text{ and}$$

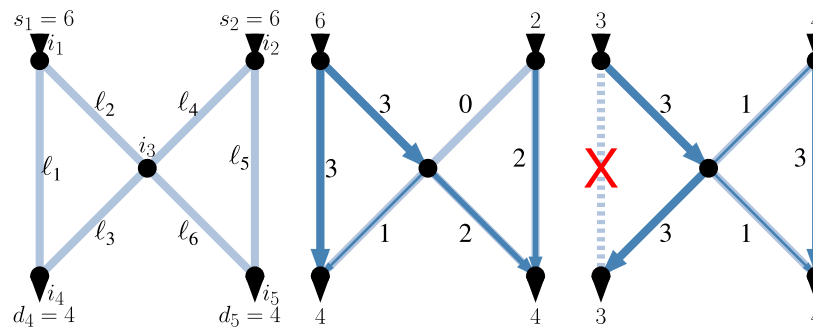


Fig. 1. A network with five nodes, its optimal and a disrupted flow.

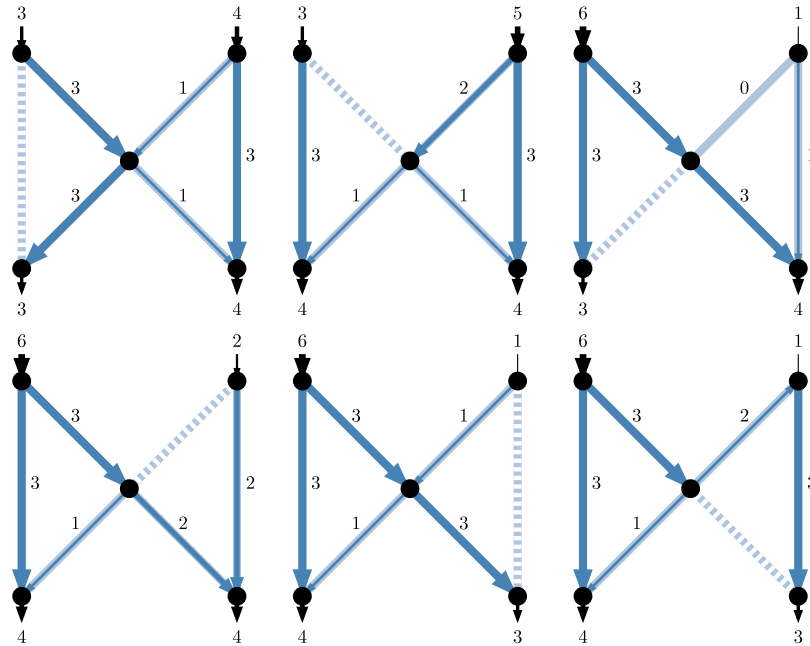


Fig. 2. Optimal flows for disruptions in the winter (disrupted lines are dotted).

$$A = \begin{pmatrix} -1 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & -1 & 1 & 0 & -1 & 0 & -1 & 1 & -1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & -1 & -1 \end{pmatrix}.$$

For such a simple network, the optimal flows (Fig. 1, centre) are easy to determine. Node i_4 obtains all the gas from the cheaper source i_1 , so that the total cost is $c_4 = 4 \times 300 = 1200$. Node i_5 gets 2 from source i_1 and the rest from the more expensive i_2 at a total cost of $c_5 = 2 \times 300 + 2 \times 400 = 1400$.

Now, let us look at a possible disruption. Assume that ℓ_1 is not available. Then $q_\ell = 0$ if $\ell = \ell_1$, since ℓ_1 is unavailable and $q_\ell = 3$ if $\ell \neq \ell_1$ while the other parameters do not change.

The optimal flows (Fig. 1, right) change drastically. Now, supplier i_1 is bound by the outgoing transmission capacity 3 via pipeline ℓ_2 ; similarly, consumer i_4 can only obtain 3 from the network via ℓ_3 .

What are the costs? How is the demand satisfied? Consumer i_4 obtains all his gas via i_3 . But is this gas from source i_1 or, at least in part, from i_2 ? By our assumption, the gas that streams from the two sources gets mixed, so from i_3 , there are four units of gas available at a price calculated as the weighted average of the inflows: $p_3 = \frac{3 \times 300 + 1 \times 400}{4} = 325$.

Notice that player i_4 cannot satisfy his entire demand. Depending on the season, the shortage can (summer) or cannot (winter) be supplied from storage.

Table 1

Costs for i_4 & i_5 in winter. The worst $\frac{1}{3}$ are highlighted. The two right columns show the case when the network does not contain ℓ_4 . Note that the disruption of ℓ_3 benefits i_5 .

Disrupted	Cost for node		Without ℓ_4	
	i_4	i_5	i_4	i_5
None	1200	1400	1200	1400
ℓ_1	1575	1525	1725	1575
ℓ_2	1300	1600	1500	1800
ℓ_3	1500	1300	1500	1300
ℓ_4	1200	1400	1200	1400
ℓ_5	1225	1575	1275	1725
ℓ_6	1200	1600	1200	1800
ES ($\alpha = 1/3$)	1537.5	1600	1612.5	1800

Winter. Consumer i_4 obtains 3 units of this gas while the remaining 1 unit is supplied from its alternative source at a cost of 600: $c_4 = 3 \times 325 + 1 \times 600 = 1575$, while i_5 has $c_5 = 1 \times 325 + 3 \times 400 = 1525$.

Summer. Consumer i_4 can try to fill the storage in the coming three months. This results in a modified demand of $4\frac{1}{3}$ which is calculated as $3 + 1 \cdot \frac{4}{3}$ (the shortage is multiplied by $\frac{4}{3}$).

Focusing on winter, we can now calculate the supply costs for all single-pipeline disruption scenarios (Fig. 2 and Table 1). Given the small number of states, calculating the expected shortfall (ES) with $\alpha = 10\%$ would be the same as looking at the worst case; instead, we consider $\alpha = \frac{1}{3}$, in other words, the average cost under the two worst scenarios (highlighted in Table 1). Therefore, the $ES_{\frac{1}{3}}$ for the two nodes are 1537.5 and 1600 respectively, which constitute a 28% and 14% increase with respect to the *status quo*. Ostensibly, i_4 can be hurt more by losing its privileged connection to producer i_1 , and a network disruption may affect i_4 more severely, according to our model.

Such comparison is more useful when different networks are considered. In the initial network, pipeline ℓ_4 carries no gas, deeming it unnecessary. The last two columns of Table 1 present the same analysis for a network with only five pipelines. It is clear that ℓ_4 plays a vital role in increasing supply security by mitigating the risks associated with disruptions. Without ℓ_4 , the expected shortfalls are 1612.5 and 1800, with a total increase of 275. While one must compare this with the construction costs to see if ℓ_4 is worth the money, it is clear that the pipeline is not useless even if it is not used — such as the Slovakia–Hungary interconnector at Beregdaróc [45].

2.6. Scenarios

We are interested in the effects of some ongoing network developments. Barring the baseline scenario, we consider certain possible developments for the Eastern corridor.

1. First, we look at the effect of a completed Nord Stream 2, whereby the transmission capacity between Russia and Germany is doubled.
2. Under the “Ukraine” scenario *all* pipelines between Ukraine and Russia are closed (have a transmission capacity of 0).
3. Thirdly, we have also looked at the effect of the opening of the Trans-Adriatic Pipeline connecting Turkey with Italy via Greece with lengths 620 and 1260 kms and capacities of 20 bcm/yr, carrying cheap gas from Central Asia to the South Balkans, Italy and beyond.

Generally, the construction of NS2 should alleviate the problem of congestion on the network, but Gazprom’s communication about the Ukrainian pipelines reaching the end of their service life and the cost of maintaining excessive transmission capacities hints that the two main connections between Russia and Europe will not coexist for long. Božić et al. [46] recorded a substantial drop in transmitted quantities (ranging from 28% to Poland to 93% to Romania) for 2020 versus 2019; so far, the war in Ukraine did not completely stop gas transits. We, therefore, think that the impact of NS2’s opening is best illustrated by comparing the first (Baseline) and last (Combined) scenarios. The opening of NS2 will have a drastic effect on Eastern Europe. It will incite interest in seeing whether the Trans-Adriatic (TAP) and the Trans-Anatolian Pipelines (TANAP) can compensate for the shift of the main East–West transmission channel to the North. The ongoing development of the Balkan Stream will be a significant contribution here.

ENTSOG [21] also consider several network scenarios, but while our second scenario happens to be their # 1 disruption scenario, we look at all possible single-pipeline failures for certain ongoing network developments.

Fig. 3 shows the optimised flow for the baseline network (in 3(a)), with the doubling of Nord Stream’s transmission capacity as well as a (major) winter disruption of Nord Stream whereby several countries experience shortages (in 3(c)).

In the following section, we present the data and results (see Figs. 4 and 5).

3. Data and calculations

The international pipeline network forms a connected network but, often, only via the national pipeline networks. Besides the assumptions explained in Section 2.2 such as

- An idealised network,
- Net positions,
- Fixed and uniform prices,
- Uniform gas quality,
- Bidirectional pipelines, and
- The availability of an expensive but unlimited energy substitute priced at a flat 600 M\$/bcm,

we make some additional simplifying and technical assumptions [See also 20]

- In the case of Russia and North Africa, distances are measured from the borders. This makes no difference in delivery prices.
- Liquefied natural gas (LNG) is added as a player with a pipeline of the same length as the liquifying–regasification costs.
- Transporting gas over these pipelines has its costs. A pipeline may travel across several regions, making it convenient to define costs by a cost matrix $C \in \mathbb{R}_+^{n \times m}$ where C_{ij} is the cost of transferring a unit of gas over pipeline j occurring in the region i . We assume that transportation cost is proportional to the length of the pipeline.
- All 150 pipelines face the same probability of incidents.
- Looking at these 150 pipelines, under the 10% expected shortfall, we are concerned with the worst 10% of the cases, that is, the 15 (directed) pipelines whose removals give the highest cost increases for the country at hand.

Data concerning national resources, including natural gas, are regularly published by several reliable sources. Transmission capacities were compiled from the datasheet provided by the IEA [47]. Consumption and production data was gathered from BP’s Statistical Review of World Energy [48]. Pipeline lengths were retrieved from the public database of the European Network of Transmission System Operators for Gas [49] and other online sources. The data are summarised in the Appendix (see Tables 4–6).

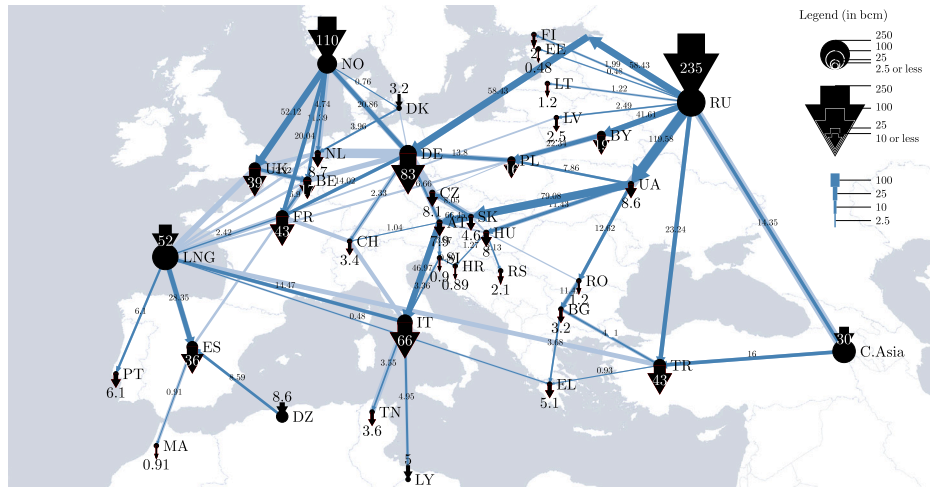
4. Results

In the calculated expected shortfall values (see Tables 2 and 3), we observe a drastic difference in the potential effects of NS2 in two parts of Europe: the East and West. While the construction of NS2 brings cheap gas and thereby substantial benefits to Western Europe, South-Eastern Europe enjoys no benefit. If NS2 is followed by phasing out the Ukrainian gas corridor, most Central- and Eastern Europe will be left with a highly concentrated supply path. If any pipelines along that path are affected, the results will be catastrophic for the region, with substantial gas outages a surety. Interestingly, shortages are not restricted to the winter. These risks far outweigh the benefits of lower transportation costs for the West.

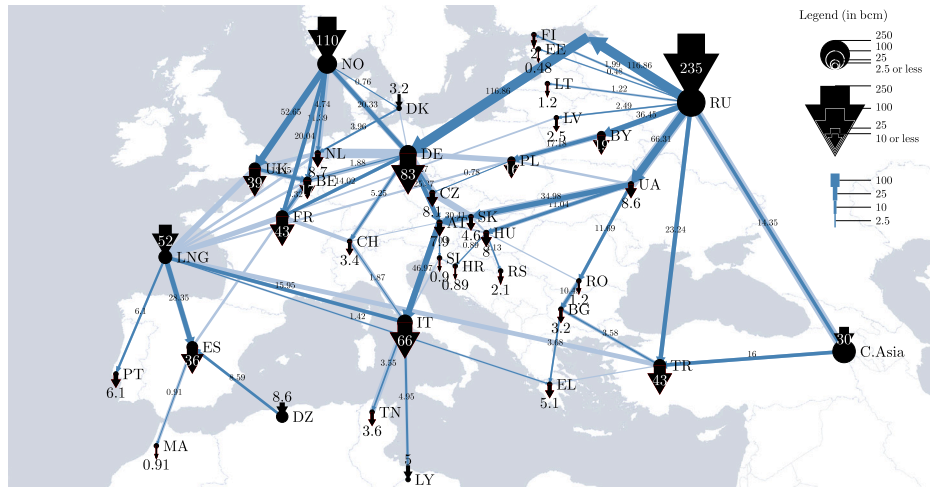
The Trans-Adriatic Pipeline system alleviates the problem in the Southern part of Europe. Unfortunately, the current plans do not extend the network to the North, benefiting only a few countries en route: Bulgaria, Greece and Italy. For some of these countries, the pipeline gives clear benefits vis-a-vis the status quo regarding supply security.

How far do the benefits of TAP reach? To see this, we look at the marginal benefit of adding TAP to the network: the TAP scenario vs Base, NS2+TAP vs NS2, NS2+UA+TAP vs NS2+UA and look at the differences without and with TAP :

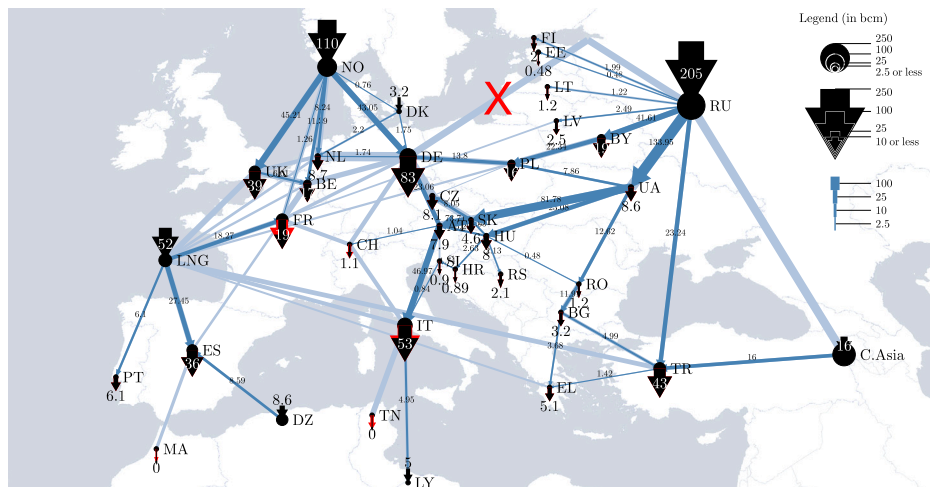
$$\frac{c_{\text{scenario without TAP}} - c_{\text{scenario with TAP}}}{c_{\text{base}}}$$



(a) The baseline scenario.



(b) The Nord Stream scenario.



(c) The network with the Nord Stream closed; winter scenario.

Fig. 3. Optimal flows in the European gas network. Hubs/links are proportional to the square root of production, consumption, transmission capacities and flow values (light/dark blue), respectively. Red arrows indicate shortages.

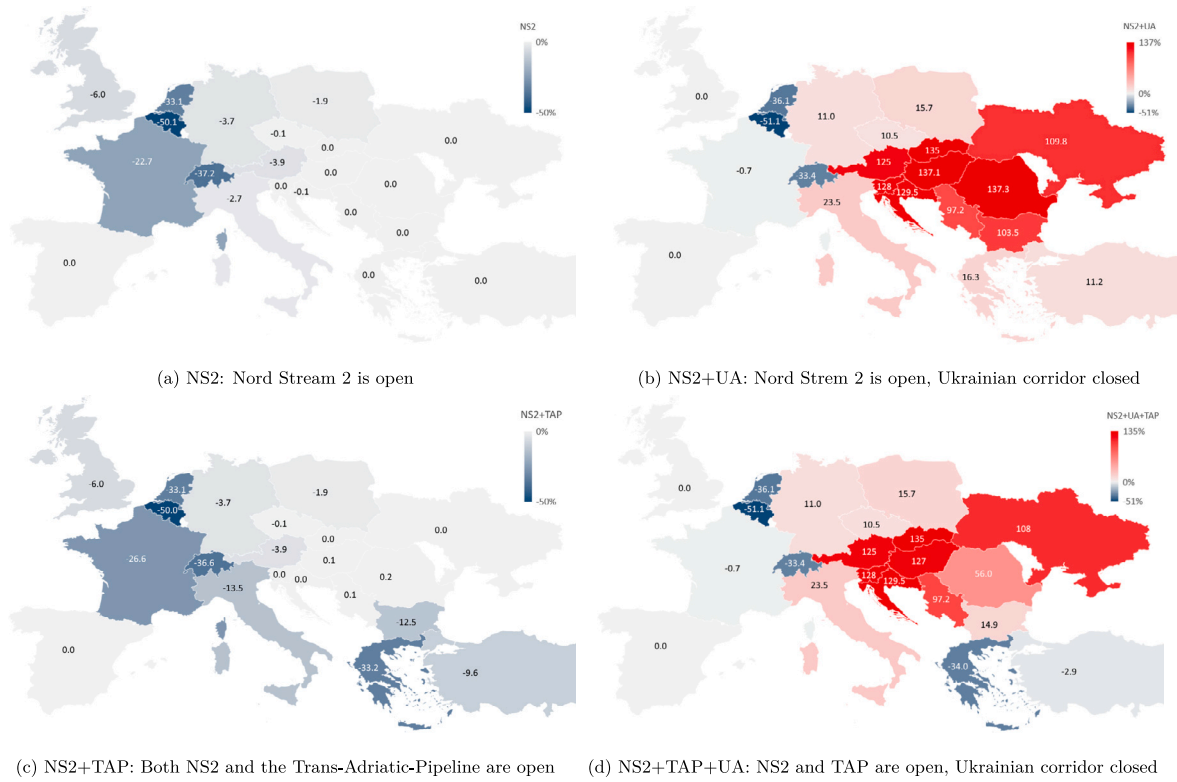


Fig. 4. Relative cost increase with respect to the Base scenario ($c_{\text{scenario}}/c_{\text{base}}$) in the *winter*.

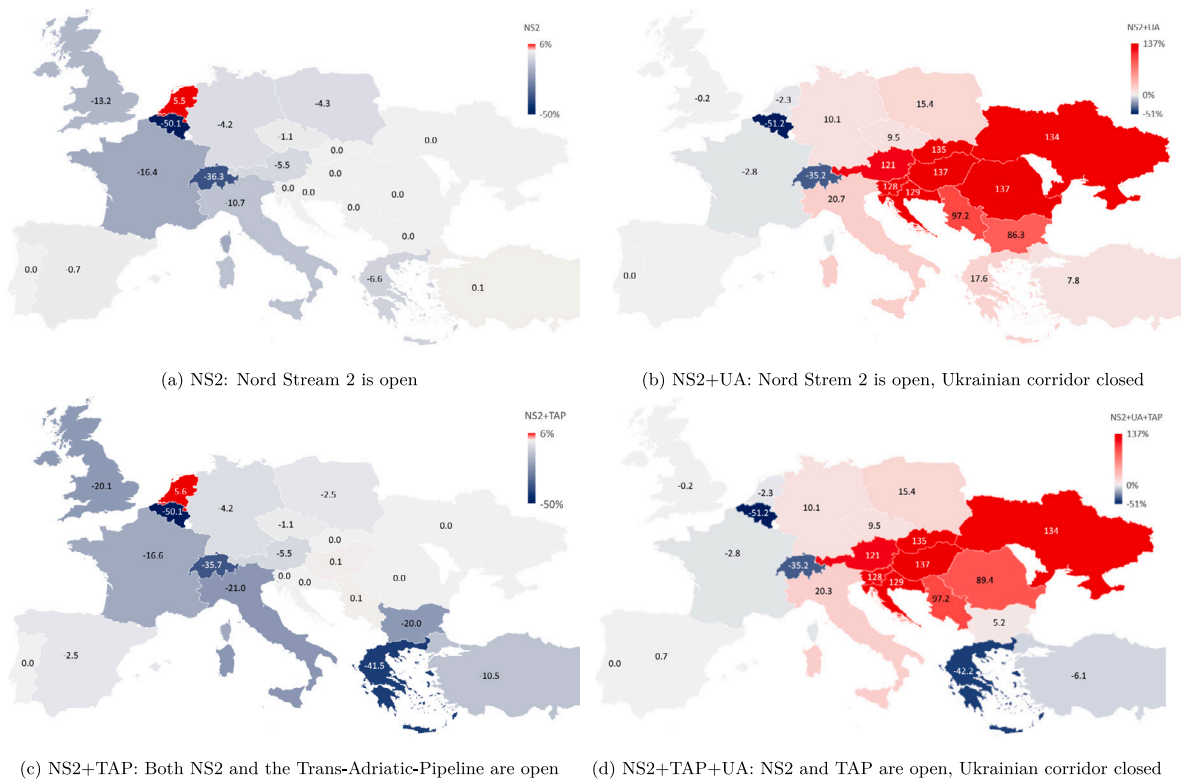


Fig. 5. Relative cost increase with respect to the Base scenario ($c_{\text{scenario}}/c_{\text{base}}$) in the *summer*.

Table 2

Expected shortfall values for the different network scenarios in winter (remaining values are constant over all scenarios). TAP and NS2 stand for a scenario where the Trans-Adriatic Pipeline and Nord Stream 2 are operational, and UA for the one where all Russia–Ukraine pipelines are closed.

Country	Base	NS2	NS2+TAP	NS2+UA	NS2+TAP+UA
Austria	2 110	2 027	2 027	4 740	4 740
Belgium	10 440	5 211	5 215	5 100	5 100
Bulgaria	954	954	835	1 940	1 096
Croatia	232	232	232	532	532
Czech Republic	2 098	2 095	2 095	2 318	2 318
France	26 023	20 107	19 111	25 836	25 836
Germany	21 527	20 721	20 738	23 904	23 904
Greece	2 629	2 629	1 755	3 058	1 736
Hungary	2 032	2 032	2 033	4 817	4 618
Italy	31 092	30 263	26 898	38 385	38 385
Netherlands	3 569	2 387	2 389	2 282	2 282
Poland	4 541	4 456	4 456	5 255	5 255
Romania	303	303	304	720	473
Serbia	647	647	647	1 276	1 276
Slovakia	1 169	1 169	1 169	2 747	2 747
Slovenia	237	237	237	541	541
Spain	19 030	19 030	19 030	19 030	19 030
Switzerland	1 724	1 083	1 094	1 149	1 149
Turkey	11 996	11 996	10 843	13 342	11 643
Ukraine	2 042	2 042	2 042	4 283	4 251
United Kingdom	23 520	22 099	22 099	23 520	23 520

Table 3

Expected shortfall values for the different network scenarios in summer (remaining values are constant over all scenarios). As before, TAP and NS2 stand for a scenario where the Trans-Adriatic Pipeline and Nord Stream 2 are, respectively, operational, UA for the one where all Russia–Ukraine pipelines are closed.

Country	Base	NS2	NS2+TAP	NS2+UA	NS2+TAP+UA
Austria	2 235	2 112	2 112	4 940	4 940
Belgium	10 440	5 208	5 210	5 100	5 100
Bulgaria	1 050	1 050	840	1 956	1 105
Croatia	379	379	379	870	870
Czech Republic	2 140	2 116	2 116	2 342	2 342
France	26 029	21 769	21 714	25 287	25 287
Germany	22 150	21 209	21 230	24 377	24 377
Greece	2 601	2 430	1 523	3 058	1 503
Hungary	2 182	2 182	2 184	5 171	5 171
Italy	28 463	25 413	22 488	34 355	34 239
Netherlands	4 316	4 555	4 559	4 219	4 218
Poland	4 993	4 781	4 869	5 762	5 762
Romania	1 123	1 123	1 123	2 660	2 127
Serbia	707	707	707	1 393	1 393
Slovakia	1 177	1 177	1 177	2 766	2 766
Slovenia	238	237	238	542	542
Spain	18 902	18 775	18 436	19 030	19 030
Switzerland	1 776	1 132	1 142	1 151	1 151
Turkey	12 443	12 452	11 137	13 418	11 685
Ukraine	3 593	3 593	3 593	8 420	8 420
United Kingdom	22 195	19 273	17 726	22 148	22 141

On average, this contribution of TAP is the highest for Greece and Bulgaria (−42 and −39%), high for Romania, Turkey and Italy (−21.4, −11.4 and −8.4%) and hits Poland most adversely at 0.16%.

A similar analysis for NS2 depends heavily on whether it is an additional pipeline or a shift in existing connections to the North. If the former is true, it brings massive benefits to Switzerland, Belgium, France, the Netherlands and the UK and reduces risks in Italy, Austria, Germany and Poland. The highest losses will strike Hungary, Serbia, and Turkey at 0.02%. On the other hand, if NS2 comes in a bundle, disruptions may create massive shortages in Slovakia, Hungary, Croatia, Slovenia, Austria, Ukraine, Romania and Serbia, additionally harming Bulgaria, Italy, Poland and, to a smaller extent, Germany, the Czech Republic and Turkey, creating savings in Belgium, the Netherlands, Switzerland and France only.

These results are generally in line with the division between supporters and opponents of the project [see, for instance, 50]. Germany

Table 4

Production and consumption data (in bcm) for each of the countries and regions. Asterisks indicate consumers where the price is assumed to be 600 M\$/bcm.

Country	Production	Consumption	Price (M\$/bcm)
Algeria	86.2	45.20	230
Austria	1	8.90	*
Belarus	0.03	19.30	*
Belgium	0	17.40	*
Bulgaria	0.079	3.31	*
Central Asia	267.2	110.10	197
Croatia	1.691	2.58	*
Czech Republic	0.247	8.30	*
Denmark	3.2	0.00	226
Estonia	0	0.48	*
Finland	0.008	2.00	*
France	0.028	43.40	*
Germany	5.3	88.70	*
Greece	0.004	5.10	*
Hungary	1.772	9.80	*
Italy	4.6	70.80	*
Latvia	0	1.22	*
Libya	9.4	4.45	230
Lithuania	0	2.49	*
Morocco	0.094	1.00	*
Netherlands	28.1	36.80	*
Norway	114.4	4.50	226
Poland	4	20.40	*
Portugal	0	6.10	*
Romania	9.7	10.90	*
Russia	679	444.30	220
Serbia	0.586	2.71	*
Slovak Republic	0.094	4.67	*
Slovenia	0.004	0.91	*
Spain	0.062	36.10	*
Switzerland	0.025	3.40	*
Tunisia	1.575	5.13	*
Turkey	0.381	43.20	*
Ukraine	19.6	28.20	*
United Kingdom	39.6	78.80	*
LNG	51.82	0.00	240

and Austria also face increased risks; their unique roles can explain their supportive stance as distributing hubs for Eastern Europe under these scenarios. Such considerations are better modelled by a cooperative game theory approach [24].

We have looked at the negative effect of the cost of disruptions in the system for each player. Our approach is straightforward: by taking the same probability, we ignore differences in political, environmental and terrorist risks or even pipeline length or transmission capacity. Given the enormous observed differences in supply risk, we are confident in having found the weak links. Concerning the methodology: The Value at Risk (VaR) and Expected Shortfall methods are the two most commonly applied risk measures. We chose the latter since, in contrast to VaR, it is a coherent measure [51]; furthermore, VaR has been heavily criticised recently, see, e.g. [52] or [53]. Heckmann et al. [54] offer a comprehensive review on measuring supply chain risks.

Ours is not the first study to measure the EU member' states supply security. Rodríguez-Gómez et al. [55] finds an improvement in the supply of security between 2009 and 2014 — except for Eastern Europe. In a complementary study, Rodríguez-Fernández et al. [56] look at supplier risk primarily and identify the usual suspects: Eastern Europe except for Romania but including Finland and the Baltics plus the smallest members.

5. Conclusion

At the time of writing, it is unclear whether Nord Stream 2 will ever be opened, and political developments may affect its operation later, too. The ongoing sanctions lead members of the European Union to find new suppliers, and at present, it seems very unlikely that Russian gas will ever return. So what do our results imply in this situation?

Table 5
Lengths and capacities of connecting pipelines.

Connection	Length (km)	Capacities (bcm)
Algeria-Spain	1345	8.6
Austria-Germany	720	7.8/6/4.5/3.9/1.8/0.8/0.6
Austria-Hungary	245	5.3
Austria-Italy	826	43.7/3.3
Austria-Slovakia	80	79.3
Austria-Slovenia	390	3.9
Austria-Switzerland	720	1
Belarus-Poland	970	35.6/5.8/0.2
Belarus-Russia	538	35.6/5.8/0.2
Belgium-France	300	24.1/9.1/8.8/0.6
Belgium-Germany	500	13.4/13.1/8.8
Belgium-Norway	864	11.4
Belgium-United Kingdom	432	20.7/19.3
Bulgaria-Greece	585	3.7
Bulgaria-Romania	317	28.6/0.6
Bulgaria-Turkey	340	16.2
Central Asia-Russia	2000	90
Central Asia-Turkey	2533	16
Croatia-Hungary	500	2.6
Croatia-Slovenia	192	1.8
Czech Republic-Germany	470	37.7/34.2/15.9/12.3
Czech Republic-Poland	620	1
Czech Republic-Slovakia	330	56.9
Denmark-Germany	520	1.8
Denmark-Netherlands	314	5.5
Denmark-Norway	124	0.8
Estonia-Russia	1096	1.5/1.1
Finland-Russia	1120	7
France-Germany	570	14
France-Norway	1140	20
France-Spain	1275	7.6/0.3/0.1
France-Switzerland	570	8.3/7.8/2.2/1.3
Germany-Netherlands	516	19.5/19.2/18.2/15.2/12.6/10.2/6/3.5/2.4/2.3/1.7/0.2/0.1
Germany-Norway	680	24.7/14.3/4.1
Germany-Poland	990	32.3/2.4/1.7/0.1
Germany-Russia	1222	58.4/58.4 ^b
Germany-Switzerland	500	23.9
Greece-Italy ^c	1260	20.0 ^c
Greece-Turkey	620	20.0 ^c /1.7
Hungary-Romania	845	1.8
Hungary-Serbia	370	4.8
Hungary-Slovakia	462	4.4/0.2
Hungary-Ukraine	1020	20.6/6.1
Italy-Libya	1565	12.8
Italy-Slovenia	482	1.8/1.6
Italy-Switzerland	1093	21/0.4
Italy-Tunisia	1565	38.5
Latvia-Russia	1096	6.9
Lithuania-Russia	1096	3.9
Morocco-Spain	1345	12.5
Netherlands-Norway	487	35.6/15.3
Netherlands-United Kingdom	432	15.1/3.5/2.4
Norway-United Kingdom	640	27.7/12.8/12.8/2.4
Poland-Ukraine	780	6/1.8
Romania-Ukraine	920	8.6/4
Russia-Turkey	1213	23.2
Russia-Ukraine	1160	28 ^a /26 ^a /26 ^a /17 ^a /13 ^a /5 ^a /2 ^a
Slovakia-Ukraine	1170	72.1/9.7

Remarks:

^aSet to 0 for the Ukraine scenario.

^bOnly for the NS2.

^cOnly for the TAP/TANAP scenarios.

In our calculations, we count on the Russian gas via Nord Stream 1 and 2. Were that not present, there would be an immediate shortage of gas. Since Nord Stream is a submarine pipeline, gas from liquefaction terminals of corresponding total capacity placed near Greifswald, the entry point to Germany, could be distributed the same way the gas via

Table 6
LNG port capacities.

Country	Capacities (bcm)
Belgium	6.6
France	17.6/10.1/5.7
Greece	4.8
Italy	9.6/5.5/4.7
Lithuania	4.5
Netherlands	8.8
Poland	6.1
Portugal	7.2
Spain	8.6/7.8/7.8/6.3/5.7/2.6
Turkey	16.2/11.9
United Kingdom	21/13.6/5.6/0.5

Nord Stream has been. Unfortunately, it is not clear if this would be enough to supply the mostly landlocked countries of Central Europe. With oil it has become clear that the European Union cannot stand up in unity when member states have widely different options for substituting Russian oil. Sanctions on Russian imports of natural gas, with its use in residential heating, is a topic that is even more sensitive. Looking at our results, we can see why certain countries are reluctant to get involved. Should the European Union want to use its leverage in energy matters, it should first put the slogans of the Energy Union into action and create a levelled access to energy and its security of supply among its member states.

CRedit authorship contribution statement

László Á. Kóczy: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Dávid Csércsik:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Balázs R. Sziklai:** Conceptualization, Methodology, Software, Data curation, Writing – review & editing, Funding acquisition.

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 from public sources, attached in an appendix in an aggregated form for easy reproduction of the results.

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Appendix. Data

In this appendix, we present our data. For the description and sources, see Section 3.

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