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Assessing supply security - A compound indicator

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Assessing supply security – A compound indicator

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Abstract

Supply security is a prominent and crucial notion which finds application in various economic sectors (energy security, food security, supply chain risks). Yet, it remains particularly difficult to define and measure. Currently used indicators of supply security focus on narrow approaches and offer limited guidance to policy makers. Considering this, we propose a novel indicator assessing the supply security of industries, conceptually or physically, based on a network structure. The indicator is based on a simulation methodology and evaluates the reaction of the market to disruptions of its network services, thereby capturing the various dimensions of supply security. Subsequently, we perform an exemplary application onto the European natural gas market, and evaluate the impact of currently debated network extensions projects and policy measures.

Keywords: Supply Security, Natural Gas

1. Introduction

Queues in front of petrol stations, soaring commodity prices following geopolitical tensions or shortages in food supply are some of the common images that come to one's mind when evoking the notion of supply security. Albeit frequently associated with energy, supply security—narrowly speaking ensuring a stable supply—is a widely shared concern in numerous markets. Food supply

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security or supply chain disruption risks are two examples thereof. Moreover, diversity, which is often argued to be the main driver of supply security (see notably Stirling, 1998), is a notion of considerable importance in economics—for instance as a hedge against "ignorance" or as a driver of innovation and growth—as well as in natural sciences. Applications of diversity can found in finance (portfolio diversification), international trade (foreign trade dependence) or industrial organization (market concentration).

Understanding, evaluating and assessing the impact of security of supply on a market is a crucial undertaking. First, interruptions of supply can result in significant negative economic consequences, especially in the context of food or commodities like metals and energy. Second, price spikes related to supply insecurity affect consumers, who are often captive and characterized by inelastic reactions. Last, various policies and measures are regularly implemented with the hope to meliorate the supply security of numerous goods. Hence, a clear and precise indicator of supply security allowing to evaluate the situation on a given market and to assess different projects or policies is of utmost interest.

While a notion of central importance, supply security is not easy to define. In the context of energy, the IEA describes it as the: "uninterrupted availability of energy sources at an affordable price"[2]. However, many different aspects and dimensions can be related to the security of supply. Kruyt et al. (2009) highlight four of the main ones: the (physical) availability of supply, its accessibility (i.e. geopolitical considerations), its affordability and its environmental or social acceptability. Alternatively, supply security is often subdivided into short-term security (mainly concerned with the resilience of the system to an outer shock) and the long-term one (linked with the diversification of the supply portfolio and the adequacy of the system).

Numerous indicators attempting to describe and quantify supply security have been designed over the years. Analyses of the diversification of the supply-mix are a classical basis for supply security evaluations. These indicators are often based on the Shannon-Wiener index (e.g. Jansen et al., 2004) or on the Herfindhal-Hirschmann one (Le Coq & Paltseva, 2009). Further, one finds aggregate indicators aiming at identifying and quantifying the main drivers of energy (in)security (see notably the Supply/Demand indicator of Scheepers et al., 2006). Alternative approaches rely on energy market models used as case study to assess the reaction of a market in a defined crisis scenario. Finally, the European Union bases its evaluation on the so-called "N-1 rule" which assesses the capability of a country to cope with the disruption of its single largest infrastructure (European Commission, 2014b).

These established approaches come with significant restrictions and offer limited guidance to their users. Diversity-based indicators, for instance, solely assess the current diversification of supplier portfolios, disregarding potential substitutes which might be used in a crisis case. Simulation approaches, on the other hand, are usually restricted to the study of a single classical scenario.

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[2] `http://www.iea.org/topics/energysecurity/`

Finally, the N-1 rule is a purely static approach, thus neglecting the global market dynamics. Overall, the approaches are often limited to a single dimension and do not reflect the broad nature of supply security. The various limitations of the existing methodologies restrict their range of application and appeal for a comprehensive and flexible indicator tackling supply security in its various dimensions.

Against this background, we propose a novel approach to evaluate the supply security of industries that are, physically or conceptually, dependent on a network. We formulate an indicator reflecting the capability of a market to secure the supply in a crisis situation. Specifically, our indicator measures the ability of a market to cope with various interruptions of the network services. The causes for interruption can be numerous, such as, e.g., technical breakdown of a transmission line, collapse of exporting countries following geopolitical turmoil or failure of a supplier to comply with the contract's terms. Our indicator measures the impact of these crises on the market by analyzing the change in consumer surplus. The results of each disruption scenario are then weighted by a risk factor, and aggregated into a synthetic compound indicator, thus leading to a quantification of the overall supply security.

Our indicator attempts at correcting for some of the caveats of currently used methodologies. We follow the idea of Stirling (1998) assessing diversity as the diversification of the supplier portfolio. We further cover both the short-term perspective of supply security (i.e. short-term availability, ability to cope with extreme events) and the long-term one by assessing the adequacy of the system. Last, related to the definition of Kruyt et al. (2009), we integrate both the quantity dimensions of supply security (availability, accessibility) as well as its price dimension (affordability). To the best of our knowledge, there exists no indicator both relying on a detailed representation of the supply side and taking into account consumers' reactions. Moreover, our methodology can be used on various types of markets, and might further be applied as a policy evaluation tool.

Using the European gas market as exemplary application, we compute our indicator and compare it to several commonly used supply security metrics. Subsequently, we make use of the proposed approach to assess a set of four projects, which are commonly thought to have a positive effect on the European security of gas supply. Specifically, we test two different gas network extension projects (the Nord Stream 2 and the Southern Gas Corridor), investments into additional LNG import capacity as well as the implementation of a strategic storage obligation at the European level. Our indicator, alongside other metrics, allows to evaluate the impact of these projects on energy security. Moreover, the variance and the range of differences between the considered indicators will highlight the complexity of estimating supply security.

2. Literature

As highlighted in the introduction, supply security is a broad and difficult to define notion that encompasses various aspects and dimensions. As the crucial importance of supply security has long been identified, numerous research efforts have been devoted to its definition and evaluation.

2.1. Conceptualizations

Supply security. The notion emerged in the 1970s in the context of energy, notably in relation to the two oil shocks which led to soaring oil prices. Initially, import dependency was considered as the first and foremost driver of energy insecurity. The notion subsequently widened over time, for instance Bohi et al. (1996) defined it as “the loss of economic welfare that may occur as a result of a change in the price or availability of energy”. This definition emphasizes on the economical and on the physical availability dimensions. Stern (2002) uses a similar approach, and adds a distinction between the short-term availability of supply and the long-term adequacy of supply and infrastructure (i.e. being able to deliver supply). In addition, he differentiates the operational security (i.e. coping with seasonal peak demand or extreme weather) from the strategic security (i.e. collapse of major supply sources). Subsequent definitions additionally consider the environmental dimension as an essential feature of supply security (see e.g. Jewell, 2011).

Finally, Kruyt et al. (2009) synthesize the various definitions by proposing four dimensions: the (physical or geological) availability, the accessibility (geopolitical aspects), the affordability (i.e. the economical dimension) and the acceptability (environmental and social elements). One also finds diverging opinions. Chester (2010) denounces the lack of attention dedicated to defining the notion of energy security, considering the common definitions to be “blurred” and “elusive”. She underlines the multi-dimensional and context-dependent nature of supply security, and calls for indicators based on four dimensions: availability, adequacy of capacity, affordability and sustainability. For a thorough review of the various definitions of supply security and its various dimensions, one can notably refer to Winzer (2012).

Diversity. A parallel yet independent notion is the one of diversity. Stirling (2010) defines it as the “pursuit of an evenly balanced reliance on a variety of mutually disparate options”. Diversity is a notion of broad relevance in economics. Portfolio diversification is certainly the best-known concept of finance theory. Its basic rationale (“do not put all your eggs in the same basket”) finds application in numbers of domains in economics including supply security. Further applications are to be found in finance (Markowitz, 1952) or economic growth theory (see e.g. Frenken et al., 2007). Stirling (1998) recognizes this relevance, and proposes a general characterization of diversity in three dimensions: variety, balance and disparity.

2.2. Indicators

Since supply security is a context-dependent notion, its measurement is necessarily an arduous task. Assigning a numerical value, ranking or even conceptually evaluating a loosely defined concept is by essence a slippery attempt.

Sovacool & Mukherjee (2011) listing more than 350 different indicators of energy security is rather symptomatic of this fact.

Simple metrics. As a first approximation, simple indicators of supply security can be used. In the context of energy, resource estimates or reserves to productions ratios provide a rough assessment of a fossil fuel's remaining duration of usage under current conditions. Alternatively, one can also take into account indicators such as the energy intensity of an economy, the share of fossil fuels or the import dependency of various energy carriers. In a non-energy context, the market share of each supplier, the proportion of long-term contracts or the share of high-risk suppliers and routes might be further considered.

These metrics allow to grasp the dependence of a market on given commodities, suppliers or routes. Yet, their narrow coverage and simplistic approach limit their usage to crude assessments. Moreover, they cover a single dimension of supply security, and are limited to static assessments.

Diversity-based indices. A further strand of indicators is characterized by the recourse to the notion of diversity as the key driver of energy security. As portfolio diversification in finance, diversity is regarded as a simple yet powerful method for mitigating risks.

Stirling (1998) argues that diversity is best represented by the Shannon index, a metric commonly used in other fields of study like biology or ecology. Neumann (2004) (and later von Hirschhausen & Neumann (2013)) introduce an extension of the Shannon index to assess supply security. Their approach integrates a political risk index as well as the ratio of domestic production to the evaluation of supply sources diversification. Building upon this idea, Jansen et al. (2004) propose four different long-term indicators derived from the Shannon index, notably considering the diversity of energy sources and of the imports thereof, the political risks and the level of resource depletion.

In parallel, other indicators of diversification have been used as basis for energy security evaluation. The Herfindhal-Hirschmann index (HHI), which is commonly known as a measure of the concentration of firms in a market, is notably used by Le Coq & Paltseva (2009). They construct separate metrics for oil, gas and coal which consider the diversification of import sources, the political and transit risks as well as the economical impact of a disruption. In turn, Stirling (2010) proposes a comprehensive framework to assess energy security; his heuristic approach reflects the three dimensions of diversity: variety, balance and disparity.

There are two main limitations to the aforementioned diversity-based indices. First, they evaluate the diversification of supplier portfolios on a static basis. The current diversification is measured, disregarding potential alternatives and substitutes. For instance, a customer who chose a supplier out of various competing offers might still be able to obtain supply from one of the turned down alternatives in case of trouble with the chosen supplier. Moreover, a consumer benefiting from a well balanced portfolio may nonetheless be exposed to shortages in the event of delivery interruptions from one of the suppliers and that the remaining providers lack the technical capacity to augment their deliveries. Since the diversity-based indicators only consider the realized market shares, they neither recognize a substitution alternative nor technical limitations of the current portfolio, thus yielding an incomplete evaluation of the situation.

Second, these indicators measure supply security along the sole dimension of the portfolio diversification. Yet, numerous other factors influence supply security; to name a few: the reaction of the demand and supply side, the possibility to stockpile the goods or the nature of the commercial relationships.

Other aggregated indices. The supply-demand (S/D) indicator has been developed by Scheepers et al. (2006) on the account of the European Commission. It aggregates numerous factors related to supply security into a single index, and adopts a holistic approach of the energy supply chain. The factors, which are either linked to the demand for energy (energy-intensity) or to its supply (e.g. import and transport capacity, share of renewable sources or storage adequacy) are then weighted to yield a quantitative assessment of the supply security.

In parallel, the IEA has developed two aggregated indices (Lefevre, 2007). The first one is based on a HHI and captures the price dimension of energy security through the market concentration of suppliers, the political risks thereof and the relative share of each energy source in the energy mix. The second one measures the physical unavailability of gas by considering the share of oil-indexed and pipe-based gas imports over the total primary energy supply. The rationale is based on the belief that pipeline supply rules out the option of a rapid switch between energy sources.

Additionally, the IEA has further developed the Model of Short-term Energy Supply (MOSES) (Jewell, 2011), aggregating various risk and resilience factors related to the external and domestic dimensions of different energy carriers. This comprehensive approach assigns numerical ranges for the value of each factor to classify them into three categories (low, medium and high level). Once all factors are weighted and combined, the MOSES yields a single index evaluating the short-term security of supply

These aggregated indicators suffer two mains caveats. First, they represent an ex-post evaluation of the situation on a given market. Hence, they offer limited guidance for decision-makers when evaluating the impact of various policies or infrastructure projects on supply security. Second, they consider the sole static viewpoint and disregard dynamic aspects, such as demand adaptation to shocks or global market trends. Thereby, they might yield an unrealistic assessment of the situation.

Stress test and simulation approaches. A parallel strand of research uses techniques of energy market modeling to evaluate the security of supply. Here, the evaluation is usually based on the implementation of a shock scenario on a model and the assessment of its consequences. Richter & Holz (2015) use, for instance, the scenario of a disruption of the Russian supply to test the resilience of the European natural gas market.

The stress tests pursued by the European Union and inspired by the financial market stress tests are further examples of this methodology. These tests attempt to model the impact of a supply disruption resulting from a selected crisis scenario that puts strain on the supply of a market. For instance, European Commission (2014a) simulates the collapse of either the Russian-Ukrainian pipeline or of all Russian exports both during a period of one and of six months.

Recently, the European Network of Transmission System Operators for Gas followed a similar approach to publish an union-wide study on the simulation of gas supply and infrastructure disruption scenarios (ENTSOG, 2017). Their study is based on a detailed technical model of the European gas system. They identify various risk scenarios for the European gas system and simulate them for three cases of peak demand. The collapse of the Russian-Ukrainian route or the disruption of all exports from Algeria are, among others, tested in the study. Simulation results are then interpreted in terms of demand curtailment.

The choice of scenario represents one of the main limitation of these approaches. They often tend to solely consider scenarios that have occurred in the past or that might seem likely to one's mind. In doing so, relevant cases might be overseen. Furthermore, these approaches lack a unified indicator for the quantification of supply security, as they generally rely on ad hoc assessments or are interpreted qualitatively. Finally, the studies tend to provide a detailed technical formulation of the supply, but neglect the demand side, thereby disregarding its adaptation possibilities.

EU's approach. Lastly, an approach regularly used in the evaluation of energy security is the so-called N-1 rule developed by the European Commission. This rule is both a methodology to evaluate supply security and a "minimum standard" of security which all member states must comply with (European Commission, 2014b). The rule aims at determining whether a country is capable of satisfying its demand in spite of the disruption of its single largest infrastructure—be it an import, transport or production infrastructure. The disruption represents an extreme event with a statistical probability of once in 20 years (European Commission, 2010). Market-based demand-side measures are also considered in fulfilling the obligation.

This methodology presents two majors caveats. First, the assessment is a purely static one. Therefore, it neglects market dynamics, for instance global shortages in supply which could result in energy insecurity even when complying with the N-1 rule. Second, the analysis is limited to a single scenario of disruption, whereas a network often consists of numerous nodes and lines that are crucial to its functioning. Owing to these flaws, the N-1 might yield unrealistic evaluations of supply security.

3. Methodology

The previous literature review highlights the limitations of the current indicators of supply security. Before explaining our attempt at filling this gap, we first address the question of what such an indicator should be capable of.

3.1. Requirements for an indicator

A first requirement for an indicator is the basic validity of its assessment. In other words, the approach must correctly depict the relevant driving factors of supply (in)security to yield an appropriate evaluation.

Second, the indicator should be capable of reflecting the broad and context-dependent nature of supply security. Existing indicators are often concentrated on a single dimension (usually the physical availability of supply), thus neglecting further important aspects like price security, geopolitical considerations or global market dynamics. Moreover, the indicator should be able to take into account the relation and interaction between various factors impacting supply security. Again, current approaches tend to focus on an unique factor. In the context of energy security for instance, most approaches assess the sole diversification of supply portfolios, without considering additional factors such as demand flexibility or the possibility to store the goods.

A third requirement for an indicator is its practicability. Given the strategical prominence of the markets concerned by supply security issues, the designed indicator should be applicable for policy or project evaluation. As a tool for policy evaluation, the metrics would ideally allow to assess the effect on supply security of various policies or infrastructure projects. In parallel, the reading and understanding of the index should be kept simple and straightforward, so that decision makers obtain a clear and quick overview of its main message.

Last, an indicator should be formulated in an as generic as possible manner. Intended here is its applicability to various markets, be it to different energy carriers, to specific food markets and to various commodities or international supply chains. Albeit addressing heterogeneous situations, a unified framework ensures a common ground for the different markets, which allows for comparability between them and uniform methodological standards.

3.2. Proposed framework

Bearing in mind the aforementioned requirements, we propose a novel approach to evaluate supply security of industries which rely on a network. The network can be physical with nodes representing different production or demand locations connected by arcs representing transmission infrastructure (e.g. roads, oil pipelines or electrical lines). The network can also be purely conceptual with node representing producers and demand actors and arcs depicting their relationships (e.g. contracts or information exchange).

We evaluate supply security by simulating interruptions of the single components of the networks, i.e., nodes and arcs. Thereby, we ask the basic question, how the market is reacting to this interruption. In doing so, we assess the ability of a market to cope with possible crisis situations and study the welfare impacts of these, both in terms of quantity and of prices. To measure the reaction of the market, we focus on the impact of the interruptions on consumer surplus.

The nature and the origin of the potential network interruptions depend on the considered market. An explosion in a production plant, a (geo)political dispute leading to the interruption of deliveries, a supplier's failure to meet the contract's terms or the breakdown of cargo freight supply chains are some examples. As a generalization, one can model all possible interruptions as disruptions of the two elements building the network: a node or a line. Our indicator relies on the study of these disruptions; their choice and design is to be performed carefully and in relation with the considered market. One should identify the potential sources of disruption on the market (e.g. technical, geopolitical or congestion) and their average duration based on a historical data-driven approach. These disruptions are then translated into scenarios of lines or node interruptions. Correcting for the caveat of the case studies literature, the chosen scenarios should cover the iterative disruption of all network elements. As an example, if explosions in oil production plants are identified as a potential cause of supply disruption, one should successively simulate this scenario for all oil producing nodes of the network.

After having measured the impact of each disruption on consumer surplus, the final step of our methodology consists in the aggregation of all results into a single metrics. To that end, the results are weighted by risk factors and, finally, averaged; thereby, one obtains a highly readable and tractable compound indicator of supply security. It is to be noted that the choice of potential sources of disruption is not restricted to a single one. When more than one set of scenarios is identified as relevant for the industry, the results of different sets can be further aggregated into a unique compound indicator.

Evaluation procedure. The evaluation and quantification procedure of our indicator pursues the following approach. First, a theoretical model of the considered market is set up. The model should synthesize the interactions of the main actors on the market (e.g. profit-maximizing producers, benevolent welfare-maximizing leader, etc.), its network dimension (e.g. transport or transmission network and the appropriate constraints) as well as further relevant economical or technical constraints (e.g. import capacity, long-term contracts, etc.). The model is then calibrated with real market data.

In the second step, interruption scenarios are designed. Scenarios are structured in scenarios classes $c \in C$ which bundle scenarios of the same type. A scenario class might, e.g., be the failure of pipelines due to technological risk, the default of suppliers due to political risk, or alike. Within a scenario class, we have different scenarios $i \in I_c$. In the case of a scenario class representing pipeline failures due to technical risk a scenario would be the failure of a single pipeline. Thus, the set of scenarios I_c would include the technical disruption of all pipeline (and maybe combinations of pipeline disruptions). Each of these scenarios i is evaluated with a probability of occurrence ω_{ic}.

For each of the scenarios, we calculate the market outcome. The impact of the interruption on economic welfare in a given country n is computed as the change in consumer surplus relative to the base case without any interruption: $\frac{CS_{icn}^{crisis}}{CS_n^{base}}$ where CS_n^{base} is the consumer surplus in country n without any interruption. Likewise, CS_{icn}^{crisis} is the consumer surplus in country n realized under scenario i in scenario class c.

To obtain a single indicator of supply security in country n, we first aggregate the relative change in consumer surplus in each scenario class using occurrence probability. Afterwards, we aggregate indicators of all classes to single indicator using class weights λ_c which are restricted to sum to one ($\sum_c \lambda_c = 1$). Formally, our indicator of security of supply Φ_n is defined as:

$$\Phi_n = \sum_{c \in C} \lambda_c \left(\frac{\sum_{i \in I} \omega_{ic} \, \frac{CS_{i,n}^{crisis}}{CS_n^{base}}}{\sum_{i \in I} \omega_{ic}} \right) \tag{1}$$

Remarks on the evaluation procedure. Focusing on the consumer surplus allows to measure both the quantity and the price effects—lower quantities supplied or higher prices— and to capture the adverse welfare impacts born by consumers. Another possibility would have been to consider the total welfare impact—consumer and producer surpluses; yet, as producers and importers might benefit from the shortage in supply thanks to higher prices, we opt for the sole consideration of the impact on consumers. Moreover, the concerns and policies around security of supply are mainly concentrated on the consumer, rarely on the producers. Finally, using the ratio of consumer surplus allows to normalize the impact of each crisis; this ensures comparability, notably when the indicator is used as a policy evaluation tool.

The formulation used for our indicator allows for a direct and simple interpretation of its results. A value of 1.0 highlights a country which is never affected by an interruption, be it in terms of missing supply or of increasing prices. Below 1.0 values represent, on the contrary, the average loss of welfare caused by the crises and which must be born by the consumers. The lower the values, the more severe the losses.

3.3. Relation to current indicators and requirements

Our indicator aims at overcoming some of the previously mentioned caveats of current methodologies. First, our methodology blends together various dimensions of the notion of supply security. As many others indicators, we assess the portfolio diversification, yet in a broader and more precise manner. Through the simulation of network service interruptions, alternatives to the current mix must be developed, if possible. These alternatives might be the augmentation of deliveries from an existing supplier or the recourse to a not yet used option (e.g. a concurrent supplier whose offer was previously turned down because of its higher cost). In addition to diversification, we further evaluate both the short-term resilience of the market (i.e. whether the demand can be fully satisfied) and the overall alignment of supply and demand in a longer term perspective. Moreover, we integrate the categorization of Kruyt et al. (2009) by directly assessing the availability, the accessibility and the affordability dimensions of supply security.

Second, one of the main novelties of our approach is the integration of both supply and demand dynamics. We model the elastic reaction and adaptation of consumers to price changes, whereas most of the current indicators rely on a fix demand (among others the diversity-based indicators or simulation approaches). Moreover, our model integrates global market dynamics for a sound assessment of the available supply, notably in opposition to the static approach followed by the N-1 rule or the diversity-based literature. To the best of our knowledge, there exists no indicator capable of reflecting both demand and supply dynamics. We thereby achieve a broader and more realistic evaluation than existing methodologies.

Third, our approach is not restricted to the study of the sole diversification of supplier portfolios. Indeed, depending on the considered market, various factors can play a significant role in the security of supply. Storage—of goods, energy, food or commodities—is for instance a prominent driver of security. Our flexible methodology allows to take these additional factors into account.

Fourth, our methodology opts for a probabilistic-like approach. To obtain a broad picture, we do not restrict the design of the scenarios to those that seem possible to one's mind, but investigate all potential sources of disruption of the network services. The amount of scenarios considered thus allows for a more realistic assessment of possible future crises.

Last, the chosen methodology allows to apply our indicator in various settings. The simulated market might mimic current conditions, but one might also take into account forecasted demand trends or projected infrastructures. Thus, our metrics can be used as a comparison tool between different settings. More specifically, various supply security-related policies or project (for instance network expansion projects or demand-side management policies) can be evaluated and compared with our model based indicator.

4. Empirical Application: Model and Indicator Design

As a first exemplary application of our methodology, we study the European natural gas market; an obvious choice since it possesses many interesting features for our indicator. First, the market is highly dependent on its network—here materialized by the pipeline and liquefied natural gas (LNG) networks. Second, the security of gas supply is a recurrent topic, notably driven by geopolitical concerns (see e.g. the gas disputes between Russia and Ukraine in 2006 and 2009). The uneven geographical distribution of the gas reserves reinforces its sensitivity to supply insecurity. Last, the liberalization of the European market and the rise of a global LNG market changed the playing field on the market, thereby also impacting the supply security. Following we will shortly present the underlying model structure as well as the scenario classes and elasticity assumptions for designing the indicator.

4.1. Model structure

We use the gas market model developed in Abrell et al. (2019) as basis for our empirical implementation. The model relies on a partial equilibrium optimization; a common approach in natural gas market modeling. Included are the main actors along the supply chain: gas extractors, pipeline and LNG shippers, storage operators and final gas users. We use a monthly formulation to capture the seasonal dynamics inherent to the gas consumption. The focus is set on the European market, with one node per country; the linkage to the global market is ensured by aggregated regional hubs. Overall, we cover approximately 98% of the worldwide demand and supply in the model.

The network infrastructure is represented by the cross-border pipeline capacities between each country. The model further considers the worldwide LNG liquefaction (export) and regasification (import) terminals, as well as the storage infrastructure.

We assume perfectly competitive market participants, so that we formulate the model as a social welfare maximization problem. Although imperfectly behaving producers are regularly used in natural gas modeling (see notably Egging et al., 2010), this assumption allows us to keep the model reasonably sized and traceable, so that it can be solved for numerous iterations. In parallel, the model is formulated in a flexible manner, and can thus accommodate various scenarios, such as the implementation of additional network infrastructures or of policies.

Data on the gas market and its infrastructure is subsequently added to the model, and the results are calibrated to the 2012-2014 period. More details on the model formulation and its calibration can be found in Abrell et al. (2019).

4.2. Disruption scenarios

For this application, we consider three classes of possible interruptions. First, the technical failures of pipelines. Second, the outage of a gas supplying countries for political reasons. Third, the disruption of pipelines due to political reasons. Table 1 summarizes the designed interruption scenarios and their weighting strategies. All scenarios classes have equal weights in the indicator ($\lambda_c = 1/3$). Possible shocks affecting the European gas market display a vast range of duration. We implement all disruptions lasting four months during winter (December to March), when gas consumption is peaking.

The technical failures of pipelines is, e.g., to an explosion or to severe leaking of a pipeline. Such a disruption is equivalent to the deletion of an arc within the European pipeline grid. We allow all cross-border pipelines to become disrupted. I.e., the failure of a single pipeline is one scenario within this scenario class. According to OGP (2010) technical failures depend linearly on the length of the pipeline. Thus, we use this length to weight scenarios within the scenario class (ω_{ic}).

Gas producing countries might default due to geopolitical reasons like wars or major internal turmoil. This represents the disruption of a node in the European natural gas market. In these scenario, the country's complete gas infrastructure is disrupted and its demand set to zero. We weight scenarios using the World Governance Index "political stability and absence of violence" provided by World Bank (2016).

Pipelines might also become disrupted due to geopolitical tensions between two countries. For this class, we simulate the disruptions of all major European import channels (e.g. Algeria-Spain, Libya-Italy, Russia-Ukraine, etc.). We use again the World Government Index as weighting factors for single scenarios (World Bank, 2016).

Table 1: Disruption classes

c	Scenario	Type	ω_{ic}	λ_c
1	Technical pipeline failure	Line	Length of pipeline	$\frac{1}{3}$
2	Geopolitical country collapse	Node	World governance index	$\frac{1}{3}$
3	Geopolitical pipeline failure	Line	World governance index	$\frac{1}{3}$

Note: Summary of the three sets of disruptions simulated, with the nature of the scenarios, the type of network failure, the chosen weights. Worldwide governance indicator corresponds to (World Bank, 2016)'s "political stability and absence of violence".

4.3. Short-term and long-term perspectives

As the indicator is based on the consumer surplus the underlying assumption on the demand elasticity is crucial for estimating supply security impacts. However, the demand elasticity of gas diverges strongly depending on the considered time horizon. In a short-term perspective, numerous consumers are captive, with limited substitution alternatives (e.g. households using gas as heating fuel). From a longer-term viewpoint, consumers may adapt and substitute more easily. Households may opt for new heating or cooking systems, while firms might invest in alternative technologies.

To account for this discrepancy, we compute our indicator twice; once in a short-term and once in a long-term perspective. The main difference between a short and a long-term setting should be the possibility for agents to invest in substitutes. Since the model we use for our empirical implementation does not allow to simulate investment behaviors, we approximate this difference with higher demand elasticities in the long-term case.

In order to maintain comparability between the short and the long-term cases, we simulate the exact same disruption scenarios in both cases. Thus, the sole difference between the two setting lies in the demand elasticities. More details on the formulation of the long-term case can be found in appendix Appendix A.

5. Empirical Application: Assessment of European Gas Supply Security

We apply our indicator to evaluate the European gas supply security under different circumstances. First, in the *base case* case we apply the indicator to the current situation in Europe, i.e., under demand, supply, and infrastructure conditions as we observe them today. We perform this evaluation for the short- and long-run perspective. Moreover, we compare the result of our indicator with the results of other metrics used to measure security of supply.

Second, as stated in Section 3, our methodology finds application both in a general assessment of supply security and as a policy evaluation tool for measures aiming at enhancing security. We build upon our application of the European natural gas market, and use our indicator to evaluate three infrastructure projects and one policy, which are broadly considered as positive for the European gas security.

Specifically, we compare the following projects:

- *SGC & Reverse Flow* – Combining two different projects: first, the Southern Gas Corridor (SGC): a three parts project consisted of the South Caucasus Pipeline (SCP), the Trans-Anatolian Pipeline (TANAP) and the Trans-Adriatic Pipeline (TAP) connecting Azerbaijan to Italy through Turkey and Greece. Second, the Reverse Flow project: the opening of a South-North route from Italy to Germany and Belgium thanks to the technical transformation of the existing pipelines.
- *LNG* – Several additional LNG regasification terminals are currently planned in Europe, notably in Croatia, France, Spain and Sweden[3].
- *NordStream 2* – Extension of the Nord Stream pipeline connecting Russia to Germany, resulting in the doubling of its transport capacity.
- *Stategic storage* – Implementation of a strategic storage policy at EU-level. We simulate a policy imposing the holding of a minimum of 30% of the storage capacity as a strategic reserve from November to December and of 20% from January to February. The strategic reserve may only be used in case of crisis on the market or at the end of the period. We formulate the policy analog to Abrell et al. (2019), yet with a more flexible approach.

5.1. Baseline

5.1.1. European gas supply security

In Table 2, our indicator displays contrasted results on the European security of gas supply. A large share of countries are graded with a high score, among others Belgium, France or Switzerland. Five states score 0.990 or higher, meaning than, on average, the crises lead to a consumer surplus reduction of less than 1%. On the other hand, numerous countries achieve poor results. Ukraine, Finland and Turkey achieve the three lowest scores, with welfare reductions of up to 5%. All three are heavily dependent on Russian gas—the entire Finish demand stems from Russia, while 69% of the Ukrainian and 33% of the Turkish ones are supplied by Moscow. In general, Western Europe tends to score high in the indicator. This is notably explained by the important interconnections of the network in Western Europe which allows for numerous alternatives.

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[3] The list of LNG and storage projects can be retrieved from Gas Infrastructure Europe (2015)

One further notices from Table 2 that countries which can rely on domestic extraction tend to do well in our indicator. Denmark, Hungary, and Great Britain all score above the average, notably thanks to their self-sufficiency ratio. Nonetheless, one also finds evident counterexamples like Ukraine, Poland or, to a lesser extent, Romania. Additionally, Austria, Belgium or France prove that countries with high import dependency are not necessarily supply insecure. Their geographical location allow them to rely on a variety of import canals—for instance Belgium has direct pipeline connections with Norway, the Netherlands, the UK and Germany, in addition to a LNG receiving terminal.

Table 2: European Supply Security in the long- and short-run

	Φ_n^{ST}	Φ_n^{LT}	Self sufficiency	$\frac{\text{cap}_{\text{LNG.}}}{\text{demand}}$	Cross-border links
AUT	98.9	99.6	-	-	3
BEL	99.4	99.7	-	46%	4
CHE	99.2	99.6	-	-	3
CRO	98.8	99.2	-	-	2
CZE	98.5	99.0	7%	-	2
DNK	98.9	99.0	131%	-	1
ESP	98.8	99.4	-	213%	4
FIN	95.4	95.2	-	-	1
FRA	99.0	99.5	-	58%	6
GBR	98.2	98.6	50%	66%	4
GER	98.5	98.8	15%	-	8
GRC	97.1	97.8	-	88%	2
HUN	98.5	98.9	22%	-	4
IRL	97.9	98.4	-	-	1
ITA	97.5	98.7	12%	21%	5
POL	96.6	97.3	34%	-	4
PRT	98.9	99.3	-	316%	1
ROU	97.6	97.6	86%	-	2
SVK	99.0	99.5	-	-	4
SVN	99.0	99.6	-	-	2
SWE	98.9	99.1	-	65%	1
TUR	96.5	97.2	-	24%	4
UKR	94.6	95.1	45%	-	3
Av.	*98.1*	*98.5*	*17.5*	*39.0*	*3.1*
St.dev	*1.2*	*1.3*	*32.4*	*76.1*	*1.7*

Note: Short and long-term values of Φ (in percent) for selected nodes. Additionally shown are some indicators of factors influencing supply security: Self sufficiency is defined as fraction of consumption served by domestic supply; ratio of LNG regasification capacity over demand; number of pipelines with direct connection to the country.

Furthermore, one notes the overall positive impact of LNG on supply security. Countries like France, Belgium, Spain or Portugal use their vast regasification capacities to ensure a diversified portfolio and a stable supply. On the other end of the scale, Greece and Turkey achieve low values of the indicator Φ; they seem to have insufficient import capacity to ensure a continuous supply in every case.

Finally, there seems to exist an inverse relationship between the number of pipeline connections and the value of our indicator. Countries with few connections, for instance Finland or Romania, have less substitution alternatives in case of a supplier disruption; they might, hence, be more prone to supply insecurity. Some of these countries nonetheless achieve good levels of supply security. Sweden for instance has a single direct liaison with Denmark, whom is in turn linked with Germany; both countries scoring high in our indicator. When relying on a single connection, the nature of one's neighbor is of utmost interest. Finland scores lower than countries in similar situations, notably owing to its dependency on a somewhat unstable neighbor—Russia.

5.1.2. Short- vs. long-term perspective

The striking feature when comparing the long-term indicators to the short-term ones in Table 2 is the overall higher level of supply security, with the sole exception of Finland. On average, the countries face a 0.4 percentage point smaller reduction of their consumer surplus; Italy even increases its score by 1.2 percentage points.

Our long-term assessment of supply security uses 50% higher demand elasticities, allowing customers to substitute more towards alternative fuels or new technologies. Consumers are thus less dependent on gas and adopt a more flexible behavior. Therefore, one is not astonished that, for the vast majority of countries, the long-term framework yields smaller welfare impacts than the short-term one.

Two remarks are to be made at this point. First, we chose an important difference between the short-term and long-term elasticities (increase of 50%) which is not based on sound scientific research, but rather a rough approximation aiming at sketching customer response. Hence, the results should not be taken for their absolute values, but rather interpreted as qualitative assessments of the impact of higher substitution alternatives for customers. Second, since our indicator is a ratio of *base case* consumer surplus over *crisis* one, we solely assess the percentage change in welfare, not its absolute value. Different elasticity means different demand curve; therefore, a smaller percentage welfare change does not automatically imply a smaller impact in absolute terms.

As a final note, there seem to be no significant difference in the ranking of countries between the short and the long-term framework. The lowest scoring countries stay on the bottom of the scale (e.g Turkey, Ukraine or Finland), the medium scoring are in the middle in both cases (e.g. Czech Republic, Germany or Great Britain), whereas the highest ranked one always achieve the best grades (e.g. Belgium, France or Portugal).

5.1.3. Comparison Security of Supply Metrics

In order to grasp how our metrics performs compared to other evaluation methodologies, we further compare it to several commonly used indicators. Specifically, we calculate the Herfindahl-Hirschman index (HHI) for supplier concentration, the Shannon-Wiener one (SWI) as well as its augmented version, the Shannon-Wiener-Neumann index (SWIN2) (von Hirschhausen & Neumann, 2013). In parallel, we also display some of the values of other metrics found in the literature; namely the S/D indicator from Jansen & Seebregts (2010), the REES from Le Coq & Paltseva (2009) and the EU's N-1 (European Commission, 2014b).

Table 3 displays the value of our indicator Φ_n for selected European nodes alongside the aforementioned indexes. Since all indicators use different scales and to ensure the readability of the table, we cluster all indicators from one, being the best achieved result, to five, the worst one.

Table 3: Comparison of Security of Supply Metrics

	Φ_n^{ST}	HHI	SWI	SWIN2	S/D	REES	N-1
AUT	2	4	4	4	4	5	2
BEL	1	4	4	2	4	2	1
CHE	1	1	1	1	n/a	n/a	2
CRO	3	1	1	2	n/a	n/a	4
CZE	3	2	1	3	2	4	1
DNK	2	5	5	5	1	1	2
ESP	3	4	4	4	n/a	2	3
FIN	5	5	5	5	4	3	4
FRA	1	3	3	1	2	2	3
GBR	4	3	4	2	1	1	3
GER	3	2	3	1	3	3	1
GRC	4	1	2	3	n/a	4	5
HUN	3	2	2	4	4	5	4
IRL	4	1	2	1	n/a	1	2
ITA	4	1	2	2	5	4	4
POL	5	5	5	5	3	2	4
PRT	2	3	3	2	5	3	4
ROU	4	3	4	4	2	4	3
SVK	1	4	5	5	5	5	1
SVN	2	2	1	3	n/a	3	5
SWE	2	3	2	3	2	1	5
TUR	5	2	3	4	n/a	n/a	n/a
UKR	5	5	5	5	n/a	n/a	n/a
Corr.	-	*-0.02*	*0.17*	*0.28*	*-0.10*	*0*	*0.34*

Note: Values of Φ_n^{ST} and of various supply security indicators for selected European nodes, categorized from one (best achieved value) to five (worst achieved value). Correlation of each indicator with Φ_n^{ST}.

At first glance, one is struck by the heterogeneity of results among the indicators. Unanimous evaluations represent an exception. Ukraine, which achieves the lowest scores in all metrics, and Switzerland, that is awarded the highest grades in all but one indicator, are the two best aligned countries—although it must be noted that not all indicators are available for these two countries. Rather well aligned results are for example: Finland, negatively judged by the large majority of indices, Poland, by most of them, or Romania, always scoring in the lower end of the scale. On the other hand, our Φ-indicator and the N-1 evaluate Austria as secure, whereas the rest of the literature sets the country on the lower end of their scale. The opposite also happens, notably for Greece or Italy, which obtain good results in the diversity-based indicators, but poor ones in the rest. Undoubtedly, the context-dependent nature of supply security and its blurred definition help to explain the heterogeneous results.

The correlation between the current metrics and our Φ-indicator allows to grasp the overall alignment between the methodologies. The best fit is achieved with the N-1 approach. Notwithstanding its limitations, the N-1 possesses some similarities with our methodology in the definition of supply security and the aspect covered, thus explaining the good alignment with our indicator. Further, the correlation between our results and those von Hirschhausen & Neumann (2013)'s SWIN2 is also important, notably explained by the indicator's broader stance on supply security than the simpler HHI or SWI. On the other hand, the IEA's S/D and the plain HHI both have a negative correlation with Φ, while Le Coq & Paltseva (2009)'s REES displays a correlation of zero. Given the important discrepancies in terms of methodology between these indices and ours, one is not particularly surprised by this result. Again, the strongly diverse nature of the supply security notion explain these deviations.

Summing up, we draw two main conclusions from the comparison of our indicator to some of the currently used ones. First, the rather weak correlation between our indicator and the established measurements—or even its absence in some cases—cannot be interpreted as a negative sign for our methodology. All indicators measure different dimensions of supply security, thereby necessarily leading to diverse results. Moreover, the broadest approaches and those which share common characteristics with ours—the N-1 or the SWIN2 for example—display the strongest correlation. This confirms our belief that our methodology covers more dimensions than the current ones. Second, the blurred definition of supply security mechanically leads to very diverse approaches for its measurement. Absent a common and accepted definition, it seems impossible to achieve a common ground so that approaches can truly be compared to one another.

5.2. Policy and network infrastructure scenarios

As indicated above, our indicator can also be used to evaluate different projects or policies aiming to improve supply security. Observing the indicator values in Table 4 for the three infrastructure projects and the storage policy, we notice that, generally speaking, the infrastructure scenarios have a rather modest impact on the European gas security. A majority of countries obtain approximately similar scores in *Baseline* and in *LNG*, *NordStream 2* or *SGC*

& Reverse Flow. Naturally, this holds for countries with an already high level of supply security (among others Austria, Denmark, Spain, France or Sweden). However, low grade ones (for instance Finland or Poland) also tend to be relatively unaffected by the new infrastructures.

Table 4: Impact of Infrastructure extensions and policies on European Supply Security

	Baseline	*SGC RvFl*	*LNG*	*NrdStrm*	*StratSto*
AUT	98.9	98.9	99.0	99.4	100.1
BEL	99.4	99.4	99.4	99.6	100.0
CHE	99.2	99.1	99.2	99.4	99.8
CRO	98.8	98.7	98.8	99.1	99.4
CZE	98.5	98.4	98.5	98.9	99.4
DNK	98.9	98.9	98.9	98.7	98.8
ESP	98.8	98.8	98.8	99.0	99.6
FIN	95.4	95.4	95.4	95.4	95.9
FRA	99.0	99.0	99.0	99.3	100.2
GBR	98.2	98.1	98.2	98.5	98.6
GER	98.5	98.4	98.5	98.7	99.0
GRC	97.1	97.9	97.2	97.3	98.2
HUN	98.5	98.5	98.5	98.8	98.9
IRL	97.9	97.8	97.9	98.3	98.5
ITA	97.5	97.5	97.6	98.0	99.0
POL	96.6	96.6	96.6	96.8	97.7
PRT	98.9	98.9	99.0	98.9	99.2
ROU	97.6	97.9	97.6	97.7	97.1
SVK	99.0	98.9	99.0	99.4	100.0
SVN	99.0	98.9	99.0	99.4	100.1
SWE	98.9	98.9	99.1	98.7	98.8
TUR	96.5	98.5	96.6	96.8	97.2
UKR	94.6	94.8	94.6	94.7	96.6
Mean	*98.1*	*98.2*	*98.1*	*98.3*	*98.8*
Std.dev.	*1.2*	*1.1*	*1.2*	*1.3*	*1.2*

Note: Values of short-term indicator Φ_n^{ST} for various European countries under different infrastructure and policy scenarios:*Baseline*, *Nord Stream 2*, *SGC & Reverse Flow*, *LNG* and *Strategic storage*.

The *SGC & Reverse Flow* project has a limited impact for the European natural gas security. On the one hand, countries directly concerned by the pipeline projects, Greece and Turkey, both obtain a large improvements of their score, up to two percentage points for the latter. On the other hand, neither Italy nor the rest of Europe seems to be significantly impacted by the additional pipelines.

The *LNG* setting also displays an overall minor impact, yet some individual effects are to be noted. Additional regasification plants are planned in Spain, France, and Sweden. Sweden sees its security improved thanks to its enhanced import capacity. France and Spain, since they already benefited from high levels of supply security beforehand, do not, or only marginally, improve their score. Croatia and Poland, who are also planning new LNG terminals, do not display significant variations of their Φ-score. Indirectly, Portugal benefits from the enhanced import capacity of its neighbors. Overall, our indicator shows limited benefits of these additional LNG terminals for the European security of gas supply.

The extension of the Nord Stream pipeline yield higher gains of supply security than the previously tested infrastructures. The positive effects are both apparent for countries situated close to Germany (e.g. Austria, Belgium, France or Switzerland), who benefit from its enhanced import capacity, and in regions more remote (e.g. Croatia, Great Britain, Ukraine or Turkey). The latter are indirectly impacted, as the Nord Stream 2 frees up capacity on other import canals, be it from Russia (e.g. towards Ukraine or Turkey) or from further sources (e.g. LNG import capacity).

In opposition to the rather mild effects of the infrastructure projects, our indicator underlines the large gains of supply security achieved through the implementation of a strategic storage policy. As highlighted in Abrell et al. (2019), the policy leads to substantial increase in the average fullness of gas storage. This additional gas is a welcome buffer in case of disruptions, as simulated in our methodology. The buffer can both be used to cover one's own demand and to be shared among European countries. Hence, the effect is important for the players with significant storage capacities as well as for those with limited storage facilities. Thanks to the policy, the vast majority of European countries obtain higher score than without the storage obligation; the average result surges by 0.7 percentage point.

One further notes the presence of indicator values above one for some countries (Austria, Slovenia and France). Since we normalize the consumer surplus during crisis over the one in the base case, this means that, on average, the simulated interruption scenarios cause an augmentation of the welfare in these countries—a puzzling result. Behind this fact lays a simple explanation. As stated above, in the *Stategic storage* setting, we impose a minimum level of all European storage during winter of successively 30% and 20%. This security buffer might only be used in case of stress on the market (i.e. any interruption of a line or collapse of a node) or once the winter is over. For many countries, this lower limit forces them to hold more storage than they would optimally do; hence, the policy yields additional costs for storage holders. The lower bound is removed in all cases of crises, regardless of whether a country is actually affected by the interruption or not. If a country is not impacted by the event, neither in terms of quantity nor of price, but is still allowed to use its security buffer sooner than in the base case, a crisis might turn out to be welfare enhancing for him. Hence, provided a country is rarely impacted by the crises, its average result might lie above the 1.0 value.[4] *Stategic storage* underlines one of the

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[4] This fact highlights a drawback of our indicator's design when used for policy comparison.

main contribution of our indicator: its broader approach. Indeed, the currently established methodologies are not capable of considering the actual levels of storage as a factor of supply security. Analyzing the positive impact of strategic storage policy would hence prove impossible.

6. Conclusion

While a notion of crucial importance for numerous sectors—food, energy or international trade to name a few— security of supply remains distinctively characterized by a blurred definition and the lack of a broadly accepted measurement method. The currently available methodologies usually rely on narrow approaches, notably focusing on the assessment of the diversification of supplier portfolios or on the simulation of case studies.

Against this background, we propose a novel approach aiming at measuring and evaluating the supply security of industries which rely, physically or conceptually, on a network. We adopt a broad methodology to address some of the caveats of the currently used indices. Our indicator evaluates the impact of various interruptions of the network services on the welfare of the concerned markets, thus exploring supply security in its numerous dimensions. Specifically, the methodology simulates a market model which is put under strain by various scenarios of collapses of its network components (i.e. each line and node). We then evaluate the impact of each crisis on consumer surplus to grasp both the quantity effect (i.e. change in supply) and the price one (i.e. demand reaction). The reduction in consumer surplus is subsequently weighted for each case and averaged to construct our final metrics.

One of novelty of our approach is that we consider both, the demand and the supply dynamics in our assessment, thereby ensuring a comprehensive statement. The chosen methodology further helps to measure the current diversification of supply as well as the potential contributions of substitutes or of additional techno-economical factors, such as storage. Moreover, we base our indicator on the study of crisis scenarios for which we sequentially test all possible occurrences in the network. Finally, the chosen framework allows for the evaluation and comparison of different policies or network extension projects.

To demonstrate the working of our indicator, we test it on the European natural gas market. Our assessment of the current security of gas supply reveals contrasted results for the EU countries. The indicators notably highlights the importance of the diversification of import sources, be it through numerous import canals or through a central geographical position in the network, and of

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The policy or the project simulated do not only impact the capability of the market to react to the crises, they also have welfare implications absent any shortage event. Thereby, the baseline on which the crisis consumer surplus is normalized is changed. One must keep this in mind when comparing the different results. Our indicator can only be used to assess the relative changes in welfare in the different cases not to derive quantitative estimations of the difference in welfare impacts between various policies.

self sufficiency ratio as drivers of supply security. Furthermore, countries possessing LNG import terminals tend to be better off. Subsequently, we compare our indicator to some of the currently used ones. Significant divergences are observed. The misalignment can notably be explained by the broader stance and the more inclusive approach obtained through our novel indicator.

Finally, we perform a case study of four different measures which are thought to be security of supply-enhancing. We assess the impact of two additional pipelines (NordStream 2 and the Southern Gas Corridor project) as well as of new LNG terminals in Europe. All three projects have rather limited benefits for the European security of gas supply, whereas the most notable impacts realize in countries directly concerned with the infrastructures. We further test the implementation of a strategic storage policy, imposing a minimum level of storage at the beginning of the winter. In turn, this policy yields substantial gains of supply security, since it increases the security buffer of storage.

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Appendix

Appendix A. Technical note on the long-term indicator

The nature of our model forces us to employ a counter-intuitive method to compute the long-term indicator. The naive approach would have been to simply use different assumptions on elasticity, and redo the calculations. Yet, this method prevents comparability between the short and the long-term perspectives. Indeed, our model uses a reference point of observed price and quantities on a given market, and assumes an elasticity to compute a linear demand. Changing the elasticity thus means using a different demand curve. In a perfect world, this would not pose a particular problem as both curves would cross each others in the reference point. Yet, since a model is the simplified description of a complex reality, notably in terms of demand curve, our model does not achieve perfect calibration; hence, the model's equilibrium point does not coincide with the observed market one. Owing to this fact, with the aforementioned approach, the two demand curves would cross at the observed market equilibrium, not at the model one. Thereby, we would loose the possibility to compare the results with each others.

To ensure comparability, we force the short and long-term demand curves to cross at the model's equilibrium. To do so, we compute the "achieved" point-elasticity at the equilibrium point of the model. As we use linear demand, this elasticity will be different from the one used for the model's calibration. Once the achieved point elasticity retrieved, we assume an increase of the elasticity by 50% to obtain a long-term one. This process is repeated for each country, consumption sector and time period.

The left part of figure A.1 displays a "perfect world" situation, where the reference point used for the calibration and the model's equilibrium coincide. Here, the long-term demand (D_{LT}) can be derived simply with a different elasticity. On the right part though, since we can only use an approximation of the real supply curve ($\tilde{S}$), the model's equilibrium is different than the reference point. Thus, we have to rely on an approximated long-term demand ($\overline{D}_{LT}$) which crosses the short-term one (D_{ST}) and the approximated supply curve at the model's equilibrium.

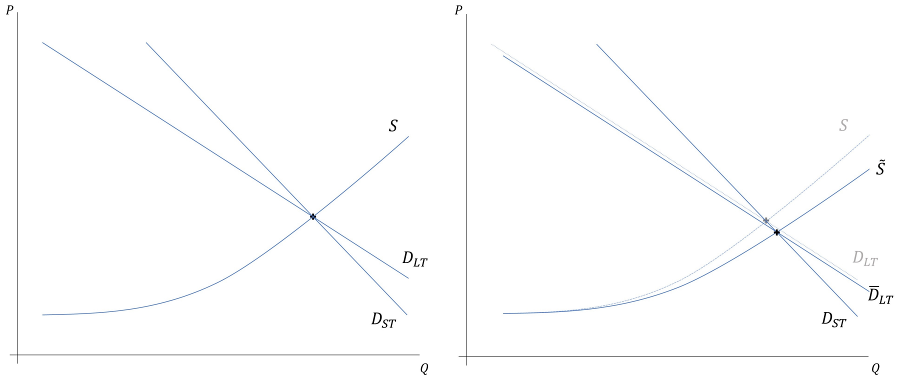

Figure A.1: Left: “perfect-world” formulation of long-term demand (D_{LT}) based on the short-term one (D_{ST}). Right: approximated long-term demand ($\overline{D}_{LT}$) at model’s equilibrium (crossing of $\tilde{S}$ and D_{ST})