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A Solidarity Mechanism to Allocate Stored Natural Gas in Crisis

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Abstract

The interruption of natural gas flows via pipeline to Europe in 2022 has demonstrated that supply crises pose a threat. Although member states have demonstrated unity and solidarity, they could be better prepared to respond to such challenges. Currently, member states fill their natural gas storages independently. Cooperation and solidarity could deliver better outcomes by allowing the accumulated reserves of one or more members to be potentially redistributed to help others in need. In this paper we propose some possible guidelines for a potential solidarity framework based on voluntary participation. We argue that the proposed framework can mitigate the risk of supply-disruption of participants and formalize a game-theoretic model in order to capture the basic features of the problem. We demonstrate the operation of the approach using a simple example with risk-averse participants.

JEL Classification: C51, C63, C72, L95, Q40

Keywords

gas supply security, EU, solidarity mechanism, reserve sharing, computational modeling

1. Background

In 2022, the EU experienced its first energy crisis since the oil price crisis during the 1970s. One of the key fuels in European energy consumption is natural gas, a significant part of which is imported. Natural gas can be stored and thus potentially compensate for seasonal demand imbalances. During summer (usually with lower prices than in winter) natural gas is accumulated in storage facilities from where it is withdrawn during the winter period to meet higher demand for heating. Storage typically provides 25 percent to 30 percent of natural gas consumed in the EU during winter, however the extent to which storage is used in EU member states differs significantly. This is due to heterogeneous size of storage infrastructure capacities, the corresponding difference in technically available working gas capacities, and the different amplitudes of seasonal swing (i.e., less need for

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heating in southern countries). In addition, not only do sizes of storage capacities vary from zero to twenty-four bcm (Germany) among EU member states, but also owenership. The current European regulatory framework (amended in 2022) allows Member states to regulate third party access to storage facilities (negotiated or regulated). Hence, although third party access is compulsory it rarely delivers “market” outcomes in practice. This holds especially in a crisis situation when short-term action is required. In some countries, all facilities are operated by independent companies (Belgium) others are state-owned (France, Denmark) and in some countries, both public and private companies are active (Germany; IEA 2022). In Italy, around 90 percent of total storage capacities are controlled by the state. In France, there is neither public nor strategic storage. In Spain, 90 percent of capacities are independent. In Hungary, all commercial facilities are state-owned, while in Poland around 72 percent are state-owned and 28 percent of PGNiG are independent. In Germany, the largest player in terms of size, around one quarter is state-controlled (the Government recently expropriated Gazprom and took over their capacities).

During the first year of war it seemed possible (if not likely) that most of European gas storages would be depleted during the winter period and several European countries would not be able to re-fill during summer 2023 to levels necessary to ensure security of gas supply for Winter 2023/2024 (Zeromski, Watine, and Reberol 2022). As of date there exist no official guidelines on cooperation mechanisms between Member States and efficient utilization of underground storage facilities in order to ensure security of supplies during crisis. While there are multiple gas exchanges (like TTF, the Dutch Gas exchange or THE, the German gas exchange) and other decentralized trading mechanisms in place in the EU, in the time of crisis, supply typically drops significantly at these trading platforms, preventing member states in need from procuring the required gas quantities at reasonable price. In this paper we propose a framework, in which participants agree on guidelines of redistribution and compensation before the onset of the shortage.

It is worth noting that both the share of natural gas in primary energy, and the distribution and use of storage capacities, vary considerably across Member States. Whereas storage capacities were filled at almost 95 percent on average in the EU at the beginning of November 2022, 14 percent were left unfilled in Hungary.[1] Hence, in the case of emergency and the need for solidarity it would be useful to have a transparent mechanism in place. Such mechanism should be based on optional participation and designed such that it is sufficiently attractive (beneficial) for decision makers to cooperate. The related literature for such a mechanism is scarce. While there are several examples for the application of game theoretic methods for oil and gas related problems (see, e.g., Araujo and Leoneti 2018; Hubert and Cobanli 2015; Jafarzadeh et al. 2021; Roson and Hubert 2015; Toufighi 2022), and for quantitative models describing the role of underground storage on the dynamics of competitive markets (see, e.g., Rubaszek and Gazi Salah 2020) quantitative models related to the coordinated use of storage in crisis in the EU are—to the best of our knowledge—lacking. Although there exist models describing reservoir operation in the context of economic implications of CO_2 storage (Schaef et al. 2014; Zhang et al. 2007), the literature on the concept of storage facility sharing is very scarce. Holland (2009) and Holland and Walsh (2013) consider the sharing of a single reservoir while taking into account characteristic technological features, but there are no analyses of sharing of multiple storages in a networked setting under uncertainty. Kiely (2016) investigates accumulation and redistribution whilst taking into account risk-pricing related to natural gas storage. Janjua et al. (2022) analyze redistribution and present an asymmetric hybrid bankruptcy and Nash bargaining model for natural gas distribution. Schitka (2014) and Rey (2020) capture the simultaneously competitive and cooperative aspects of gas-related issues.

[1] Note that in June 2021 Hungary’s capacities were filled at almost 58%, the average European level was only 38% (Gas Infrastructure Europe, AGSI

The goal of this paper is to provide a framework for a supply security cooperation mechanism assuming voluntary participation and financial compensation. For this we formulate and analyze a stylized cooperation model. Although we account for financial compensation in the model, we assume that compensation prices are inherently determined by the parameters defined by the participants at the beginning of the cooperation and are not affected by actual prices at the time of the crisis when the potential redistribution takes place. We demonstrate the operation of the proposed mechanism under the assumption of risk-averse participants and discuss possible critical issues related to implementation possibilities.

2. The Proposed Solidarity Mechanism

In this section we present the underlying key assumptions of the proposed mechanism, introduce the formal game and the corresponding network model.

2.1. Basic Assumptions

We study the interaction of strategic decision makers of countries, who aim to cover the energy demand of the country's economy. These entities, who will correspond to the players of the implied game, may be best interpreted as state-owned national energy companies, who have access to storage facilities. These companies are also for-profit firms, but their decisions are subject to governmental policies.

The proposed solidarity framework is interpreted in an environment where every potential participant (player) individually bargains with external suppliers in order to fill its storage capacity for the winter period. However, the success of this bargaining is (at least partially) uncertain at the time of solidarity contracting.

According to the proposed framework, solidarity contracting, which represents the first phase of the mechanism, takes place in the spring period, before any player would begin to gather resources. In this period, every player has to decide whether or not to participate in the proposed cooperation framework. The voluntary aspect of the proposed mechanism implies that each participant has the exclusive right to determine this value $\left(q^P\right)$. If a player n decides positively, it defines its nonzero level of participation $\left(q^P(n) > 0\right)$. No participation corresponds to $q^P(n) = 0$. This value limits the quantity that could be taken away from the player to serve others, and also the quantity that could be received by the player during the redistribution process. If $q^P(n) > 0$ applies, the participant also reports its expected demand in the form of a piece-wise constant inverse demand function. The assumption regarding the piece-wise constant nature of the reported functions helps to limit the computational demands. The multiple piece-wise constant parts (i.e., steps) of these functions may be interpreted as various components of the total individual demand of a player (i.e., the total demand of a country), corresponding, for example, to domestic demand (e.g., residual heating), heating demand of public/governmental entities, industrial demand and so on. The different importance of such components is represented by the different price of the relevant step in the function, characterizing the demand elasticity of the player in question [2].

Phase two of the mechanism, when the redistribution and the connected compensation takes place, corresponds to the winter period, when higher demands and potential resource shortages arise. We assume that at the beginning of the second phase, the following factors, which are still uncertain in phase one, are already determined and known for all participants: (1) The quantity of accumulated resource available to individual participants and (2) the actually available network transmission capacities. In the second phase, resources are redistributed among participants

[2] Note that revealing such information may negatively affect bargaining potential of participants in latter transactions. Thus, these reported data should be handled as confidential.

with non-zero participation levels, according to individual needs, to previously determined levels of participation and considering the available transmission capacities. In other words, resources subject to the solidarity mechanism are routed to those participants who are in the highest need according to the demand data reported in phase one, taking into account network constraints. Decision variables of this phase are line flows and consumption/injection values at each of the nodes of the network. Players who have chosen not to participate in phase one do not receive any additional resource during the redistribution process, but can fully use their accumulated resources. Furthermore, if any non-zero redistribution transactions take place, the participants from whom resources are reallocated to other players are financially compensated, and the compensation price is determined according to the previously reported (inverse) demand functions.

The solidarity mechanism may be viewed as a special secondary market with obligatory participation by those players who decided to declare a nonzero level of participation. In the following we show how the elements of the above solidarity mechanism may be formalized using a computational model, and how such a model may provide insight into the potential operation of, and strategic decisions in, the framework.

2.2. Formal Game Theoretic Model

It is easy to see that the participation levels and demands reported by other players affect the potential benefit the solidarity mechanism provides to any single player (e.g., if only a single player participates, no redistribution may take place). Thus, the proposed supply-security related accumulation-redistribution process can be formally described as a game. For this we define the class of transaction-constrained resource-redistribution games under uncertainty (TCRRGU), and demonstrate the operation using an example. The proposed TCRRGU framework is based on a strategic game in which the strategic decisions of the players correspond to the choices of $q^P(n)$ in phase one of the solidarity framework. The payoffs of the players are determined in phase two, after the resolution of the uncertainties regarding resource accumulation and transmission capacities available for the redistribution. We assume that every participating player provides its (future) natural gas demand in the form of a parametrized inverse demand function that forms the basis for the latter redistribution processes.

The redistribution process in phase two, which determines the outcome of the game, depends on the determined participation levels, on the accumulated resources and also on the available transport paths, which are subject to uncertainty at the time of solidarity contracting in phase one. For our model we assume that the nature and parameters of uncertainty are known to every player during the bargaining process (i.e., the uncertainty is structured, as described in subsection 2.2.3). In addition, as described earlier, a compensation process is defined related to the redistribution process.

2.2.1. Network Model. The natural gas network is represented by a directed graph with N nodes and M edges where individual nodes represent players of the game. Each edge m is characterized by direction-dependent capacity values. $q^+ \in R^M > 0$ and $q^- \in R^M < 0$ denote the maximal transfer capacity vectors of edges in the positive and negative direction respectively. [3]

The differentiation of transfer capacity over edge directions makes it possible to describe direction-dependent transfer capacity of pipelines, which may, for example, depend on the presence of compressor stations along the pipeline.

[3] Taking into account a sign convention, i.e. the maximal transferable quantity of edge m in the negative direction is equal to $-(q^-(m))$. This allows us to use a single variable for the description of the flow on the edge, the sign of which defines the direction of the flow.

2.2.2. Consumer Demand. We assume that the piece-wise constant inverse demand functions reported by the players are composed of W steps. Each piece-wise constant part is characterized by two parameters: A price $\left(p^c\right)$ and a consumption quantity $\left(q^c\right)$. In this formalism $p^c_{n,j}$ denotes the price (per unit) level of the $j-$th step of the inverse demand function of player n, while $q^c_{n,j}$ defines the quantity (width) of the j-th step $\left(j \in \{1,...,W\}\right)$.

2.2.3. Uncertainty. We take uncertainty into account on two levels. First, we assume that resource accumulations by players between phase 1 and 2 are uncertain. Second, we assume that available capacities for redistribution in phase two are also uncertain because of technological factors (e.g., completion or delay of projects or possible faults) and external flows might limit the redistribution of resources. Flows are "external" when they are not related to the supply-security cooperation.

Uncertainty is represented in the model by a finite number of "*states of nature*" or "*scenarios*," one of which is randomly realized at phase two. The total number of scenarios is equal to S. State of nature s occurs with probability p_s at the second phase and $\Sigma_{s=1}^{S} p_s = 1$. This representation of uncertainty modeling is, for example, used in the financial literature discussing risk measures and allocations (see, e.g., Csóka, Herings, and Kóczy 2009). In our model each scenario s is characterized by an ordered tuple $\left(r_s, q_s^-, q_s^+\right)$, where $r_s \in R^n$ defines the amount of resources available for the players in the case of the scenario s, while $q^- \leq q_s^- \leq 0$ and $0 \leq q_s^+ \leq q^+$ define the available transfer capacities of edges in the case of the scenario s.

2.2.4 The Redistribution Process. Let us assume that the vector describing the levels of participation, denoted by $q^P \in R^N$ is defined (the $n-$th element of the vector is q_n^P, the participation level of player n). The redistribution process is described by an optimization problem, where the resources subject to the solidarity mechanism that are available in the particular scenario $\left(r_S\right)$ are redistributed to maximize the total utility of gas consumption, according to the predefined inverse demand functions (i.e., gas is routed to those who need it most), while considering the participation levels and transmission constraints of the scenario. The linear program of the redistribution process in the case of scenario s is described by the formulas (1) to (3).

$$\max_x \; gx \quad \text{w.r.t.} \tag{1}$$

$$-q^P(n) \leq \sum_{i \in E_n^{in}} f_i - \sum_{i \in E_n^{out}} f_i \leq q^P(n) \quad \forall\, n \tag{2}$$

$$\sum_{i \in E_n^{in}} f_i - \sum_{i \in E_n^{out}} f_i - \sum_w c_{n,w} + r_s(n) = 0 \quad \forall\, n \tag{3}$$

The variable vector $x \in R^{M+nW}$ of the problem is composed as

$$x = \begin{pmatrix} f \\ c \end{pmatrix}. \tag{4}$$

$f \in R^M$ denotes the vector of edge flows $f = \left[f_1, ..., f_M\right]^T$, where f_m is the signed flow of edge $m \left(q_s^-(m) \leq f_m \leq q_s^+(m)\right)$, and $c \in R^{nW}$ is the vector of consumptions $c = \left[c_{1,1}, c_{1,2}, ..., c_{N,W}\right]$, where $c_{n,w}$ is the consumption related to the $w-$th step of the inverse demand function of player $n\left(0 \leq c_{n,w} \leq q^c_{n,w}\right)$.

The objective function, described by (1), where g is composed as $g = \left[0^{1\times M}, p^c_{1,1}, ..., p^c_{N,W}\right]$, is defined in order to maximize the consumption utility $\left(U^c\right)$ of participants. Let us note however that the objective function coincides with the total consumption utility of players only in the case when the players truthfully reveal their real consumption demands when reporting the values of the inverse-demand functions. Later, in subsection 4.2, we briefly address the issues related to this aspect.

Constraint (2) describes that the difference of the total inflow and outflow of any node is constrained by the respective participation level $\left(q^P\right)$ from both above and below for each node n. In this formalism, E_n^{in} and E_n^{out} denote the set of incoming and outgoing edge indices of node n respectively. The conservation constraint (3) describes that the sum of inflows minus the sum of outflows must be equal to the consumption minus the available resources for each node n. Let us note that in the current work we restrain ourselves to model only the redistribution of stored gas quantities. However the applied model may be straightforwardly extended to consider the uncertainty of the availability of pipeline gas as well, interpreted as potential inputs at different nodes of the network, described by parameters which are also subject to scenario-dependent uncertainty.

2.2.5. Compensation. During the redistribution process (if the outcome is non-trivial, that is, a nonzero redistribution takes place, producing flows in the network), the reserves (and thus the consumption utility) of some participants are decreased, while those to whom the gas is redistributed gain additional consumption utility. The resulting consumption utility $\left(U^c(n)\right)$ of each player n may be easily derived based on the respective inverse demand function, and the consumption values $\left(c_{n,w}\right)$, as described by equation (5).

$$U^c(n) = \sum_w c_{n,w} p_{n,w}^c \tag{5}$$

The proposed framework assumes that players receiving additional gas during the redistribution have to financially compensate those suffering a decrease in reservoir levels Accordingly, the financial utility of player n $U^f(n)$ is defined simply as the amount of money they receive or pay in the redistribution process. This value is nonzero if and only if resource is allocated to them from other participants or rerouted from them to other players. Furthermore, $\Sigma_n U^f(n) = 0$. The compensation is based on the redistribution clearing price (RCP_s denotes the redistribution clearing price in the case of scenario s). RCP_s is calculated as follows. If a nonzero redistribution takes place, the resulting consumption for at least a subset of players is not equal to the resources originally available for them. The marginal increment in $U^c(n)$ in the case of the scenario $s\left(\mu_s(n)\right)$ is defined as the consumption utility increment (or decrement) implied by the last unit of gas redistributed to (or from) n.

2.2.6. Risk Measurement and Aversion. Let us emphasize that the model elements described up to this point are the principles, which may serve as the basis for a voluntary redistribution mechanism (based on the choice of $q^P(n)$ for each player n). In the following we discuss how the players of the game choose their level of participation in the mechanism. In order to do this, we have to define how players of the game measure the risk in this context. For this aim, we will use the concept of expected shortfall (ES; Acerbi and Tasche 2002; Adam, Houkari, and Laurent 2008), which is a coherent measure of risk (Artzner et al. 1999). The α-expected shortfall is calculated as the expected value of the worst $\alpha\%$ of the scenarios. In the context of the proposed game-theoretic model, the strategic aim of the players is to minimize the ES of their consumption utility values $\left(ES(U^C)\right)$, assuming that they are aware of the details of the later redistribution mechanism, and the related optimization process. In the next section, using an example, we show that risk-aversion of players is sufficient to motivate them to participate in the proposed framework.

3. Example

Figure 1 depicts the network of the considered simple example, with $N = M = 3$, where the edge labels include the index of the edge (m), and the $\left(q^-(m), q^+(m)\right)$ values. Nodes are labeled with their indices (n).

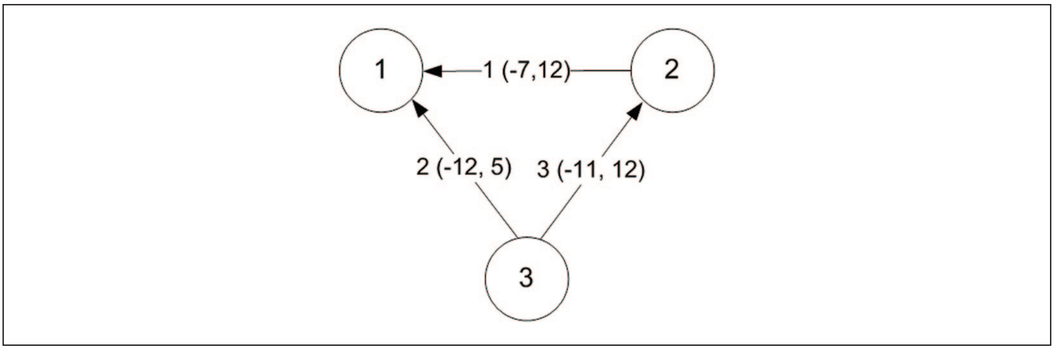

Figure 1. Simple example network network. Edges are labeled with their index m, and $q^{-}(m)$ and $q^{+}(m)$ in parentheses.

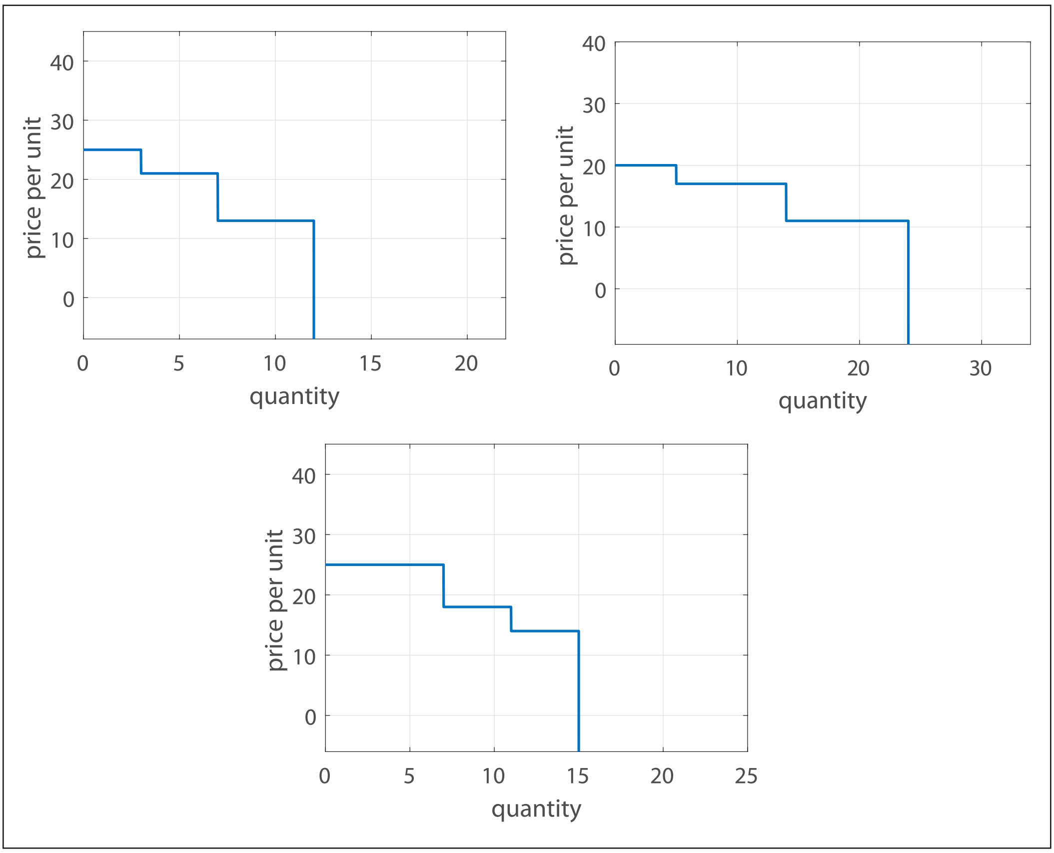

Figure 2. Inverse demand functions of consumers.

The parameters of the demand functions used in the example and depicted ion Figure 2 are summarized in Table 1.

To represent the uncertainty in our simple example, assume $S = 4$ and $p_s = 0.25 \ \forall s \in \{1,...,S\}$. Furthermore let the scenario parameters be as described in equations (6) and (7), where q_s^{+} and q_s^{-} are describing the available edge capacities in the case of scenario s regarding positive and

Table 1. Parameters of the Inverse Demand Functions Considered in the Example.

$p^c_{1,1}$	25	$p^c_{2,1}$	20	$p^c_{3,1}$	25	$q^c_{1,1}$	3	$q^c_{2,1}$	5	$q^c_{3,1}$	7
$p^c_{1,2}$	21	$p^c_{2,2}$	17	$p^c_{3,2}$	18	$q^c_{1,2}$	4	$q^c_{2,2}$	9	$q^c_{3,2}$	4
$p^c_{1,3}$	13	$p^c_{2,3}$	11	$p^c_{3,3}$	14	$q^c_{1,3}$	5	$q^c_{2,3}$	10	$q^c_{3,3}$	4

Table 2. Resulting Consumption and Financial Utilities and RCP Values in the Example. In the Rows of U^c the Original U^c Values Without Redistribution is Indicated in Parentheses.

Scenario	1	2	3	4
$U^c(1)$	198 (224)	159 (138)	172 (198)	159 (138)
$U^c(2)$	253 (219)	308 (330)	253 (275)	264 (286)
$U^c(3)$	261 (261)	289 (275)	261 (193)	289 (275)
$U^f(1)$	30	−12.5	27	−12.5
$U^f(2)$	−30	25	27	25
$U^f(3)$	0	−12.5	−54	−12.5
RCP	15	12.5	13.5	12.5

negative directions respectively, and r_s is the vector of available resources (gas amount in the storage) in the case of the scenario $s\left(r_s(n)\right)$ corresponds to the resource of player n).

$$\begin{gathered}
q_1^- = \begin{pmatrix} -7 \\ -3 \\ -4 \end{pmatrix} \; q_1^+ = \begin{pmatrix} 7 \\ 5 \\ 12 \end{pmatrix} \; q_2^- = \begin{pmatrix} -5 \\ -12 \\ -7 \end{pmatrix} \; q_2^+ = \begin{pmatrix} 12 \\ 0 \\ 12 \end{pmatrix} \\
q_3^- = \begin{pmatrix} -1 \\ -12 \\ -1 \end{pmatrix} \; q_3^+ = \begin{pmatrix} 12 \\ 1 \\ 12 \end{pmatrix} \; q_4^- = \begin{pmatrix} -5 \\ -12 \\ -6 \end{pmatrix} \; q_4^+ = \begin{pmatrix} 12 \\ 0 \\ 12 \end{pmatrix}
\end{gathered} \tag{6}$$

$$r_1 = [12\ 12\ 12] \quad r_2 = [6\ 21\ 13] \quad r_3 = [10\ 16\ 8] \quad r_4 = [6\ 17\ 13] \tag{7}$$

To give an example for the calculations of the compensation mechanism, assuming the inverse demand functions depicted in Figure 2 and summarized in Table 1, if player 3 had originally five units of gas in the case of scenario $s\left(r_s(3) = 5\right)$ and during the redistribution it receives an additional five units $\left(\Sigma_w\, c_{3,w} = 10\right)$, then $\mu_s(3) = 18$, since the last unit of received gas implied increased $U^c(n)$ by eighteen units. According to this, RCP_s is defined as described in equation (8).

$$RCP_s = \frac{\min_{n:\mu_s(n)>0} \mu_s(n) + \max_{n:\mu_s(n)<0}\left(-\mu_s(n)\right)}{2} \tag{8}$$

Thus, the financial utilities of players, denoted by U^f are determined by transactions related to redistribution, cleared on the price of RCP_s. As RCP_s is always higher than the marginal consumption utility of any player from whom gas is rerouted to others, and always less than the marginal utility of any player receiving gas, the sum of the change in the consumption utility due to redistribution $\left(\Delta U^c\right)$ and the financial utility $\left(U^f\right)$ is always nonnegative for each player by construction.

3.0.1. Example Scenario Calculation. Before we discuss the questions related to the determination of q^P values, to give an example, let us calculate the outcome of scenario 1, assuming $q^P = [2\ 2\ 4]$.

According to equation (7), the available resources are equal to twelve units for each of the players in the case of this scenario. If we solve the optimization problem (1) to (3) taking into consideration the inverse demand functions defined in Table 1 (and depicted in Figure 2), and the pipeline capacity constraints defined in equation (6), we obtain the solution, in which two units of gas from player 1 are redistributed to player 2, via edge 1 (implying a flow of −2 because of the opposite flow compared to the reference direction of the edge). This implies that the vector of consumption utilities $\left(U^c\right)$ changes from $[224\ \ 219\ \ 261]$ (the reference U^c vector of the scenario, implied by r_1 without redistribution) to $[198\ \ 253\ \ 261]$ thanks to the redistribution process. In this case $RCP_1 = 15$, implying $U^f = [30\ \ -30\ \ 0]$.

We may calculate the other scenarios similarly. In scenario 2, two units of gas are redistributed from player 2 to players 1 and 3 (one unit for each), implying a resulting $U^c = \left[159\ \ 308\ \ 289\right]$ and $U^f = [-12.5\ \ 25\ \ -12.5]$. Regarding scenario 3, players 1 and 2 both provide two units of gas for player 3, resulting in $U^c = \left[172\ \ 253\ \ 261\right]$ and $U^f = [27\ \ 27\ \ -54]$. Finally, in scenario 4, two units of gas are redistributed from player 2 to players 1 and 3 (one unit for each), implying a resulting $U^c = [159\ \ 264\ \ 289]$ and $U^f = [-12.5\ \ 25\ \ -12.5]$. Table 2 summarizes the utility results for the various scenarios.

Turning to the risk measure defined in subsection 2.2.6, we assume that the players consider the value of U^c as basis of their calculations, and in this simple example we use the $\alpha = 25\%$ expected shortfall. In this very case, the ES value of each player may be calculated as taking the worst U^c value over the possible (4) scenarios.

We may compare the ES values of players, without or with cooperation, assuming $q^P = \left[0\ \ 0\ \ 0\right]$ and $q^P = \left[2\ \ 2\ \ 4\right]$, respectively. Based on Table 2 we may easily conclude, that the ES values are increased with the cooperation: From 138 to 159, from 219 to 253 and from 193 to 261 in the case of player 1, 2, and 3, respectively. Overall, the sum of ES values is increased from 550 to 673. This increase in the ES values of players clearly shows that cooperation (with $q^P = \left[2\ \ 2\ \ 4\right]$ in this case) reduces the risk for all participating players.

3.0.2. The Implied Strategic Game. Are the values $q^P = \left[2\ \ 2\ \ 4\right]$ the most efficient choices for players to reduce risk, that is, to maximize their ES values in the current context? In general, the resulting ES value of player n in the case of choosing $q^P(n)$ clearly depends on the choice of q^P of other players (e.g., if other players choose $q^P = 0$, it is sure that the cooperation will not bring any benefit for player i). Thus, the framework defines a nonzero-sum matrix game, where the strategy space of the players is given by their possible choices of q^P, and their payoff is their respective ES value in the resulting multi-player strategy space. If we constrain the possible set of choices for q^P to integer values for simplicity, we can also state that $q^P = \left[2\ \ 2\ \ 4\right]$ is a Nash-equilibrium of this non-cooperative game.

4. Discussion

4.1. Equilibrium Aspects

The reader may ask how the equilibrium point of the example has been determined, or in general, how is it possible to determine equilibrium point(s) of the implied non-cooperative game. Although a deep discussion of the equilibrium properties of the non-cooperative game class implied by the TCRRGU problem is beyond the scope of this article, we can make some observations.

Since the expected benefit of participation in the mechanism strongly depends on the defined participation quantities of other players, an iterative scheme (repeated game) may be used for the definition of the q_n^P values, which potentially allows the players to reach a Nash equilibrium.

The iterative application of best-response strategies (see, e.g., Csercsik and Sziklai 2015) potentially leads to equilibrium. In the case of the proposed example, the initial q^P vector was determined

Table 3. Some Equilibria of the Model and the Resulting Sum of the Expected Shorfall (ES) Values.

q^P	$\Sigma_i ES_i$
[0 0 0]	550
[2 2 4]	673
[1 2 3]	659
[3 3 5]	687

based on the parameters of the inverse-demand functions, as $q^P(0) = [5\ \ 10\ \ 4]$, that is, all players defined their initial q^P value as the quantity parameter of the last step of their inverse demand function. Iterating the best response functions in this case led to an equilibrium after three steps.

Even in the case of the proposed simple example, this equilibrium is not unique. As Table 3 shows, several other equilibria of the implied strategic game exist and they may correspond to lower or higher values of the total expected shortfall, that is, they are differently efficient in the context of risk reduction.

4.2. On incentive Compatibility

Let us return to discuss a key assumption of the proposed framework. The cooperation framework is based on the reported inverse demand functions, which are used in the objective function of the optimization steps. It is easy to see that a player submitting an inverse demand function with high price parameters is likely to gain gas in most of the scenarios. However, the RCP is also determined by marginal utilities, and such a strategy will likely result in a higher RCP, implying greater loss for the player through U^f (since the player will have to pay for the gas received). Let us emphasize that this does not mean at all that the proposed framework necessarily motivates players to reveal the parameters of their true inverse-demand functions—this, and more details related to incentive-compatibility (Nisan et al. 2007) may be the subject of later studies.

4.3. Potential Practical Implementation

The proposed model made the further simplifying assumption that the possible scenarios and their realization probabilities are determined and known for each player. In practice, the uncertainty is much less exactly defined, various players potentially have different beliefs about it, and they calculate their risk measures and strategies according to these individual considerations. In other words, an abstract game such as the one proposed will never be realized in practice, which also implies that the theoretical properties of the proposed formal model briefly discussed above (equilibrium aspects and incentive compatibility) would have moderate significance in the case of a potential real-world application. Nevertheless, some elements of the proposed model and its solution concepts (like reporting of inverse demand functions, iterative determination of the levels of participation) may represent useful approaches in the process of designing realistic mechanisms in the future.

Our main aim in this article was to show that under textbook-like simplifying assumptions, such a mechanism based on voluntary participation may indeed work and could have practical value. The more fundamental question one would like to answer is "*How can supply-security related cooperation of the EU-member countries be improved, and the more (internationally) efficient usage of storage facilities be enabled*."

5. Conclusions

There are two possible ways of using storage facilities to enhance the supply security of the EU in future years. (1) Constitute EU-level reserves and redistribution mechanisms, which aim to help the member states in potential future need. Since under the current circumstances, the construction/exploitation of new reservoirs and gas for this aim do not seem to be realistic in the short term, this approach would require the partial expropriation of national gas reserves and/or storage capacities. Such centralized approaches are likely to meet resistance by countries who consider that they previously sacrificed more than others to ensure their own supply security. We do not argue that such initiatives are necessarily doomed, but it is possible that obtaining sufficient political support for such a regulation framework will be challenging. (2) The EU might also act as a catalyst of voluntary supply security cooperations by defining the appropriate transparent and predictable regulatory frameworks. Such approaches may complement or maybe even partially substitute for the initiatives of the first type to further enhance the dynamism and flexibility of the reaction of the Union in the case of an emergency event. Based on simple computational modeling studies, this paper argues that multilateral voluntary supply security cooperation mechanisms may have significant potential in encouraging voluntary participation and reducing the individual risk of participants.

6. Appendix

Table 4 summarizes the abbreviations and notations used throughout the mathematical formalisms of the paper.

Table 4. Abbreviations and Notations Used in the Model.

Abbreviation/notation	Meaning
TCRRGU	Transaction-constrained resource-redistribution games under uncertainty
$q^P(n)$	Level (amount) of participation of player n
N	Number of players/nodes of the network
M	Number of edges (pipelines) of the network
$q^+(m) / q^-(m)$	Signed maximal capacity of edge m in the positive and negative direction $\left(q^+(m) \geq 0, q^-(m) \leq 0\right)$
W	Number of steps in the inverse demand function of players
$p^c_{n,w}$	Price parameter of the $w-$th step of the inverse demand function of player n
$q^c_{n,w}$	Quantity parameter of the $w-$th step of the inverse demand function of player n
S	Number of scenarios
p_s	Probability of scenario s
$q_s^+(m) / q_s^-(m)$	Signed edge capacities in the case of scenario s
$r_s(n)$	The amount of resources available for player n in the case of scenario s
f_m	Flow on edge m
$c_{n,w}$	Consumption related to the $w-$th step of the inverse demand function of player n
$U^c(n)$	Consumption utility of player n
g	Objective vector of the redistribution problem
RCP_s	Redistribution clearing price in the case of scenario s
$\mu_s(n)$	Marginal utility increment of player n in the case of the scenario s
$U^f(n)$	Financial utility of player n
ES	Expected shortfall

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Supplemental Material

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