Journal of Natural Gas Science and Engineering 3 (2011) 341–348

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Modeling the European natural gas market during the 2009 Russian–Ukrainian gas conflict: Ex-post simulation and analysis

Stefan Lochner*

Institute of Energy Economics at the University of Cologne (EWI), Vogelsanger Str. 321, 50827 Cologne, Germany

ARTICLE INFO

Article history:
Received 28 January 2011
Accepted 31 January 2011
Available online

Keywords:
Natural gas market
Security of supply
Russian exports
Economic modeling

ABSTRACT

Analyzing short-term security of supply or the degree of physical market integration in the European gas market requires models with high spatial and temporal granularity which allow to do so in a comprehensive manner taking interdependencies in the supply infrastructure into account. This paper presents an infrastructure and dispatch model of the European gas market which enables such analyses. The ex-post application of the model to the January 2009 Russia–Ukraine crisis yields that the market's reaction to the crisis was close to the optimal least-cost response implying a very efficient handling of the transit disruption by the gas sector. While large diversions of gas flows from the west to the east were possible, a high dependence on one import route, limited infrastructure flexibility and storage volumes in eastern Europe hampered security of supply in this region. Generally, the results confirm the importance of gas stocks in mitigating risks from supply disruptions as additional storage withdrawals compensated more than two thirds of supply shortfalls during the crisis. Further simulations also demonstrate that increasing flexibility of the transport system (reverse flow capabilities) enhances security of supply for further consumers in eastern Europe, but not for all of them.

1. Introduction

With a total market share of 25 percent, Russia is the single largest supplier of natural gas to the European Union. As there does not yet exist a direct transportation route from Russia into the EU (with the exception of pipelines to Finland and the Baltic states), the majority of the gas volumes are transported via (non-EU) transit countries. These are mainly Belarus and Ukraine, with the latter one transiting 65 percent of total Russian exports to the Europe, or more than 100 billion cubic meters of natural gas per year (see (BP Statistical Review of World Energy, 2010)).

In January 2009, these transits via Ukraine were halted for almost two weeks. This constituted the longest and most severe disruption of natural gas imports into Europe since the commodity is imported - even during the Cold War western imports from the Soviet Union were never severely disturbed. The cause of the crisis, a failure to agree on new gas purchasing and gas transit contracts and the settlement of outstanding debt for previous imports by Ukraine, is not the focus of the paper. The conflict was finally resolved when both countries agreed to a 10 year contract which envisages the gradual increase in both transit fees and natural gas prices to the European level. (An extensive account of the political and economic reasons and consequences of the crisis is for instance provided by Pirani et al. (2009)).

At the focus of this analysis are the gas sector's immediate reaction to and the consequences of the supply disruption during the January 2009 crisis. The latter differed greatly between countries within Europe: In some eastern European countries, disruptions were severe with some observers even speaking of humanitarian emergencies in the Balkans as household consumers could not continue to heat their homes during the cold winter (Pirani et al., 2009). In central and western Europe, practically no shortages for consumers were observed. Apart from initial price spikes, even natural gas prices at the various western European trading point rose only slightly during the crisis.

To investigate why consumers were affected differently and to evaluate the measures taken during the crisis requires a detailed short-term modeling of the European gas supply infrastructure taking interdependencies in the gird into account.

In this paper, we present a model of the European gas market with high spatial and temporal granularity which allows such analyses. The model is applied to an ex-post investigation of the security of supply situation in January 2009 by replicating the disruption scenario in the model. Thereby, we simulate and investigate natural gas flow diversions, price effects and their implications on security of supply. The benchmark results from the

* Tel.: +49 221 27729 303.
E-mail address: Stefan.Lochner@uni-koeln.de.
URL: http://www.ewi.uni-koeln.de.

1875-5100/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jngse.2011.01.003

model, i.e. how an efficient and competitive market would have optimally responded to the crisis allows us to further evaluate actual observations in the gas market.

The next section describes the applied model and the assumptions of the simulations. The results are then presented in three categories: First, we simulate natural gas flows in the European natural gas market during the crisis to show how flows were diverted compared to the normal situation. The same is done for modeled locational short-run marginal gas supply costs for the European natural gas market: They can be interpreted as price estimators. Secondly, model results with respect to gas flows and prices are quantitatively and qualitatively compared with actual observations in the market during the crisis. Finally, we perform a scenario analysis removing some of the constraints provided by the infrastructure, e.g. non-reverse flow capabilities of some pipelines. This demonstrates how relatively small investments in market integration, such as the one which were implemented in the aftermath of the crisis, can improve security of supply for some of the severely affected consumers in eastern Europe. The final section offers some concluding remarks.

2. Methodology

To analyze gas flows and price effects in January 2009, we apply the TIGER natural gas infrastructure and dispatch model, which was developed to address such issues (as well as the investigation of gas infrastructure projects and analyses regarding physical market integration) in the context of the whole European gas infrastructure. With a daily temporal granularity and the incorporation of capacity data on all major transmission pipelines, gas storages, LNG import terminals (see Fig. 1 and Table 1) as well as regionalized gas supply and demand, the model allows a detailed simulation of the optimal gas dispatch. The model is based on an extensive database of the European natural gas infrastructure by the Institute of Energy Economics at the University of Cologne (EWI).

Table 1
Model characteristics for January 2009.

Covered countries	31
Gas supply regions	19
Demand regions	59
Transmission pipelines	851
Gas Storages	147
LNG regasification terminals	16
System nodes	627
Temporal granularity	Daily
Modeled time period	01/04/08 to 31/03/09

Short-term investigations of the European gas grid with dispatch models are provided by Lochner and Bothe (2007), Neumann et al. (2009), Monforti and Szikszaia (2010), EWI (2010) and Lochner (2011). Lochner and Bothe (2007) develop the so-called TIGER model, an enhanced version of which is used in this paper, to model gas flows and the impact of new pipeline projects. Neumann et al. (2009) maximize social welfare by including an estimated demand elasticity and compute gas flows and identify congestion. However, their spatial granularity of one node representing one country does not allow them to consider specific assets individually. Similarly to Lochner and Bothe (2007), the temporal granularity of one month might underestimate the strain on the systems on individual days during a supply disruption, which is also typically shorter than a month. The model by Monforti and Szikszaia (2010) was specifically set up to investigate system resilience in the light of security of supply stress situations. It abstracts from modeling storage operations explicitly but alters the amount of gas available from storages through Monte-Carlo simulations. With the same regional resolution as Neumann et al. (2009), they cover a wider geographical area

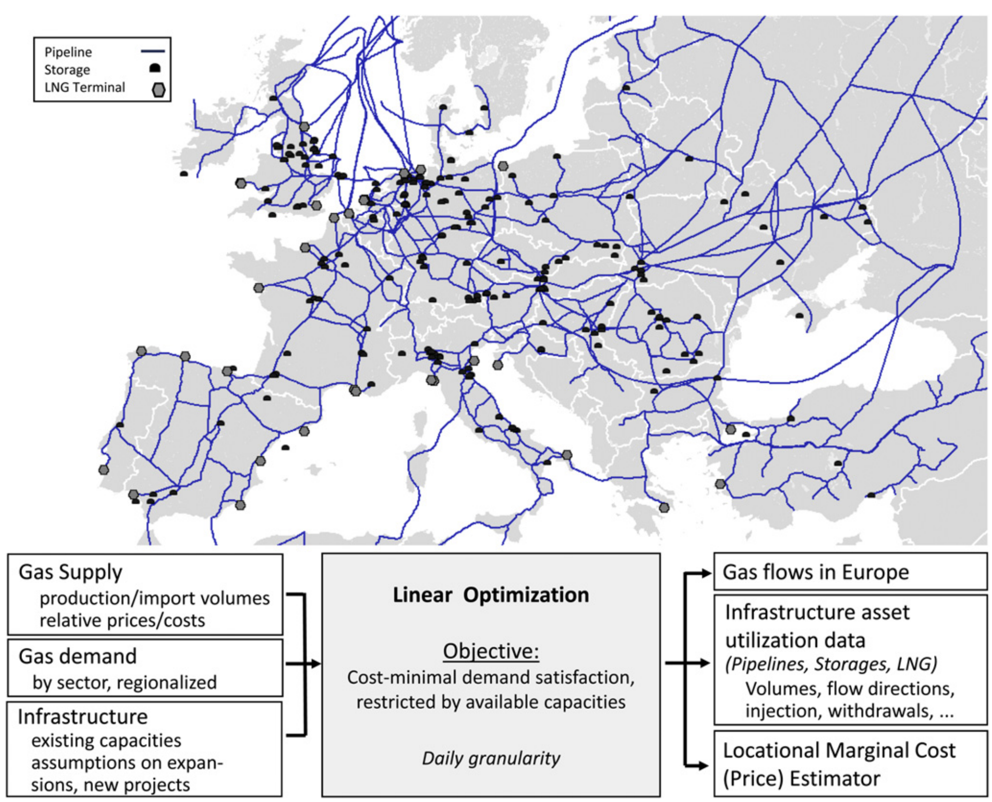

Fig. 1. TIGER Model Overview.

(EU-27 plus Norway and Switzerland). Although it is also a network model consisting of edges and nodes, gas dispatch is not based on costs or prices but certain "rules".[1] However, this approach allows to simulate security of supply situations, albeit with a lower spatial granularity than our approach. The large scale European infrastructure study by EWI (2010) applies a version of the model from Lochner and Bothe (2007) with increased temporal granularity to model a repetition of the Russian–Ukrainian gas crisis for four weeks in 2019 to identify how potential new pipeline projects in the region (Nabucco, South Stream) improve security of supply. (A similar analysis is done for 2020 by Dieckhoener (2010)). Lochner (2011) uses the same model but focuses on identifying bottlenecks and the quantification of congestion costs in general. We use the same model in this paper.

TIGER stands for Transport Infrastructure for Gas with Enhanced Resolution. TIGER is a European infrastructure and dispatch model which optimizes the European gas supply in the short-term, i.e. without investment decisions, under given infrastructure and demand assumptions. The pipeline infrastructure as well as the utilization of LNG terminals and storages are displayed in detail within the model. Natural gas supply and dispatch of volumes is optimized for Europe, subject to the available infrastructure, by minimizing the total cost of gas supply.

Methodologically, TIGER is essentially a linear network flow model consisting of nodes and edges. Nodes represent locations in the European gas supply infrastructure where there are connections between pipelines, connections to storages, gas injections into the grid from gas production or LNG regasification facilities and withdrawals from consumers (locations of demand or off take locations for local distribution networks). The edges represent the pipelines in the European gas grid. They are assigned with the individual characteristics of each pipeline like geographic location, connection between specific nodes, technical capacity, length, directionality, availability (in case of a new project entering operation at some point in the future). Similarly, the individual characteristics of storages (working gas volumes, storage type, maximum injection and withdrawal rates and respective profiles) and LNG terminals (import, LNG storage and regasification capacity) are likewise included and assigned to the respective element located at the nearest geographic node.

2.1. Optimization problem

Objective of the linear optimization is the minimization of the total costs of gas supply subject to the relevant constraints, i.e. meeting the location-specific demand and observing all technical restrictions of the infrastructure as well as on the supply side (availability of volumes). Intertemporal interdependencies, e.g. concerning gas storage or annual production profiles and flexibilities, are also taken into account.

Costs in the optimization (objective function) include commodity, transportation and, where applicable, regasification and storage costs. With the model's focus on the dispatch of natural gas, the latter three cost factors essentially represent variable costs, the assumptions of which are based on different studies such as OME (2001) for LNG regasification costs and per-unit and distance pipeline transport costs and United Nations (1999). Commodity costs were based on published border prices at the time.[2]

The total cost function *TC* which is minimized in the model can, hence, be described as follows:

$$\begin{aligned}\min TC = & \sum_{t,i} \text{commodity cost}_i * \text{SUPPLY}_{t,i} \\ & + \sum_{t,i,j} \text{transport cost}_{i,j} * \text{FLOW}_{t,i,j} \\ & + \sum_{t,i} \text{storage cost}_i * \text{STORAGELEVEL}_{t,i} \\ & + \sum_{t,i} \textit{regasification tariff}_i * \textit{LNGIMPORTS}_{t,i} \\ & + \sum_{t,i} \textit{voll} * \textit{DEMANDREDUCTION}_{t,i}\end{aligned}$$

for all nodes i, all pipelines from nodes i to j, the respective storages and LNG terminals located at nodes i and all time periods t. Time periods t, thereby, equal one day, i.e. $t = 1, \ldots, 365$ in the simulation. Applying assumptions on a value of lost load (*voll*) from Ukerc (2009) allows to include the costs of reducing consumption if demand cannot be met. The model will, however, only do so if it is less expensive to incur the specified threshold price than to supply gas to the respective location in the respective time period. However, the assumption selected here is sufficiently high to ensure gas is physically supplied (rather than consumers being switched off) as long as it is technically possible. Hence, all remaining cut offs to consumers found in our simulation are due to a shortfall of supply, which allows us to determine the consequences of the security of supply situation(s).

The optimization of the cost function is subject to a number of relevant technical constraints of the gas market. These include:

- Supply constraints (upstream production limits and flexibilities, import constraints at border points),
- Pipeline transmission constraints (maximum technical capacities, flow directions),
- Storage restrictions (working gas volume, injection and withdrawal profiles and maximum rates, intertemporal storage balance),
- LNG import constraints (maximum regasification rates, annual import capacities, LNG storage capacities),
- and an energy balance constraint ensuring for all time periods and all nodes that the supply of gas (production, inflows from other nodes, supply from past time periods (withdrawals from storages), LNG imports) equals the demand of gas (consumer demand, outflows to other nodes, future demand (injections into storages)) (minus potential demand interruptions).

The energy balance holding true for all periods also ensures that the system as a whole is in equilibrium at each time period and over time. The optimization, with a daily granularity, takes place subject to these restrictions. Decision variables for the model are the natural gas flows on each pipeline and the utilization of storages and LNG terminals. The linear cost minimization approach, thereby, assumes that the transport of natural gas in the European Union is organized efficiently and that all technically and economically possible swaps of natural gas are realized by transmission system operators. Interpreting the dual variable (shadow costs) of the energy balance constraints further indicates the total system costs of supplying one additional unit of gas at the respective node and the respective time. These can, hence, be interpreted as location- and time specific marginal costs (nodal prices in a competitive market) which are required for analyses of security of supply scenarios or congestion. In the analysis in this paper, marginal supply costs would increase to the threshold price if demand

[1] Domestic demand is first covered from domestic sources such as local production and storages; then, gas volumes flow in from neighboring countries or even from further upstream, if possible.

[2] See ICIS Heren European Gas Markets newsletter and German government's customs agency Bafa.

cannot be met. For detailed descriptions of the model, see also EWI (2010) and Lochner (2011). A validation of the model is also provided by EWI (2010).

2.2. Model parameterization

Generally, the inputs into the model are depicted in Fig. 1 and can broadly be categorized into assumptions on natural gas supply, demand and infrastructure, which have to be made for the whole region covered by the model.

Geographically, TIGER covers Europe and the surrounding production countries (Algeria, Azerbaijan, Iran, Libya, Russia) as visible in Fig. 1.

For the analysis at hand, we parameterize the model for the 2008/2009 winter with actual infrastructure availability and (estimated) demand and supply data: Demand was estimated based on historic country-specific demand profiles taking temperatures in the relevant time period into account. Supply was included based on historic data for January 2009. Infrastructure availability was based on the actual infrastructure in place and operation in January 2009; in the disruption simulation, all transits via Ukraine are assumed to stop.

In a second simulation, we assume an enhanced market interconnection as envisaged by the European Commission to increase security of supply. Therefore, we allow the model to use pipelines for gas flows in the reverse direction if necessary during a crisis. This implies that further physical market integration takes place by upgrading compressor stations but without new pipeline constructions. Hence, this simulates a relatively low cost solution for additional market integration.

3. Analysis of the january 2009 Russia–Ukraine dispute

This section describes the results of our model simulation of the crisis.

3.1. Gas flows during the crisis

In order to maintain the gas supply for the majority of European consumers during the gas conflict, gas suppliers had to resort not only to natural gas stocked in gas storages - they also had to divert gas flows within the European natural gas transmission system. What did these measures incorporate specifically and how did they interact?

Reactions gathered from different publications of the companies involved as well as the European Commission only draw an incomplete and barely quantified picture of the measures taken in order to minimize the impacts of the crisis. Therefore, we first present the results of our modeling exercise before comparing these with selected data.

The results regarding the changing gas flows in the European natural gas transmission system during the January 2009 crisis are depicted in Fig. 2 with the left-hand map representing a “normal winter day” (same assumptions as crisis scenario but without Ukraine disruption) and the right-hand one the crisis scenario. (The thickness of the lines in the maps serves as an indicator for the absolute level of volume flow on the respective long-distance transmission pipeline. The arrows roughly indicated the general flow directions.)

The left-hand map illustrates that on winter day without disruptions large quantities of natural gas reach Europe via Ukraine. On a regular winter day, these flows amount to more than 300 million cubic meters. Transiting Slovakia, the Czech Republic and Austria, these volumes also supply Italy, Germany and France. The optimal reaction to the supply disruption as calculated by the model can be summarized as follows:

1. Russia delivers (small) additional gas volumes via the Yamal-Route.
2. Other gas suppliers from western European countries increase their short-term deliveries in particular the Netherlands, Norway and the United Kingdom. In addition, the regasification of liquefied natural gas (LNG) is enhanced, for instance at the Zeebrugge terminal.
3. However, the biggest impact is achieved through a diversion of the gas flows against the usual east to west route (see red arrows in Fig. 2). This allows for the supply of additional gas from the west via the Czech Republic and Austria to the east, namely to Slovakia, Hungary, Slovenia, Croatia, Serbia and Bosnia–Herzegovina.
4. These west-to-east deliveries are only possible due to extensive additional withdrawals from underground storages in central Europe. Hence, stored natural gas quantities are also supplied to consumers beyond the borders of the country where the storage is located. In the 2009 crisis, this was especially true for Germany (which supplied gas to eastern Europe), but for instance also for Hungary which delivered gas from its storages to its more severely affected neighbor Serbia.

These measures protected the consumers in western and central Europe from supply cut-offs. Prerequisites for preventing the disruptions were the diversification of natural gas sources and

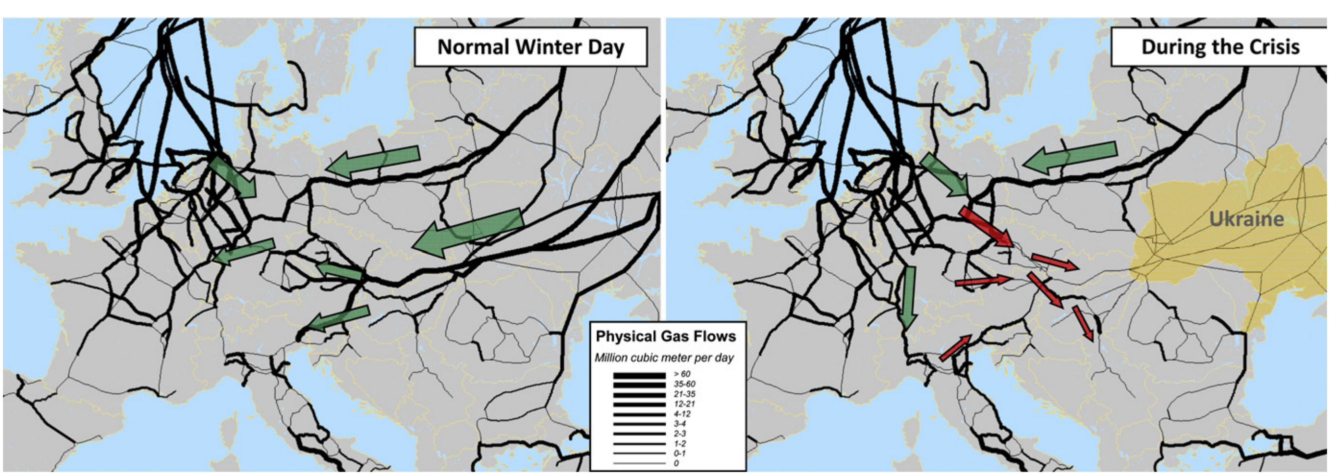

Fig. 2. Winter gas flows with and without Ukraine disruption.

supply routes in large parts of Europe in combination with sufficient volumes of natural gas stocked in storages. In the beginning of 2009, the latter were on average filled up to 73 percent of working gas volumes in western Europe.[3] This, of course, was also the consequence of lower than anticipated demand in the fourth quarter of 2008 due to the economic crisis and milder than usual temperatures.

The supply to countries further in the east by means of supplying gas from western and central Europe, which has been described by the EU Gas Coordination Group as "solidarity" between these countries (European Union, 2009), nevertheless had its limits.

Our model simulations - and the observations in reality - show that supply to consumers, particularly in Bulgaria and Romania, but also in Hungary and the western Balkans, was disrupted. The model highlights the reasons for this situation: Firstly, due to their geographic location, these countries are more dependent on Russian natural gas delivered via the transit country Ukraine than those in western Europe. Furthermore, most of them do not maintain natural gas stock levels (in their storages) exceeding quantities required in order to balance seasonal load differences.

However, physical market integration and infrastructure also has to be part of the explanation. For example, while the argument of unilateral dependency and insufficient stock levels also applies to Slovakia, the country managed to minimize supply disruptions thanks to gas volumes from the west.

The simulation demonstrates that substantial west-to-east transport could only be realized up to Hungary and Slovakia in 2009. Shipping gas from the west further to the east is prevented by the low level of physical market integration and the lack of flexibility in the pipeline network which would allow reversing flow directions. Hence, the results highlight that, apart from diversification of supply sources and sufficient gas storage levels, the physical integration of markets can substantially enhance security of supply.

In addition to this qualitative analysis the model also allows a quantification of the diverted and missing volumes of natural gas, which then also enables a comparison with actual data from other sources. In total, our simulations yield that transits via Ukraine amount to 303.5 million cubic meters on a normal winter day. Hence, the lack of these volumes had to be compensated by other sources during the crisis in order to maintain a balance of supply and demand. The largest compensation is provided by gas storages in eastern Europe, Italy and Germany. The remaining volumes are provided through storage outflows in other European countries, through additional Russian deliveries on the Yamal-Route via Belarus, additional production in the North Sea as well as additional LNG deliveries.

A detailed list of how the model replaces the Ukrainian transit volumes is depicted in Fig. 3, which compares these results with estimations for how gas was actually replaced in the market.[4]

The data, thereby, illustrate the importance of gas storage volumes in mitigating the consequences of the crisis, especially those in Germany, Italy and eastern Europe: Together, they make up more than 75 percent of the "missing" gas volumes in the simulation. Although actual data for eastern Europe is not available, it is likely that storages there did indeed also make a significant contribution. The contributions of gas diversions from Russia to Europe via other routes, or production increases in the Netherlands, were rather small in relative terms. Absolute differences between

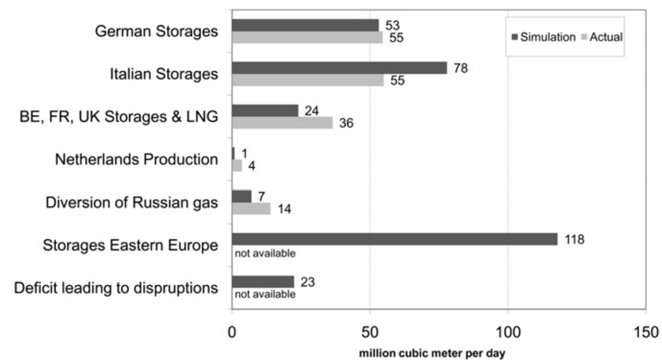

Fig. 3. Compensation of deficit due to missing Ukraine transits.

the observed data and the model simulation largely arise with respect to storages in Italy (negative difference), and north-western Europe (positive). The latter is thereby a consequence of the former as our simulation results suggest that more gas could have been released from Italian storages during the crisis if the market had worked perfectly competitive and efficient. (In reality, these volumes were instead provided from the north-west.) Analyzing the reasons why this may not have happened is beyond the scope of this paper. Possible explanations might include insufficient transparency regarding possible supply and demand needs and the availability of capacity to get the two together, inefficient allocation of available transmission capacity, and state intervention.

Fig. 3 further points out that about 22.5 million cubic meters of daily demand in Bulgaria, Romania, Hungary and Serbia cannot be satisfied in such a crisis scenario in the model. Thus, the model has to cut-off demand to this extent. While it is known that some consumers were actually not supplied in those countries, the exact figure is unknown.

3.2. Price effects

What impact did the diverted gas flows and the reduced gas supply have on the costs of gas supply and prices of natural gas? The isolation of the actual price effects at the European natural gas trading hubs caused by the delivery disruptions is hardly possible (apart from the fact that such hubs do not exist in eastern Europe): Gas prices in western Europe were not only influenced by the halt of transits via Ukraine but also by the low temperatures in the first two weeks in January, the temporary production stop at a Norwegian gas field and high oil prices which temporally rose to between 42 and 49 US-$ from below 36 US-$ in late December 2008.[5]

In the very short term these effects and - mainly - the uncertainty regarding the interruptions on the first day of the crisis led to price increases of the day-ahead prices at various trading hubs ranging between 30 (PEG Nord, France) and 70 percent (TTF). However, in the course of this day prices fell again significantly and were, for instance on January 14th in the middle of interruption period, at a level between seven (NBP) and 16 percent (TTF) above the end of December level.[6]

As described in the Methodology section, the model can evaluate the shadow costs of the individual demand balance constraints for each point in the system, which yield locational marginal costs.

[3] Based on Gas Storage Europe data for 05/01/2009 for Germany, France, Belgium, Netherlands, UK, Italy and Austria.

[4] Estimates are derived based on data from Gas Storage Europe, German regulator Bundesnetzagentur, DG ENER and Pirani et al. (2009). As comparing two identical situations with and without crisis is not possible in reality (other than in the model simulation), the comparison is based on the two week period before the crisis.

[5] Based on Brent spot market price time series from US Energy Information Administration.

[6] For the NetConnect-Germany market area in Germany price increases ranged between 35 percent at their peak and 9 percent on average. All data based on Dow Jones Trade News Energy and ICIS Heren European Gas Markets newsletters (day-ahead OTC prices).

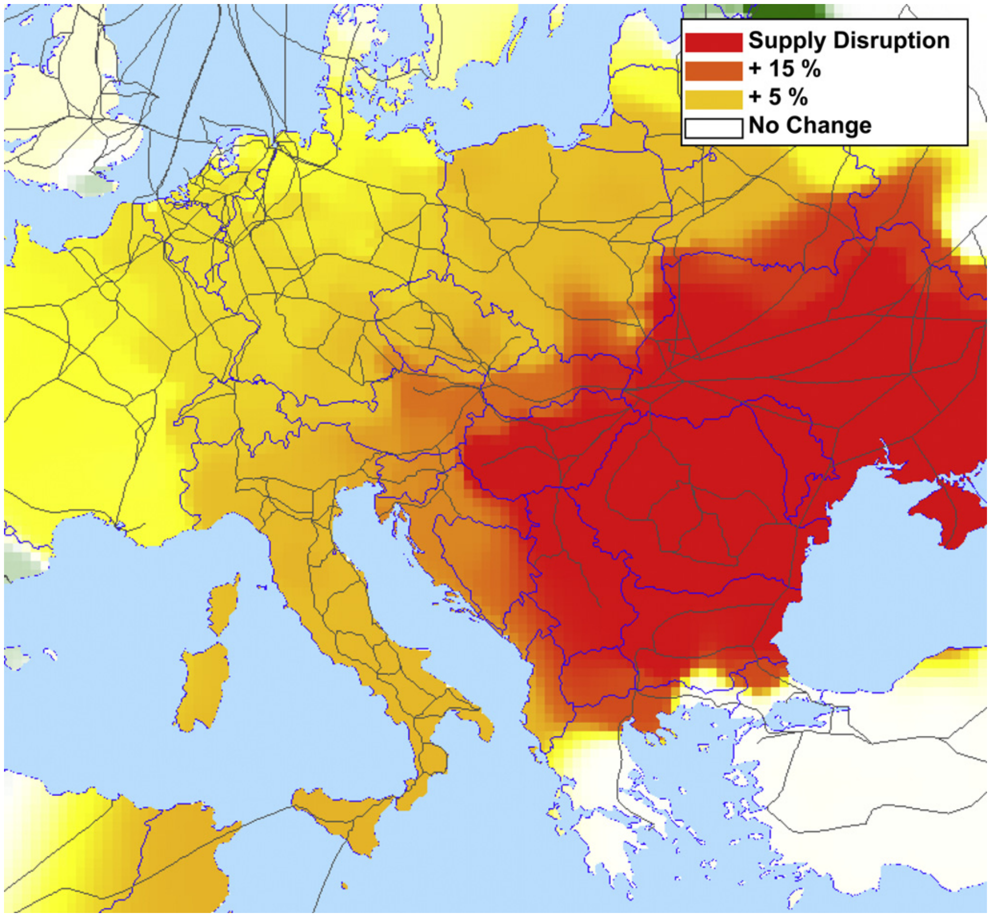

Fig. 4. Effects of the crisis on locational marginal supply costs.

In a competitive market, these marginal costs might be interpreted as a price estimator. Fig. 4 displays how these changed due to the interruption in the different regions in Europe (in comparison to a "regular" winter day with the same demand).

Price increases ranging from 0 to 20 percent are depicted in white to (dark) orange; the red color implies that the (step-wise) inelastic demand assumed by the model can no longer be met. This reveals again, that the supply disruptions which occur in the model correspond to the ones observed in reality: This is the case not only for the Ukraine but in particular for Bulgaria, Romania, and Hungary and countries in the Balkans. In countries where the entire demand could theoretically be satisfied, the model observes the highest increase in marginal supply costs in Slovakia (18 percent). This increase is thereby mainly caused by gas supplies from the west during the crisis, which is of course more costly than supply from Russia during "normal times". Marginal supply cost increases averaging around 14 percent are observed in Austria, Slovenia and Croatia. In the case of Germany, modeled marginal supply costs differ between northern and southern Germany indicating that there are physical bottlenecks in the German long-distance gas transportation grid: While the marginal costs of gas supply in northern Germany increase by only around 2 or 3 percent, the rise is up to 10 percent in Bavaria, the German state most dependent on gas supplies via Ukraine. Again, these changes of locational marginal costs correspond to the observations from the trading hubs rather well.[7]

Generally, the good match of modeled and actual outcomes implies that (a) the model is a suitable tool to investigate such issues and that (b) the measures taken by the market were fairly close to an optimal least-cost reaction.

3.3. *Improving security of supply*

Application of the model in a second step then also enables the evaluation of further crisis mitigation measures in the long and medium term. In the context of this paper, we look at the impact of increased physical market integration through enhanced reverse flow capabilities in eastern Europe, which are proposed by the industry as a measure to increase security of supply (GTE, 2009), and which have already partially been implemented since January 2009.

An illustration of the resulting marginal supply cost effects and disruptions in presented in Fig. 5 (in the same fashion as in the Fig. 4). Three effects of the increased reverse flows (in comparison to Fig. 4) are clearly visible: (i) Some supply disruptions, notably in Bulgaria and Romania, can be avoided but not all of them. (ii) Supply cost increases which translate to "price" increases in selected regions, e.g. northern Germany, are lower than they are without increased reverse flows. However, it also becomes evident that (iii) increased physical market integration means that lower "prices" in one region can imply increasing "prices" in another. In this case, southern Germany and Greece and Turkey see their marginal supply costs increase due to higher physical market integration, which is easily explained by trade theory: Without (Greece, Turkey) or with limited (Germany) reverse flow capabilities to the affected region in eastern Europe, these countries were to differing extents autark as the limited transport

[7] Not taking into account the price spikes on the first day of the crisis.

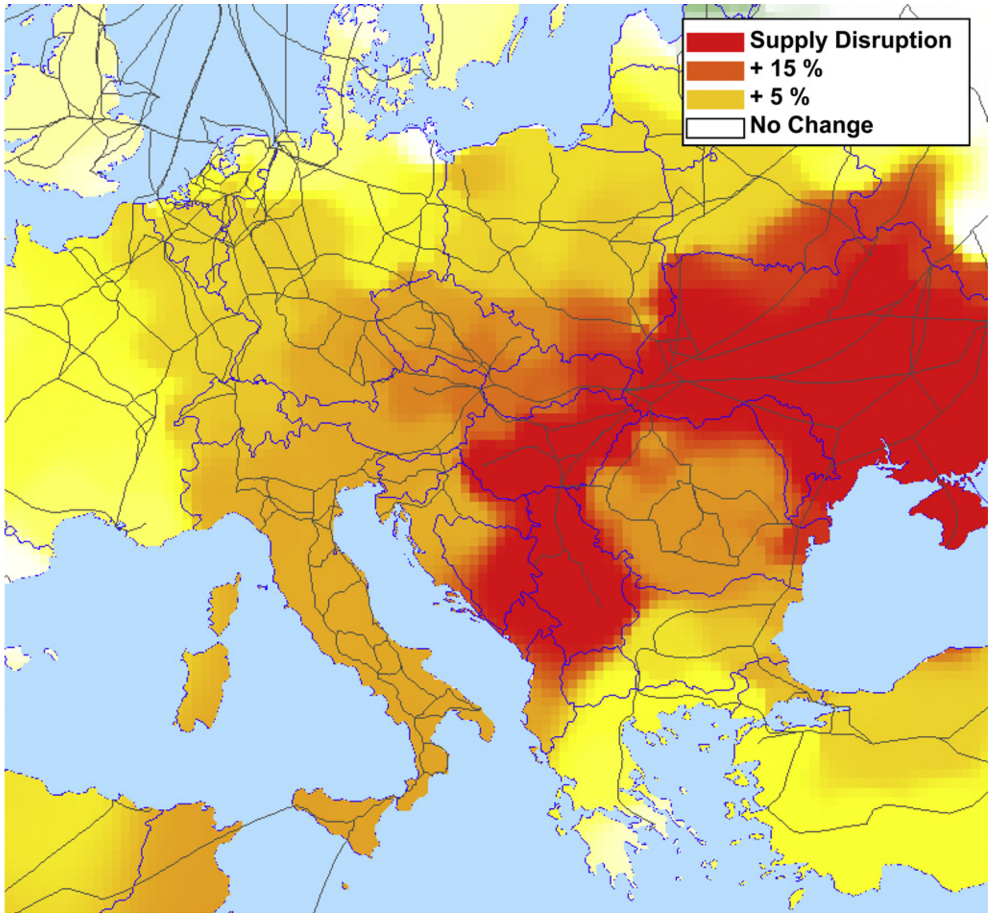

Fig. 5. Effects of a simulated identical crisis with enhanced reverse flows.

infrastructure (partially) prohibited trade. Prices formed in the residual local markets. Additional trade (reverse flows) allows extra flows of gas from low to high price countries, prices converge: marginal supply costs increase in the named countries while consumers in eastern Europe benefit. Hence, the solidarity described the European Union (2009) would improve the situation of some consumers, but can also have "losers" who might face higher gas prices in return as a consequence. Of course, in line with trade theory, general welfare increases as the loss of consumer surplus in one country is more than compensated by the gains in others.

Fig. 5 also illustrates that reverse flows do not allow a full physical market integration or security of gas supply to all consumers: the assumed expansion of reverse flows does allow further transport of gas from the west to the east and from the south (Greece, Turkey) to the north. However, there are still supply disruptions implying that preventing gas shortages to all consumers in eastern Europe will also require additional pipelines.[8]

4. Conclusions

This paper presented the TIGER natural gas infrastructure and dispatch model of the European gas market as a suitable tool to investigate issues ranging from physical market integration to security of supply issues in a comprehensive manner taking interdependencies in the supply infrastructure into account.

Regarding the analysis of the Russia–Ukraine dispute of 2009, how can the TIGER model results be interpreted? With respect to the ex-post analysis of the January 2009 crisis, the model yields the cost-optimal, efficient measures in the gas market to best mitigate the consequences of the crisis. Thereby, the simulation results roughly match the actual gas flows and storage withdrawals of the European gas market. This finding allows the conclusion that - given the availability of the infrastructure and the available storage levels - the European gas industry reacted in the almost best possible way to the crisis. Diversion of gas flows and reverse flows allowed transports of gas from the west, for instance from German storages, to eastern European countries. This helped to prevent larger supply shortfalls for consumers in the region. In volume terms, the largest contributions to replacing the "missing" imports via Ukraine came from storages in central Europe emphasizing the importance of gas stocks in mitigating risks from supply disruptions. Full solidarity, meaning the supply of gas to all affected consumers through deliveries from the west, was not possible due to limited physical integration of the markets and insufficient storage capacities for such a crisis scenario in eastern Europe.

Market integration and storage reserves therefore partially emerge as substitutes: the presented results do not imply that total storage capacity is insufficient in general - it was just not sufficient in order to supply all the affected regions using the available storages in a larger geographic distance. The enhanced market integration simulation showed that a small increase of the flexibility of

[8] Announced new pipeline projects, e.g. between Croatia and Hungary and Romania and Hungary, seem to confirm this finding (GTE, 2009). However, a full investigation of all projects in the context of a wider study by EWI (2010) indicates that even this is not enough to eliminate all disruptions to consumers in future crises of possibly prolonged durations.

the present gas pipelines (i.e. installation of compressors enabling bidirectional flows) in eastern Europe does already improve security of supply significantly. However, additional investments in new pipeline (or storage) infrastructures will also be required to increase security of supply for all consumers in eastern Europe.

Furthermore, the large contributions to mitigating the 2009 crisis by stored gas volumes emphasis the favorable circumstances in that year: Normally, gas volumes are stored for cold winters with high demand (and to a lesser extent for supply disruptions). In 2009, the winter was rather mild and the financial and economic crisis depressed industrial gas consumption significantly. Hence, there was much more gas available from storages than would have been in a cold winter with normal economic conditions. Further research will have to investigate if the gas volumes would also have been available under different circumstances and if and how, in a liberalized market, gas suppliers should be incentivized to store natural gas - not just for cold winters but also for potential supply disruptions.

Acknowledgments

This paper presents a substantial extension to a non-academic article in the German trade journal *Energiewirtschaftliche Tagesfragen* (which illustrated some selected early findings of this study). The author would like to thank Prof. Dr. Marc Oliver Bettzüge, who also co-authored the aforementioned article, for his contributions. This work also benefited from comments by the participants of the 32nd IAEE International Conference (San Francisco), the marcusevans 2009 Gas Infrastructure Forum (London), the EU's Gas Coordination Group and the European Parliament's Mini-Public Hearing on Security of Supply (both in Brussels) on November 9, 2009.

References

BP Statistical Review of World Energy, June 2010. BP p.l.c., London.

Dieckhoener, C., 2010. Simulating Security of Supply Effects of the Nabucco and South Stream Projects for the European Natural Gas Market. EWI Working Paper 10/7.

European Union, 2009. Gas Coordination Group: Solidarity Works and the EU's Gas Market Adapts to Challenges of Gas Crisis Press Release. Reference: IP/09/75, Date: 19/01/2009.

EWI, 2010. Model-based Analysis of Infrastructure Projects and Market Integration in Europe with Special Focus on Security of Supply Scenarios. Study Initiated by ERGEG. Institute of Energy Economics at the University of Cologne, Cologne.

GTE, 2009. GTE + Reverse Flow Study TF Technical Solutions. URL. http://www.gie.eu.com/publications/indexframe_plus_reverse.html.

Lochner, S., Bothe, D., 2007. From Russia with Gas - An Analysis of the Nord Stream Pipeline's Impact on the European Gas Transmission System with the TIGER-Model. EWI Working Paper 07/2.

Lochner, S., 2011. Identification of Congestion and Valuation of Transport Infrastructures in the European Natural Gas Market. Energy 36, doi:10.1016/j.energy.2011.01.040.

Monforti, F., Szikszaia, A., 2010. A MonteCarlo approach for assessing the adequacy of the European gas transmission system under supply crisis conditions. Energy Policy 38, 2486–2498.

Neumann, A., Viehrig, N., Weigt, H., 2009. InTraGas - A Stylized Model of the European Natural Gas Network, Globalization of Natural Gas Markets Working Papers WP-RM-16. DIW, Berlin.

OME, June 2001. Assesment of Internal and External Gas Supply Options for the EU, Evaluation of the Supply Costs of New Natural Gas Supply Projects to the EU and an Investigation of Related Financial Requirements and Tools. Chapter 3-Assessment of Future Supply Costs to Europe [Online] Available:. Observatoire Méditerranéen de l'Énergie (OME) <http://www.ome.org/PDF/Etudes/gas_study/documents/chapter_3.pdf> (accessed on 22.01.08.).

Pirani, S., Stern, J., Yafimava, K., February 2009. The Russo-ukrainian Gas Dispute of January 2009: A Comprehensive Assessment. Oxford Institute for Energy Studies, Oxford. NG 27.

Ukerc, 2009. UKERC Energy 2050, Project Report by UK. URL. Energy Research Centre, London. http://www.ukerc.ac.uk/Downloads/PDF/U/UKERCEnergy2050/0906UKERC2050.pdf.

United Nations, 1999. Study on Underground Gas Storage in Europe and Central Asia. UN Economic Commission for Europe - Working Party on Gas, New York City/Geneva.