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Simulating security of supply effects of the Nabucco and South Stream projects for the European natural gas market

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Abstract

Because of the decrease in domestic production in Europe, additional natural gas volumes will be required. In addition to Nord Stream, the major import pipeline projects, Nabucco and South Stream, have been announced to provide further gas supplies to Europe. This raises the question concerning whether and how these projects contribute to the European Union's focus on security of supply. Applying the natural gas infrastructure model TIGER, this paper investigates the impact of these pipeline projects on southeastern Europe's gas supply. Gas flows and marginal cost prices are evaluated in general and considering the possibility of supply disruptions via Ukraine for the year 2020. The model results show a positive impact of these pipelines on security of supply despite few consumer cut-offs that result from intra-European bottlenecks. South Stream is only highly utilized in case of a Ukraine crisis, supporting the idea that its main purpose is to bypass Ukraine.

Keywords: Natural gas, security of supply, Nabucco, South Stream, linear-optimization, transport infrastructure

JEL classification: L95, C61, Q41, Q34

1. Introduction and Background

The declining European gas production will lead to an increasing dependence on imports (European Commission, 2008; IEA, 2008). Several plans for major pipeline projects will be commissioned in the next decade to provide sufficient capacity for additional natural gas imports, and investments in interconnections among countries are planned to improve market integration. Moreover, several projects in focus should

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provide large-scale gas volumes from non-European gas producers to European regions. In addition to Nord Stream, which is online in 2011, the Nabucco and South Stream pipelines are the largest projects planned. Although both pipelines could enhance the security of the gas supply in the European Union (EU), they are expensive projects. The ambitious objectives of the EU in terms of the percentages of renewables in the energy mix by 2050 may lead to only a moderate growth in natural gas demand in the next decade and probably to a significant decrease by 2050. Natural gas demand for heating is even expected to decrease in northwestern Europe until 2030 through implementation of energy efficiency measures in buildings (European Commission, 2010). It follows that not all major pipeline projects may be essential for the security of supply in Europe, especially the Nabucco and South Stream projects, which are designed to supply southeastern Europe.

A quarter of Europe's gas demand is satisfied by imports from Russia, and 80 percent of these volumes are transported from Russia through pipelines via Ukraine (European Commission, 2006). The Russia-Ukraine gas dispute of January 2009 caused an unprecedented disruption of gas supplies to the EU, described as the worst gas crisis in International Energy Agency's (IEA) history (IEA, 2009). Disputes between Russia and Ukraine on the pricing of the commodity natural gas and its transit to the EU were recurrent during the past decade (Stern, 2009).

Because of these threats to the security of the natural gas supply, European policy will have to cope with several challenges. First, gas supply from non-European countries has to be secured. However, since importing a high proportion of gas volumes for the European market from one or only a few suppliers increases the risk of political pressure and price increases, supply sources and means of transport to different European regions should be diversified (Weisser, 2007; Reymond, 2007; European Commission, 2006). Political conflicts, such as the Russia-Ukraine crisis, could cause supply disruptions, and a halt to these transits has a significant impact on the European gas market, especially during times of high demand, such as the winter months. To secure gas supplies, additional gas infrastructure, that is, liquified natural gas (LNG) import terminals, storage areas, and major import pipelines, will have to be built (Lise et al., 2008; Cayrade, 2004).

This paper investigates the effects of each of the Nabucco and South Stream pipeline projects on European natural gas supply security in general and with a particular focus on a Ukraine crisis simulation. The paper also analyzes the major supply risks associated with the EU's dependence on the main transit country, Ukraine, and the mitigating effects of Nabucco and South Stream and elaborates on the European gas infrastructure system's vulnerability, as well as its ability to respond and compensate. The scenarios are simulated with the European natural gas infrastructure and dispatch model TIGER from the Institute of

Energy Economics, Cologne. The conclusions of the paper depend on these specific assumptions, in particular on assumptions on publicly announced infrastructure projects[1] and on demand projections. Possible effects of alternative assumptions are briefly discussed in the conclusion.

The next section provides a literature overview on issues related to the security of supply in the context of major European gas pipeline projects and describes the Nabucco and South Stream pipeline projects in detail. Their contribution to the two objectives of European security of gas supply – the security of natural gas imports and import diversification – is addressed. Section 3 describes the TIGER model which simulates three infrastructure scenarios to analyze the effects of route diversification by Nabucco and South Stream in case of supply disruptions: a baseline scenario without either of the two pipeline projects, a scenario that implements only the Nabucco pipeline, and a scenario that implements only the South Stream pipeline. In Section 4 the general effects of the Nabucco and South Stream pipeline projects – especially the effects on marginal supply costs – are analyzed for the year 2020 for a hypothetical peak winter day, when supply disruptions are most probable. Section 5 analyzes the impact of the two pipeline projects during a hypothetical Ukraine crisis on a peak winter day in 2020 on disruptions to consumers. Changes in marginal supply costs and gas flows for the three infrastructure scenarios in comparison to the results of the no-crisis simulation are presented. Section 6 concludes.

2. Security of natural gas supply and the Nabucco and the South Stream pipeline projects

2.1. Security of natural gas supply

The issue of security of supply in natural gas markets has been addressed by European energy policy (European Commission, 2000, 2006; European Union, 2004). Dimensions of security of supply cover a wide range of issues. Luciani (2004) defines security of supply as "the guarantee that all the gas volumes, demanded by non-interruptible (firms or protected) customers, will be available at a reasonable price" (Luciani, 2004, p. 2).

Thus, physical availability of natural gas and the price play significant roles in guaranteeing security of supply. However, defining a precise threshold for a threat of security of supply is a challenging task on which academics have not reached agreement. Many studies have addressed the issue of security of energy supply, albeit without a specific focus on natural gas (CIEP, 2004; Correlje and van der Linde, 2006). Gnansounou (2008) develops a composite energy vulnerability index to benchmark industrialized countries in a long-term security perspective regarding oil and gas supplies. Cabalu (2010) evaluates different gas supply security

[1] The data on capacities based on current planning status is taken from ENTSOG (2009).

indicators. These cover gas intensity, net gas import dependency, a ratio of domestic gas production to total gas consumption and the geopolitical risk for Asian countries. Cabalu (2010) introduces a composite gas supply security index, based on Gnansounou's energy vulnerability index, that incorporates four of the presented indicators to analyze an overall security of natural gas supply measure for Asia. For the European market, Victor (2007) discusses aspects of global geopolitical security of supply for natural gas, but only a few studies focus on specific pipeline projects. Holz et al. (2009) analyze European gas supplies until 2025 using the strategic model GASMOD and find that pipeline availability remains a critical issue. Stern (2002) analyzes the impact of dependence on natural gas imports and the influence of liberalization on security of gas supply and recommends a policy framework to prevent disruptions to consumers. He analyzes European relationships with non-European gas-exporting countries and the influence of a liberalized European market on security of gas supply and differentiates between short-term and long-term adequacy of supply and infrastructure in the transport of gas to the demand regions. Stern (2002) also discusses operational issues, such as stresses of weather and other operational influences, and strategic security, such as catastrophic default of infrastructure or supply sources. Further, associated with import dependence Stern distinguishes among source dependence, transit dependence and facility dependence.

The current paper addresses transit dependence and facility dependence with a focus on the effects of the two pipeline projects, Nabucco and South Stream,[2] on security of supply. The major security of supply risks associated with the EU's dependence on the main transit country of Ukraine (transit dependence) are reflected in the results of the Ukraine crisis simulations in which the mitigating effects of the Nabucco and South Stream projects, the European gas infrastructure system's ability to respond and compensate, and its vulnerability (facility dependence) are analyzed.

Stern (2002) addresses the problem of attributing costs to events that have a low probability of occurrence but a high impact on supply and the difficulties for policy makers to balance costs and risks in order to find measures to cope with these events. This paper presents an approach to the analysis of such events.

2.2. The Nabucco project

According to Nabucco Gas Pipeline International GmbH (2010), the Nabucco project describes a gas pipeline connecting the Caspian region, the Middle East and Egypt via Turkey, Bulgaria, Romania, and Hungary with Austria and further on with the Central and Western European gas markets. The pipeline

[2] Currently, there are three further "southern corridor" pipelines discussed, that could connect the Middle East or Caspian Region with Europe: The Trans Adriatic Pipline (Trans Adriatic Pipeline, 2011), the Interconnection Turkey Greece Italy Pipeline (IGI Poseidon, 2011) and the recently announced South-East Europe Pipeline (Financial Times, 2011). These pipelines, however, connect only a part of the regions connected by Nabucco and South Stream.

route with a length of approximately 3,300 km should start at the Georgian/Turkish and/or Iranian/Turkish border and run via Bulgaria, Romania and Hungary to Baumgarten, Austria. The pipeline's transport capacity is expected to amount to 31 bcm per year, and total investment costs are approximately 7.9 billion Euros. From an EU point of view the Nabucco project should present an opportunity to diversify gas supply options and to reduce the EU's dependence on Russia.[3] The Caspian region, especially Turkmenistan and Azerbaijan, and the Middle East-Egypt, Iran and Iraq, are discussed as supply sources for the project. However, no supply contracts have yet been concluded, a fact that may affect the commissioning of the project. Problems that have arisen in the context of suppliers for the Nabucco pipeline are often discussed (Bilgin, 2009, 2007).

The Nabucco pipeline will be built only if sufficient volumes are contracted. The political risk of defaulted supply contracts is difficult to estimate and will depend on who the suppliers are. Turkey plays a major political role in the negotiations on supplies because it will need significant additional gas volumes in the future to meet projected rising demand (and the country neither has an own production nor sufficient gas storage) and because Turkey is the first transit country for the Nabucco pipeline. Turkey has already been negotiating with the EU on the volumes that should be withdrawn from Nabucco to satisfy the Turkish demand, and it has already signed and extended many of its gas contracts with its surrounding gas-producing neighbors. However, Turkey is interested in withdrawing as much Caspian and Middle Eastern gas as possible. Therefore, Turkey's geopolitical position could be both an opportunity and a threat for the EU.[4] Based on a geopolitical analysis, Bilgin (2009) recommends including at least two countries from the Middle East and Caspian regions as suppliers for the European gas market, which could be possible via Nabucco. Erdogdu (2010) analyzes strength and weaknesses of the Nabucco project with a focus on the policies of different countries involved and concludes that its realization largely depends on non-European actors and their interests.

In short, the Nabucco is an uncertain and cost-intensive project that could help to cope with the EU's security of supply challenges because it could provide significant gas volumes from non-European countries, it diversifies supply sources, and it diversifies supply routes that transit mainly European Member States.

[3] The Nabucco project is designated as of strategic importance by the European Union in the Trans-European Networks - Energy (TEN-E) programme.

[4] Kardaş (2011) analyzes actual political Turkish-EU relations in the context of the Nabucco Intergovernmental Agreement (IGA) and the discussion on Turkish-EU membership. He concludes that the latter has negatively affected an energy cooperation. However, he makes the point that the signing of the IGA in July 2009 gave indication for a better future energy cooperation. Turkey reduced its claims on access to Nabucco volumes and on discounted prices whereas the EU agreed on reverse flows on Nabuccco to Turkey and access to European gas stocks in case of emergency. Nonetheless, the future of Turkish-EU relations in terms of Nabucco remain uncertain.

2.3. The South Stream project

A number of routes for the pipeline are being discussed, including onshore sections across the Russian Federation and several European countries, as well as offshore gas pipelines via the Black Sea and the Adriatic Sea. South Stream is expected to provide a capacity of 63 bcm per year by 2016 and to diversify the Russian natural gas supply route to Europe, thereby strengthening European energy security (South Stream, 2010)[5]. The source of Russian gas for South Stream is as uncertain as the source for Nabucco. Natural gas production in the Volga Region is declining (Stern, 2005), and there will not be enough gas for 63 bcm to be exported per year. For the coming decades, large explored gas reserves in Russia are mainly in western Siberia and the Yamal Peninsula. Production in Yamal was approved to start in 2011 but is delayed because of the economic crisis and the uncertainty on European demand developments (Pirani, 2010). Russian exports to Europe are not likely to be much higher than 200 to 220 bcm in 2020 (Socor, 2009). Another issue is that this area is more than 3000 km away from the start of South Stream at Dzhubga. However, Russia is already importing Turkmeni gas and is also interested in purchasing gas from Shah Deniz II, an Azerbaijani gas field (Kupchinsky, 2009), which could also be used to supply South Stream. In addition, to avoid transit and political costs, Russia could also consider transporting its gas from the Yamal Peninsula to Europe via South Stream. However, Nord Stream, with 27 bcm (or 54 bcm after the expansion), seems to be a much cheaper option for Russia because of the higher costs of Caspian gas volumes and the long-distance of South Stream to future production regions. Moreover, Nord Stream avoids the Ukraine and other transit countries in transporting the gas farther on within Europe and even to southern Europe. Considering these circumstances, South Stream seems to be more a strategic option than a cost-efficient one for transporting Russian gas to Europe. Barysch (2010) states that it is a political project with the purpose to cut out transit countries like Ukraine and Belarus, and to prevent Nabucco which threatens Gazproms monopoly.

About 80 percent of Russian gas exports go to Europe, and about 40 percent of EU imports stem from Russia (IEA, 2009). Therefore, each party is dependent on the other, which may lower the default risk for Europe and may be a lower risk than it would bear with contracts with Middle Eastern countries. However, South Stream does not support the EU's goal of diversifying supply sources. Moreover, although South Stream's planned extremely large capacity could be a strategic tool, it is not clear whether or how the pipeline could be completely filled. In summary, South Stream offers the option to import large-scale (i.e., twice as much as Nabucco) gas volumes from non-European countries, gas transported via South Stream would have to be

[5] 50 percent of the South Stream AG is owned by Gazprom.

contracted with the mainly Russian state-owned natural gas company Gazprom, even if it originally stems from a Caspian country, and South Stream offers an alternative route to the existing routes from Russia. In general, the development of the European gas market is very uncertain with several risks for the planning of pipeline constructions. In addition to the access to supply sources, European gas demand development in the context of the EU's ambitous climate change targets and the role of unconventional gas remain uncertain (Barysch, 2010).

3. Methodology

This section presents the framework and methodology for the model-based analysis that has been conducted to identify the impact of the two pipeline projects Nabucco and South Stream on security of natural gas supply. Thereby, importance of the routes and capacities of these two projects for security of supply is identified. Regarding that both pipelines are major import routes in addition to the old-established route via Ukraine, which is fraught with risk, their impact on security of natural gas supply in case of a hypothetical Ukraine crisis is analyzed.

3.1. The TIGER-model

Different types of natural gas market models are presented in literature. Theoretical natural gas transport optimization models include those presented by De Wolf and Smeers (1996), De Wolf and Smeers (2000), Ehrhardt and Steinbach (2004), Ehrhardt and Steinbach (2005) and van der Hoeven (2004). Midthun et al. (2009) present a modeling framework for analyzing natural gas markets that accounts for further technological issues related to gas transportation – primarily the relationship between flow and pressure. The mixed-complementarity models presented by Gabriel et al. (2005), Gabriel and Smeers (2006) and Holz et al. (2009) focus mainly on modeling competition and agents with focus on natural gas trade determinining supply volumes to the European market in different types of competitive environments. The results presented in this paper for the year 2020 are based on simulations with the natural gas infrastructure model TIGER (Transport Infrastructure for Gas with Enhanced Resolution). Developed by Lochner and Bothe (2007), it enables an integrated evaluation of the utilization of gas infrastructure components – pipelines, storages and terminals – and their interaction. Therefore, the model can be used for a comprehensive analysis of the short-term supply situation and gas flows within the European long distance transmission grid. TIGER's focus is on the optimal dispatch within the European gas infrastructure system.[6] The results of the TIGER model thus represent the first best distribution of natural gas and utilization of infrastructure components within

[6] A similar modeling approach for the US market is presented by Ellison (2007).

Europe assuming that the European Commission's regulative objective to achieve an efficient functioning of the natural gas transport infrastructure within the next decades is accomplished.[7]

Maximum supply volumes to the European market, demand developments as well as capacity and start-off dates of existing infrastructure and infrastructure projects are exogenous to the model. The results cover flows in the pipeline system, the utilization of pipelines, LNG terminals, and the system of storage. The infrastructure components are considered with respect to integration, and effects on marginal supply costs. (See Figure 1 for an overview of the model.)

The marginal supply costs or nodal prices (Lochner, 2009, 2011) quantify how much it would cost to meet an additional unit of demand at a specific node in terms of determinating the next cost-optimal solution to satisfy this additional unit. Within the linear optimization framework, the marginal supply costs represent the shadow costs on each node's balance constraint for each period. They indicate the marginal system cost of supplying one additional cubic meter of natural gas to a specific node at a certain point in time. These additional cost estimates thus cover the sum of all costs such as production, commodity, transport, regasification or storage costs that are accumulated in the cost-minimal solution to meet the node-specific additional unit of demand. Hence, they also account for opportunity costs. In a perfectly competitive and efficiently organized gas transport market, the marginal supply costs at each node in the system should be equal to a theoretical wholesale price at that node. Therefore, an analysis of changes in marginal supply cost indicates the effects the simulated scenarios could have on market prices in a perfectly competitive market. If there is a disruption in supply, the marginal supply cost estimator rises towards infinity within the model.[8] Based on marginal supply costs and disruptions computed, the model gives an indication where additional infrastructure might be needed as a starting point for further cost-benefit analyses.

3.2. Data assumptions

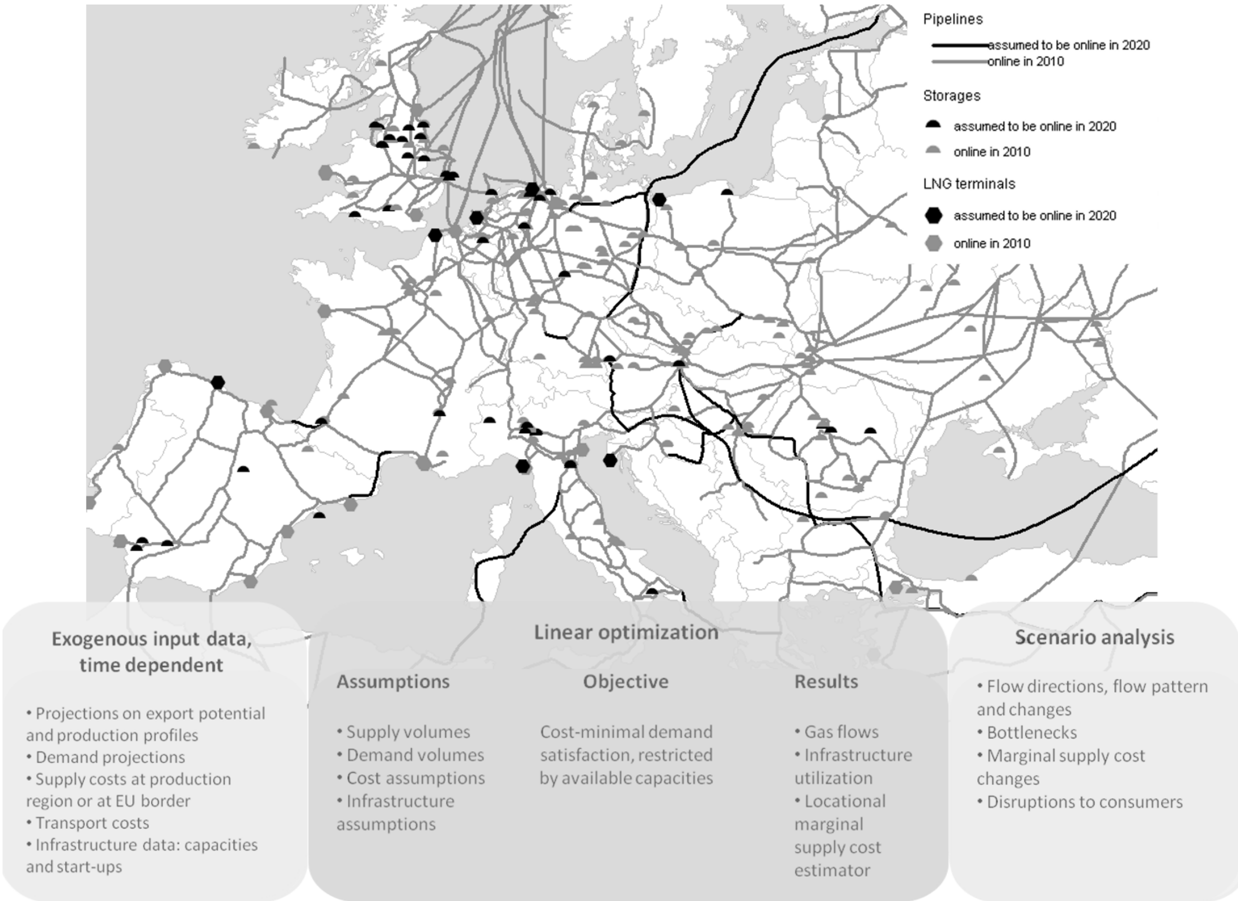
Demand, supply and infrastructure assumptions are based on EWI (2010a).[9] The demand scenario used is the EWI/ERGEG demand scenario, which is based on European Commission (2008) and adapted to the economic crisis from 2009 on. The peak day demand assumptions applied are published in the Ten Year

[7]Fast steps into this direction have already been made by introducing and revising Gas Market Directives (European Union, 1998, 2003, 2009). A model validation presented in EWI (2010a) shows that the model can adequately reflect real flows apart from minor deviations. Efficient swaps in the model's pipeline system reflect the higher willingness to pay in regions where supply shortages occur in comparison to regions where supply is still adequate. In an efficient transport sector contracted volumes will be resold to regions with a higher willingness to pay, if sufficient transport capacity is available.

[8]A detailed description of the objective function, the main constraints, the computation of marginal supply costs, a list of all cost components, their sources and application in the model is presented in the Appendix.

[9]For a detailed overview of additional primary sources applied in EWI (2010a), the parameterization, the cost assumptions of the model, and the respective data sources, see Appendix B.

Figure 1: TIGER-model composition



Network Development Plan of the European Network of Transmission System Operators (ENTSOG, 2009). This is the highest possible daily demand level published and reflects a worst case scenario in terms of security of supply. In terms of pipeline projects in general – new pipelines, expansions and reverse flow projects – the scheduled projects are included based on EWI (2010a) which are those projects that the European regulators considered likely. With respect to the several intra-European pipeline projects and planned expansions of interconnector capacities between countries, those published in ENTSOG (2009), slightly adapted according to EWI (2010a), are implemented in the simulations. Table 1 gives an overview of European demand, the maximum pipeline import volumes, as well as the aggregated European production and infrastructure capacities that are available in 2010 and that are assumed to be online in 2020. The upper limit of pipeline import volumes available to the European market is either predefined by pipeline capacity restrictions or by the maximum export potential of the producer country.[10]

Table 1: European gas market in 2010 and assumptions for 2020

in billion cubic meter	2010	2020
Demand	489.1	533.31
Upper limit imports*	374,86	548.81/579.81**
from Russia	197.15	201.48
from Norway	121.22	112.82
from Algeria	45.40	55.35
from Caspian Region	} 0.99***	18
from Middle East		15.5/46.5**
from Lybia	10.10	9.9
LNG import capacity	164.92	279.02
European production capacity	190.61	124.7
Storage working gas volume	85.17	140.39

Gas Infrastructure Europe (GIE), BP (2011), Eurostat (2010), and EWI (2010).
All data refers to EU-27.
Data for 2020 sum up model inputs.
*Imports are restricted either by export potential or pipeline capacities.
LNG imports are only constrained by the capacity of regasification terminals (LNG import capacity).
**Only in Nabucco Scenario, based on the assumption that capacity to Turkey is extended then.
***From Caspian and/or Middle East.

3.3. Scenarios

To analyze the impact of the two pipeline projects three different scenarios are simulated:

- The Baseline Scenario uses the assumptions listed above and includes one line of Nord Stream with an annual capacity of 27.5 bcm.
- The Nabucco Scenario is based on the Baseline Scenario, but it also assumes the Nabucco pipeline will provide an additional 31 bcm in 2020. The route of Nabucco, based on data published by Nabucco Gas Pipeline International GmbH (2010), runs from Turkey via Bulgaria, Romania and Hungary to Baumgarten, Austria with several connections to the national grids that allow for withdrawal and consumption of Nabucco gas along the way.
- The South Stream Scenario incorporates the South Stream pipeline instead of the Nabucco pipeline, but it otherwise makes the same assumptions as the Baseline Scenario. The pipeline's route is implemented as published by South Stream (2010) from Russia via the Black Sea to Bulgaria and from there on with two different onshore connections: one via Serbia, Hungary and Slovenia to Arnoldstein in Southern Austria and the other via Serbia and Hungary to Baumgarten, Austria. A pipeline connecting Greece and Italy is included based on EWI (2010a). A third route of South Stream via Greece to Brindisi,

[10]More details on these assumptions, see EWI (2010a).

Italy is assumed to be unlikely if the pipeline connecting Greece and Italy is commissioned. It is thus not implemented in the simulations.

The three infrastructure scenarios are first simulated allowing for supplies via Ukraine in order to generate some general results and to establish a basis for comparison of the simulation of a hypothetical Ukraine crisis. The evaluations presented in the following section are based on simulated daily gas flows.

4. Results of no-crisis simulation for 2020

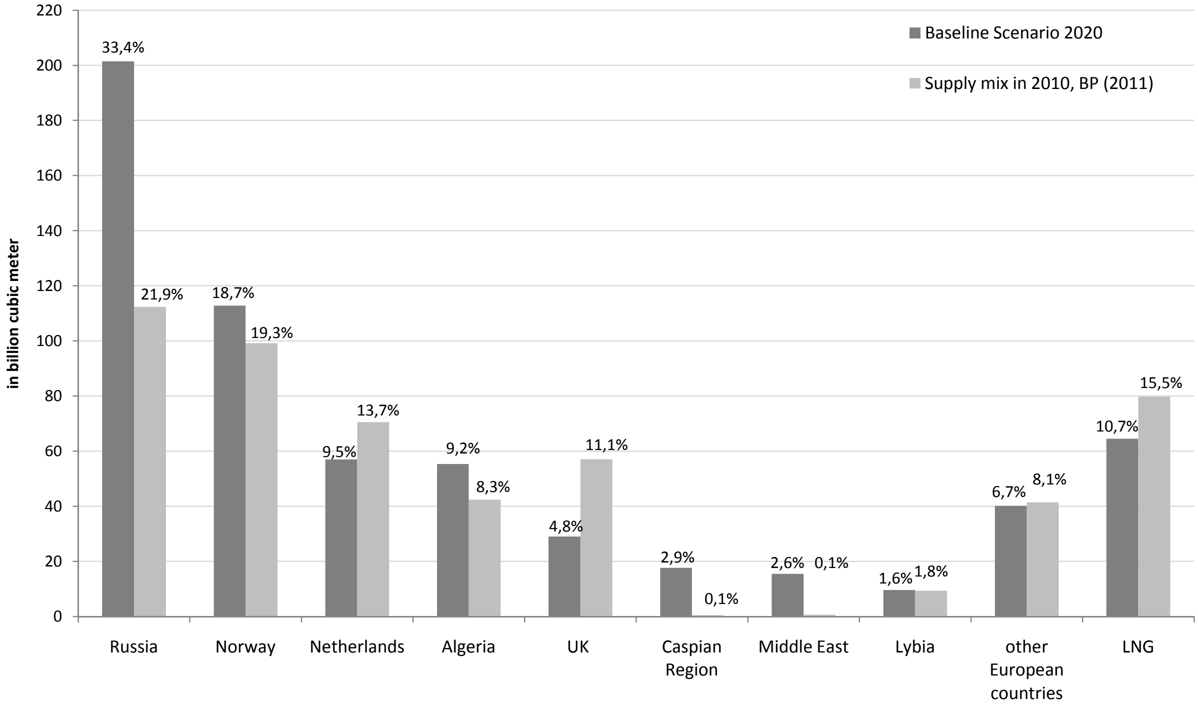
This section first presents general results on security of natural gas supply in Europe based on the Baseline Scenario. Second, the Nabucco and South Stream Scenario are compared with the Baseline Scenario. The results of the three infrastructure variations focus on a peak winter day in 2020, i.e. the day with the highest demand and therefore the strongest impact on security of supply.

4.1. Baseline Scenario results of no-crisis simulation

Increasing import dependency has a crucial impact on security of natural gas supply in Europe in the next decade which is shown in Figure 2 presenting the supply mix for 2009 and the simulated supply mix for 2020. Russia's role as a major exporter to the European Union increases. Russia covers additional 11.5 percentage points of European gas supplies in 2020. These additional Russian volumes are mainly transported via the Nord Stream pipeline (27.5 bcm in 2020), the Yamal pipeline via Belarus and Poland (about 32 bcm) and via Ukraine. European production decreases especially in the UK, where production is at 11.1 percent in 2009 and decreases to only 4.8 percent of EU-27 gas supply in 2020. Thus, intra-European gas flows from the production regions in the UK and the Netherlands are decreasing and flows on all new and existing pipeline import routes are increasing. Nord Stream causes a reduction of flows via the Czech Republic in comparison to 2010. In 2020, the additional volumes sent via Ukraine are transported further on to Hungary, Slovakia and Austria, to meet higher demand in this region.

The Baltic region, eastern Europe and Italy exhibit low marginal supply costs in comparison to Western Europe in 2020 (see Table 2). Western European countries are distant from non-European gas producers and the marginal unit of natural gas supplied to this region is comparatively cost-intensive because the incurred costs cover either additional transport costs or relatively high LNG import costs. In the Balkan region bottlenecks occurring on the peak day, the worst case scenario in terms of security of supply, lead to disruptions to consumers. These occur because of a lack of interconnector capacities to the adjacent countries relative to the high level of demand. The only import pipeline from Bulgaria to Former Yugoslavian Republic

Figure 2: Supply mix in 2020



of Macedonia (FYROM) provides an average daily capacity of 2.6 million cubic meters per day (mcm/d), which is not sufficient to meet the Macedonian peak demand of 3 mcm/d assumed for 2020 by ENTSOG (2009). The same holds for the interconnector from Serbia to Bosnia and Herzegovina with 1.9 mcm/d compared with a peak demand of 2 mcm/d, and the Serbian demand of 20 mcm/d, which is significantly higher than the assumed cross-border capacity of about 13 mcm/d from Hungary, and about 4.3 mcm/d from Romania.

Table 2: Overview marginal supply costs - South Stream and Nabucco in comparison to Baseline Scenario

	Marginal supply costs on peak day in EUR/MWh					**Peak day**
Country*	Baseline	Nabucco	% Change to Baseline	South Stream	% Change to Baseline	**demand (in mcm)**
AT	21.56	20.97	-2.71%	21.62	0.27%	**86**
BA**	peak day disruption	peak day disruption	peak day disruption	peak day disruption	peak day disruption	**2**
BE	22.61	22.53	-0.37%	22.63	0.07%	**182**
BG	20.87	19.97	-4.32%	21.09	1.07%	**15**
CH**	22.51	21.99	-2.30%	22.62	0.51%	**23**
CS**	peak day disruption	peak day disruption	peak day disruption	21,59	prevention of disruption	**20**
CZ	21.17	20.47	-3.29%	21.47	1.43%	**71**
DE	21.80	21.39	-1.90%	21.77	-0.14%	**500**
EE	18.46	17.73	-3.95%	19.27	4.41%	**3**
ES	22.06	22.08	0.07%	22.07	0.04%	**294**
FI	18.53	17.80	-3.93%	19.35	4.39%	**24**
FR	22.79	22.77	-0.09%	22.76	-0.12%	**417**
GB	22.32	22.06	-1.19%	22.23	-0.44%	**483**
GR	21.62	21.81	0.89%	21.51	-0.47%	**35**
HR	21.66	21.08	-2.68%	21.71	0.25%	**37**
HU	21.61	20.30	-6.10%	21.50	-0.55%	**99**
IE	22.81	22.53	-1.22%	22.71	-0.44%	**28**
IT	20.26	19.80	-2.28%	20.34	0.42%	**433**
LT	19.66	18.96	-3.53%	20.06	2.05%	**14**
LU	22.72	22.60	-0.55%	22.75	0.11%	**7**
LV	18.82	18.10	-3.82%	19.55	3.90%	**8**
MK**	peak day disruption	peak day disruption	peak day disruption	peak day disruption	peak day disruption	**3**
NL	22.32	22.25	-0.33%	22.32	-0.03%	**431**
PL	20.62	19.93	-3.38%	20.74	0.57%	**85**
PT	21.89	21.88	-0.08%	21.88	-0.06%	**32**
RO	20.24	19.65	-2.91%	20.61	1.80%	**90**
SI	21.74	21.18	-2.58%	21.82	0.37%	**9**
SK	20.78	20.08	-3.36%	21.15	1.79%	**40**
EU-27 averages weighted by demand	**21.79**	**21.48**	**-1.39%**	**21.81**	**0.10%**	

*ISO Country Codes

**Non-EU and disrupted countries not included in averages.

4.2. Nabucco and South Stream Scenario results of no-crisis simulation

The inclusion of Nabucco and South Stream in the simulation changes gas flows on major import routes. Flows on Nabucco push Russian volumes further to the West and cause a higher utilization of the routes via Ukraine and Slovakia. On the contrary, South Stream takes over volumes from these routes and sends them directly to Bulgaria. In the Baseline Scenario these volumes are transported via Ukraine and further on to Romania and Bulgaria. Figure 3 shows the gas volumes transported to the European market by Nabucco and South Stream sorted by the countries where these volumes are withdrawn and consumed. Nabucco and South Stream volumes remain in eastern Europe. Based on the cost-minimizing simulation of a peak-day scenario without crisis, Nabucco brings more gas to the European market than does South Stream. Nabucco volumes provide main supplies to Bulgaria and Hungary, as well as Turkey, and minor volumes are withdrawn in Romania.

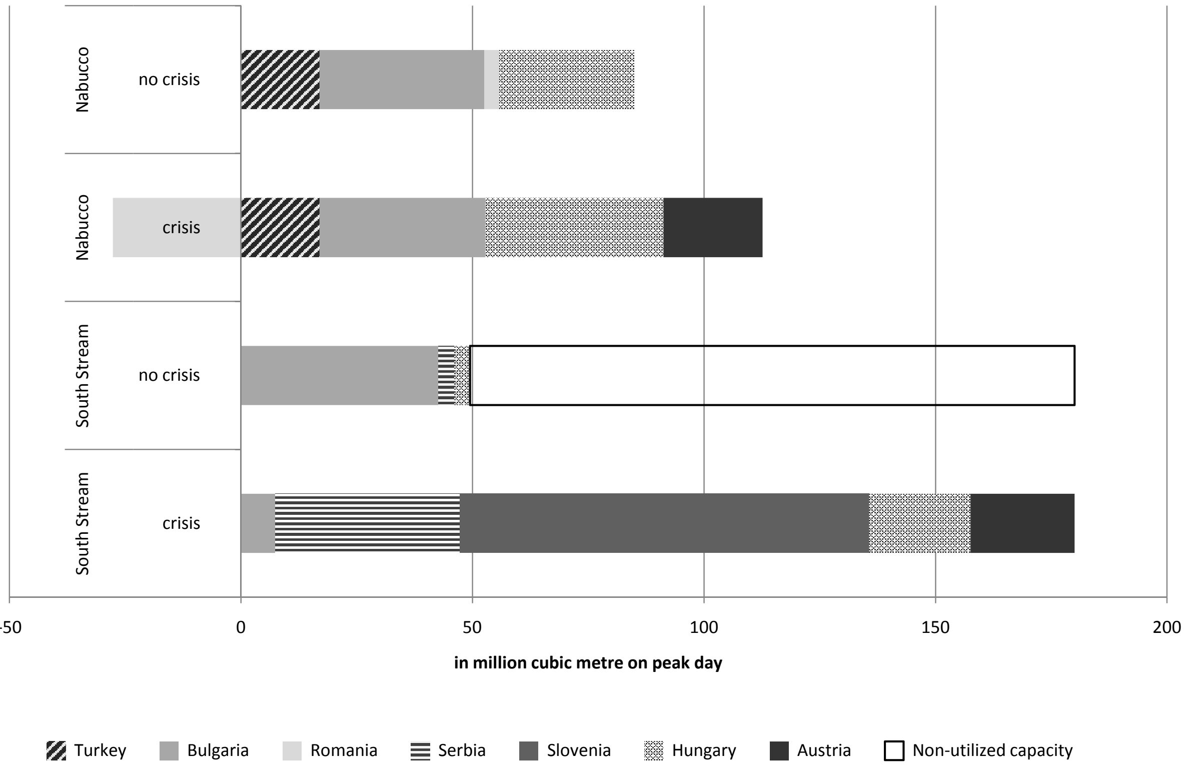
These volumes reduce marginal supply costs significantly in eastern Europe, especially in Hungary and Bulgaria (see Table 2). Only minor marginal supply cost decreases of around one percent can be observed in Western Europe. Belgium, Netherlands, Luxemburg (BeNeLux countries), France, Spain and Portugal are not significantly affected by the commissioning of Nabucco. On average, marginal supply costs decrease by 1.4 percent within EU-27.

South Stream only transports natural gas to Bulgaria and minor gas volumes to Serbia and Hungary (see Figure 3). In opposition to the Nabucco, Scenario disruptions in Serbia are avoided in the South Stream Scenario, which simultaneously causes slight average marginal supply cost increases (0.1 percent, see Table 2) in the European Union, especially in Romania, Bulgaria, Slovakia and the Czech Republic because of the rerouting of Russian volumes.

However, the disruptions in the Balkan countries Bosnia and Herzegovina and the FYROM cannot be prevented on a peak winter day even with the inclusion of Nabucco and South Stream because both pipelines bypass this region.

In summary, Nabucco and South Stream provide additional capacity and another option to transport gas to the European market, so they both improve the supply situation in terms of changes in marginal supply costs or the avoidance of disruptions, which are observed only in eastern and central Europe. Significant effects for Western Europe occur neither in the South Stream nor the Nabucco Scenarios.

Figure 3: Withdrawal of gas volumes along the route



The negative values in the Nabucco crisis scenario indicate injections into the pipeline in Romania.

5. Results of Ukraine crisis simulation for 2020

Since about 80 percent of Russian gas to the European Union is currently transported via Ukraine, a supply disruption on this route is the most threatening scenario for the European gas supply. Therefore, the effects of a disruption of four weeks of gas imports via Ukraine on the locational marginal cost price estimators are evaluated for the Baseline Scenario. Subsequently, the effects of the inclusion of the Nabucco pipeline or the South Stream pipeline are investigated. The analysis of the simulation results is carried out as a comparison of the three infrastructure scenarios.

5.1. Baseline Scenario results of Ukraine crisis simulation

A disruption of gas supplies via Ukraine causes major gas flow changes mainly in eastern Europe. Natural gas is withdrawn from storages in eastern Germany and partly transported to Poland, the Czech Republic and further on to the gas hub in Baumgarten, Austria. Storages in southern Germany provide volumes for Austria and volumes from western German storages are partly sent further on to Switzerland. Volumes withdrawn in northern Italy remain in the domestic market. (See Figure 4 for the additional volumes withdrawn from storages during the crisis.)

The respective changes in marginal supply costs analyzed result from a simulation with a stoppage of gas supplies via Ukraine in comparison to a scenario without such a crisis. On a peak winter day, the simulated four-week stoppage in gas supplies via Ukraine leads to disruptions to consumers and significant effects on marginal supply costs in large parts of southeastern Europe. For the Baseline Scenario presented in Table 3, given the planned pipeline infrastructure expansions, a peak day scenario itself would already cause disruptions in a no-crisis simulation (see Section 4). These peak day disruptions are aggravated in a crisis simulation. Without a Ukraine crisis only 4 percent of peak day demand is disrupted in Bosnia and Herzegovina, 17 percent in Serbia and 27 percent in Macedonia, which increase to a complete disruption of peak day demand in Bosnia and Herzegovina and Macedonia during a Ukraine crisis. In addition, in a Ukraine crisis simulation, between 15 to 27 percent of consumers in Romania, Bulgaria and Hungary are also cut off from gas supplies (see Table 3 and Table 4).

In Croatia, no consumers are disrupted. However, marginal supply costs indicate that disruptions would occur at the margin if demand increases only slightly. Increases in marginal supply costs of more than 3 percent occur in eastern Europe, while Germany, the BeNeLux countries and Poland are confronted with slight changes in marginal costs that result from the compensation through German storage volumes (see Figure 4). Western European countries, which are supplied by Norwegian and Algerian pipeline gas as well as LNG imports (i.e. UK, Ireland, Switzerland, Italy, Portugal, France and Spain) are not significantly affected by the crisis.

In the Baltic countries, Finland and Estonia, marginal supply costs even decrease by more than 40 percent in the crisis simulation. Because of the cut-off of Russian volumes to Western Europe via Ukraine and the available Russian export potential, these countries receive additional Russian volumes. In contrast to marginal costs being driven by expensive storage withdrawals in a no-crisis simulation, these additional Russian volumes lead to significant reductions in marginal supply costs.

Table 3: Change of marginal supply costs during crisis

Country*	**% change Baseline**	**% change Nabucco**	**% change South Stream**
AT	4.23%	4.52%	1.28%
BA	peak day disruption	peak day disruption	peak day disruption
BE	1.41%	0.53%	0.48%
BG	crisis disruption	marginal crisis disruption	-1.92%
CH	0.58%	0.02%	0.03%
CS	peak day disruption	peak day disruption	-1.87%
CZ	3.09%	4.74%	0.70%
DE	1.31%	1.42%	0.37%
EE	-42.94%	-40.59%	-7.01%
ES	-0.14%	0.07%	-0.03%
FI	-42.44%	-40.08%	-6.99%
FR	-0.02%	-0.11%	0.00%
GB	0.18%	-1.06%	0.00%
GR	crisis disruption	crisis disruption	-1.34%
HR	marginal crisis disruption	3.37%	-0.55%
HU	crisis disruption	crisis disruption	-0.07%
IT	0.19%	0.31%	0.00%
IE	0.72%	0.37%	0.10%
LT	-9.22%	-9.38%	-7.42%
LU	1.80%	0.73%	0.69%
LV	-5.86%	-5.78%	-5.81%
MK	peak day disruption	peak day disruption	peak day disruption
NL	1.37%	0.34%	0.47%
PL	1.13%	2.66%	0.01%
PT	0.03%	0.11%	-0.02%
RO	crisis disruption	marginal crisis disruption	crisis disruption
SI	4.33%	0.00%	0.64%
SK	8.39%	0.00%	3.89%

The wording "marginal crisis disruption" indicates that no volumes are disrupted,
but an additional unit would be.
Therefore, no marginal supply costs can be computed.
*ISO Country Codes

Table 4: Disrupted volumes during crisis

in million cubic meter on peak day	Baseline				Nabucco				South Stream			
Country*	**no disruption**		**disruption**		**no disruption**		**disruption**		**no disruption**		**disruption**	
BA	0.08	4.00 %	2.00	100.00%	0.08	4.00%	2.00	100.00%	0.08	4.00%	0.08	4.00%
BG	0.00	0.00%	3.98	26.51%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
CS	3.42	17.11%	4.00	20.00%	3.42	17.11%	4.00	20.00%	0.00	0.00%	0.00	0.00%
GR	0.00	0.00%	5.25	15.00%	0.00	0.00%	2.38	6.81%	0.00	0.00%	0.00	0.00%
HU	0.00	0.00%	26.83	27.10%	0.00	0.00%	8.31	8.40%	0.00	0.00%	0.00	0.00%
MK	0.81	26.96%	3.00	100.00%	0.81	26.96%	0.81	26.96%	0.81	26.96%	0.81	26.96%
RO	0.00	0.00%	13.52	15.02%	0.00	0.00%	0.00	0.00%	0.00	0.00%	9.20	10.22%
Sum	**4.31**		**58.57**		**4.31**		**17.51**		**0.89**		**10.09**	

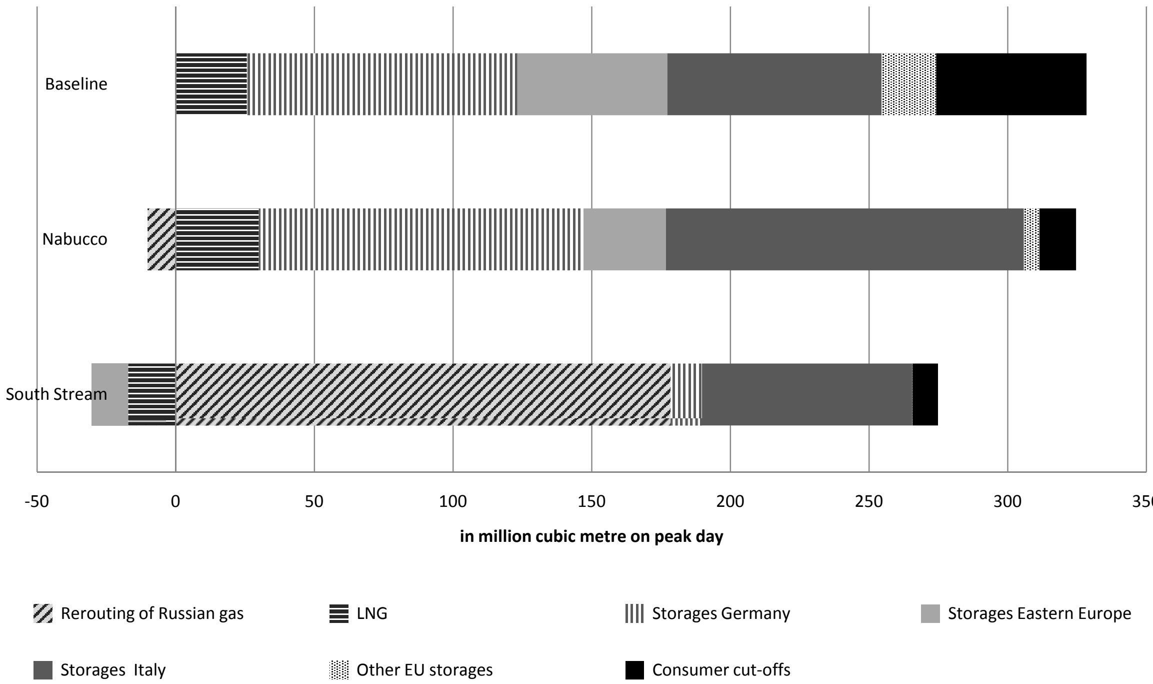
The percentages indicate proportions of peak day demand.
*ISO Country Codes

5.2. Nabucco and South Stream Scenario results of Ukraine crisis simulation

The compensation for the missing Ukraine transits causes overall changes in the utilization of infrastructure components and gas flows. The differences of supply volumes between the crisis and the no-crisis scenario are presented in Figure 4. The compensation within the applied overall optimization framework could even reduce the utilization of alternative infrastructure to the Ukraine route, which is indicated by the negative bars. Therefore, including all changes between the crisis and no-crisis scenarios, the net length of the bar in Figure 4 reflects the aggregated compensated or disrupted volumes via Ukraine for each of the three infrastructure scenarios. These aggregated volumes differ because the utilization of the Ukrainian routes in a no-crisis simulation varies depending on the major pipeline available to supply the European market. Without a Ukraine crisis South Stream already takes over some of the volumes that are transported via Ukraine in the Baseline Scenario. Thus, in the South Stream Scenario, given that Ukraine transits were already lower than in the Baseline Scenario, the missing volume – about 77 mcm/d less than in the Baseline Scenario – must be substituted if there is a supply disruption via Ukraine. Rerouting of Russian gas volumes and only a small proportion of withdrawal from storage in Germany and other European countries can then substitute for the missing Ukrainian volumes. Rerouting here turns the volumes that have been transported via Ukraine in the no-crisis simulation to another route from Russia in a crisis simulation.[11] Thus, less west-to-east gas flows take place with South Stream than in the Baseline Scenario and no significant gas flow changes occur in western Europe. Because of several bottlenecks in southeastern Europe, 15 million cubic meters (mcm) less LNG are imported into the Krk terminal in Croatia and 13 mcm less gas is withdrawn from eastern European storage on the peak day during the simulated Ukraine crisis. These supply reductions are also compensated by additional supplies via South Stream.

[11] These routes could be Nord Stream, the Yamal route via Belarus and Poland to Germany, Blue Stream or South Stream depending on the Scenario. In the South Stream Scenario, Russian gas is rerouted via South Stream because Nord Stream and the Yamal route are completely utilized.

Figure 4: Differences regarding supply volumes between crisis- and no-crisis simulation



The net length of the bars – positive part less the negative part – indicates the sum of the missing Ukraine transits and how these are compensated.

South Stream being only poorly utilized in a no-crisis simulation offers generous redundant capacity during a crisis simulation (see Figure 3 on page 15). During a halt of gas supplies via Ukraine, gas transported on South Stream more than triples on a peak demand day, which demonstrates the extent of redundant capacity available. Because of this alternative supply option, gas flows in west Europe remain mainly unaffected by the crisis except for north Italy where the missing volumes are compensated for by storage withdrawals and South Stream supplies. South Stream then provides less volumes for the Bulgarian market, but significant volumes for the Serbian, Slovenian, Hungarian and Austrian market. It eliminates persistent supply disruptions in Serbia; avoids the crisis-induced disruptions that occurred in the Baseline Scenario in Bulgaria, Greece and Hungary; and reduces increases in marginal supply cost significantly in Slovakia, Croatia, Austria and Germany. Disruptions to consumers can be observed in Romania due to a lack of pipeline capacity from Hungary to Romania and South Stream bypassing Romania,[12] although large vol-

[12] Gazprom and Romania have started negotiations on Romania joining the South Stream pipeline network. A feasibility study

umes are transported to neighbouring Bulgaria. But the disruptions in Romania are reduced from 15 to 10 percent of peak day demand in comparison to the Baseline Scenario. Referring to the mitigating effects these extra volumes have on the marginal supply costs and on disruptions to consumers, South Stream's large-scale capacity has a significant impact on security of supply in terms of transit country risks. So it significantly reduces the dependence on Ukraine. However, based on cost-minimization, even in a peak day scenario South Stream is poorly utilized if other transport options from Russia are available.

By contrast, gas volumes transported via Nabucco do not have a crowding-out effect on Ukraine transits in a no-crisis simulation, so the missing Ukraine volumes are much greater during a crisis simulation. These missing volumes are mainly compensated for by withdrawals from storage in eastern Europe, Germany, Italy and other European countries. Germany, which has the largest storage working gas volumes in Europe, with more than 25 bcm, provides additional volumes during the crisis to be transported east. Nabucco provides additional volumes for Italy and Austria, which in addition receive some volumes from northern Italian storages during the crisis. In comparison to the Baseline Scenario more German storage volumes can therefore be sent to northeastern Europe. In the Nabucco Scenario, in the simulated crisis on a peak day, 10 mcm less volume than in the no-crisis simulation is rerouted from Russia, that is, transported on a route other than the Ukraine route (Blue Stream in this case). The simulated Ukraine crisis causes a bottleneck in the interconnector from Turkey to Bulgaria, which results in this decrease in Blue Stream flows. Again subtracting these negative volumes from the positive bar for the Nabucco Scenario mirrors the missing Ukraine volumes.

During the halt of Ukrainian transits, Nabucco gas supplies to Bulgaria and Turkey remain the same as in the no-crisis simulation, and additional volumes are transported to Hungary and Austria (see Figure 3 on page 15). These additional volumes are mainly injected in Romania, as Nabucco is already completely utilized from the start of the pipeline in a simulation without a crisis. Since some volumes are consumed in Bulgaria, capacity is then available in Romania. The gas volumes injected into the pipeline are withdrawn from storage in Romania, mainly to reduce disruptions in Hungary and to mitigate increases in marginal supply costs in Austria. Introducing the Nabucco pipeline does not reduce the peak day disruptions that result in Serbia, Bosnia and Herzegovina[13]. However, during the simulated Ukraine crisis, disruptions in

will be worked out, but it is not yet clear whether this could result in a different route that excludes Bulgaria. (Euractiv.com, 2010)

[13]The Bosnian natural gas company BH-Gas has already shown interest in extending its gas supplies through connections to major pipeline projects. It has asked Turkey's Bota to help it connect to the planned Nabucco and TAP pipelines in an effort to diversify its gas supplies (Balkans.com Business News (2010)).

Bulgaria, Romania and parts of Greece are avoided such that only increases in marginal supply costs occur, rather than consumer cut-offs. In addition, disruptions in FYROM are reduced from a 100 percent in the Baseline Scenario during the Ukraine crisis to the peak day disruption level of 27 percent. However, the improvement of market integration with Nabucco leads to minor increases in marginal supply costs in Austria, Czech Republic, Poland and Northern Germany over the marginal supply costs in the Baseline Scenario. Again, it is cost-efficient, within this modeling framework, to accept these slight increases in order to prevent disruptions to customers in other regions.[14]

Additional consumer cut-offs caused by the Ukraine crisis on the peak day are reduced by both South Stream and Nabucco. In the Baseline Scenario about 54 mcm are additionally cut off during the crisis, but only about 13 mcm are additionally cut off with Nabucco included, and South Stream's extensive capacity further reduces the disruptions to about 9 mcm. (See Figure 4. These numbers reflect the differences between the crisis and no-crisis scenarios in Table 4.)

6. Conclusion

The Nabucco and South Stream Pipelines are often discussed in the context of security of European gas supply. The results of the simulations with the TIGER model show that security of supply in Eastern Europe increases with the inclusion of either Nabucco or South Stream based on assumptions covering currently publicly announced infrastructure plans. Nabucco reduces marginal supply costs in many Eastern European countries and South Stream prevents disruptions to consumers in Serbia that occur in the Baseline Scenario. However, consumer cut-offs in some Balkan countries cannot be avoided by either Nabucco or South Stream because these cut-offs occur as a result of insufficient interconnector capacity. These results are conditional on the specific assumptions.[15] Additional not yet announced interconnector capacity expansions that may occur during the interim would mitigate or even prevent these consumer-cut-offs. The same holds for a lower demand scenario whereas significantly higher demand could even worsen the disruptions.

Without either Nabucco or South Stream, the European market is strongly dependent on transits and on a functioning pipeline system in Ukraine. Not even flexible LNG imports can reduce this dependence because of the bottlenecks that occur in the European pipeline system during a halt of Ukraine transits.

Generally, the inclusion of Nabucco and South Stream in model simulations of a Ukraine crisis both increases security of supply and leads to a reduction of disruptions to consumers and to lesser price increases. The

[14] These effects reflect a higher willingness to pay in regions confronted with supply shortages.

[15] Bottlenecks identified in the paper that might lead to disruptions refer to congestion which occurs in an efficiently working market. Potential additional bottlenecks as a consequence of market inefficiencies are not detected by the modeling approach.

impact of these improvements varies significantly over different European regions and is most effective in southeastern Europe. Nabucco prevents disruptions in Bulgaria and Romania and South Stream in Hungary, Serbia and Bulgaria. However, not all disruptions within the European market can be avoided by these pipeline projects because of intra-European bottlenecks. Persistent disruptions remain in Bosnia and Herzegovina and Former Yugoslavian Republic of Macedonia. These results are based on assumptions on significant demand increases in this region and publicly announced plans on infrastructure developments. A connection of South Stream to Romania or (reverse flow) capacity from Hungary to Romania could mitigate disruptions to consumers there. The same holds for a connection of Nabucco to the Serbian market or a better integration of the Hungarian and Serbian market. Moreover, because of the significantly lower capacity of Nabucco, additional LNG volumes imported into Croatia would be needed to eliminate disruptions in Hungary and Serbia, but these volumes could be transported only if bottlenecks in Croatia were removed. The effects of the pipeline projects in Western Europe are small.

Based on cost-minimization, the model results show that South Stream, which is poorly utilized even on a peak winter day in a no-crisis simulation, supplies primarily Bulgaria. However, South Stream offers redundant capacity in a crisis simulation to reroute Ukraine transits during the simulated halt of supplies via Ukraine. In the crisis simulation, South Stream is highly utilized, so it would be built primarily to bypass Ukraine. Both pipeline projects enable a diversification of supply routes especially with respect to the main routes via Ukraine and, if implemented, should contribute to securing gas supplies. However, only Nabucco would reduce the dependency on Russian gas, assuming adequate alternative suppliers in the Middle East and Caspian region were available to provide gas for the pipeline, and would support a diversification of supply sources.

In summary, Nabucco and South Stream provide additional large-scale pipeline capacity in southeastern Europe, but they also increase security of supply by extending supply options and mitigating the effects of potential supply disruptions via Ukraine in this region. However, the attribution of relevant costs, apart from relative changes in short-term marginal supply costs, and the probability of events that have high impact on security of supply are not evaluated.

The determination of the optimal security of supply level by comparing marginal costs of investments into the Nabucco and South Stream pipeline with marginal benefits of additional security of supply provided remains open for further research. For measuring these benefits a detailed investigation on country-specific demand profiles and elasticities is needed, especially because of the uncertain demand developments in the EU within the next decades. Moreover, an efficiency analysis of a potential investment in the Nabucco and

South Stream pipeline projects would complement a long-term economic analysis of security of supply.

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Appendix A. Main equations of the TIGER model

The TIGER model developed by Lochner and Bothe (2007) optimizes the European natural gas dispatch given the infrastructure components, i.e. long-distance transmission pipelines, storages and LNG import terminals, minimizing the total costs of gas supply. A detailed model description can be found in EWI (2010b). The **Objective Function**

$$
\begin{aligned}
C = & \sum_{t,n_1,n_2} [(T(t,n_1,n_2) + T(t,n_2,n_1)) \cdot c_{trans}(t,n_1,n_2)] \\
& + \sum_{t,n_1,p} [P(t,n_1,p) \cdot c_{prod}(t,n_1,p)] \\
& + \sum_{t,n_1,s} [St(t,n_1,s) \cdot c_{stor}(t,n_1,s)] \\
& + \sum_{t,n_1,r} [LNGSt(t,n_1,r) \cdot c_{LNGstor}(t,n_1,r)] \\
& + \sum_{t,n_1,r} [LNGR(t,n_1,r) \cdot rt(r)] \\
& + \sum_{t,n_1} [DD(t,n_1) \cdot dc(n_1)]
\end{aligned} \tag{A.1}
$$

is minimized over the vector $X = (T, P, St, LNGSt, LNGR, DD)$.

Gas supply and demand need to balanced. At each node, gas supply, that could either be storage withdrawal, pipeline supply, LNG import or production, needs to equal gas demand. Thus, the **Node Balance Constraint** holds for t and n_1:

$$
\begin{aligned}
& \underbrace{\sum_{dr} d(t,n_1,dr)}_{\text{demand}} = \\
& \underbrace{\sum_{n_2} T(t,n_2,n_1) + \sum_{pr} P(t,n_1,pr) + \sum_{r} LNGR(t,n_1,r) + DD(t,n_1)}_{\text{inflow at node}} \\
- & \underbrace{\sum_{n_2} T(t,n_1,n_2) - \sum_{st} [StIn(t,n_1,st) - StOut(t,n_1,st)]}_{\text{outflow at node}}
\end{aligned} \tag{A.2}
$$

The marginal supply costs estimator at a certain node n_1 at time t is the dual variable associated with the Node Balance Constraint. The dual variable reflects the increase of the Objective Function's optimal value by marginally increasing demand in the Node Balance Constraint. The dual variable is thus interpreted as the shadow price of supply. For a more detailed model description with focus on the determination of marginal supply costs (or nodal prices) see Lochner (2009) and Lochner (2011).

The following **Technical Constraints** must hold:

Production capacity constraint for t, n_1 and p: For each y the sum of daily supply volumes from a production region has to be smaller or equal to the annual supply capacity.

$$\sum_t P(t, n_1, p) \leq cap_{annualsupply}(n_1, p) \tag{A.3}$$

Daily production is constrained by daily peak capacity.

$$P(t, n_1, p) \leq cap_{peaksupply}(t, n_1, p) \tag{A.4}$$

Pipeline capacity constraint for t, n_1 and n_2: Transported gas volumes are restricted by pipeline capacity.

$$\begin{aligned} T(t, n_1, n_2) &\leq cap_{pipe}(t, n_1, n_2) \\ T(t, n_2, n_1) &\leq cap_{pipe}(t, n_2, n_1) \end{aligned} \tag{A.5}$$

LNG constraint for t, n_1 and r: Similar to the supply constraints, LNG imports are restricted by daily and annual capacity constraints.

$$\begin{aligned} LNGR(t, n_1, r) &\leq cap_{peakregas}(t, n_1, r) \\ \sum_t LNGR(t, n_1, r) &\leq cap_{annualregas}(y, n_1, r) \end{aligned} \tag{A.6}$$

LNG volumes to be imported are only restricted by LNG import capacity. The LNG costs assumptions (presented in Appendix B) mirror a long term equilibrium and are therefore higher than pipeline costs. LNG costs cover the costs of volumes on the tanker in front of the terminal.

Storage constraint for t, n_1 and s: Storage volumes depend on withdrawals and injections of the previous period and are restricted by storage specific working gas volumes.

$$\begin{aligned} St(t, n_1, s) &= St(t-1, n_1, s) + StIn(t, n_1, s) - StOut(t, n_1, s) \\ St(t, n_1, s) &\leq wgv(t, n_1, s) \end{aligned} \tag{A.7}$$

The storage level is determined by withdrawals and injections (minus compressor consumption) and restricted by working gas volume. The gas volumes injected into and withdrawn from the storages $StIn(t, n_1, s)$ and $StOut(t, n_1, s)$ are a function of maximum injection and withdrawal rates and the storage level. The maximum injection and withdrawal rates depend on pressure and thus on the current storage level as well as on the storage type. LNG storages operate in the same manner.

List of symbols

Sets and identifiers

$dr \in D$: demand region

$n_1 \in N$: (start) nodes

$n_2 \in N$: (end) nodes

$p \in P$: production region

$r \in R$: LNG regasification terminal index

$s \in S$: storage index

$t \in T$: time period (days in this model version)

Parameters

$d(t, n_1, dr)$: demand at node n in period t at demandregion d

$c_{trans}(t, n_1, n_2)$: transportation costs between n_1 and n_2 in period t

$c_{stor}(t, n_1, st)$: storage costs s at node n_1 in period t

$c_{LNGstor}(t, n_1, r)$: LNG storage costs at regasification terminal r at node n_1 in period t

$c_{prod}(t, n_1, pr)$: production costs in production region p in period t

$rt(r)$: regasification tariff at LNG import terminal r

$dc(n_1)$: disruption costs at node n_1

$cap_{peaksupply}(t, n_1, p)$: peak supply capacity at node n_1 in production region p in period t

$cap_{annualsupply}(y, n_1, p)$: annual supply capacity at node n_1 in production region p in year y

$cap_{pipe}(t, n_1, n_2)$: pipeline capacity in period t from node n_1 to node n_2

$cap_{pipe}(t, n_2, n_1)$: pipeline capacity in period t from node n_2 to node n_1

$cap_{peakregas}(t, n_1, r)$ peak regasification capacity at terminal r at node n_1 in period t

$cap_{annualregas}(y, n_1, r)$ annual regasification capacity at terminal r at node n_1 in year y

$wgv(t, n_1, s)$ working gas volume of storage s at node n_1 in period t ,

Optimization Variables

$T(t, n_1, n_2)$: gas volumes transported from n_1 to n_2 in period t

$T(t, n_2, n_1)$: gas volumes transported from n_2 to n_1 in period t

$P(t, n_1, p)$: production at node n_1 in production region p in period t

$St(t, n_1, s)$: gas volumes in storage s at node n_1 in period t

$StIn(t, n_1, s)$: gas volumes injected into storage s in period t at node n_1

$StOut(t, n_1, s)$: gas volumes withdrawn from storage s in period t at node n_1

$DD(t, n_1)$: demand disruption at node n_1 in period t

$LNGR(t, n_1, r)$: LNG volumes regasified in terminal r at node n_1 in period t

$LNGSt(t, n_1, r)$: stored LNG volumes at regasification terminal r at node n_1 in period t.

Table B.5: Data and sources

Input data	Specification of parameters	Sources
supply	export potential of non-European production regions and indigenous production	EWI (2010a)
costs	transportation costs and regasification tariffs	Observatoire Méditerranéean de l'Energie (OME) (2001)
	storage costs	United Nations (1999)
	production costs and costs of gas supply from a certain production region	EWI (2010a)
demand	annual demand	European Commission (2008), EWI (2010a)
	peak day demand	ENTSOG (2009)
infrastructure	all capacity assumptions and working gas volumes	publicly available sources from pipeline, LNG and storage operators and the respective European associations' databases GLE, GTE and GSE (see for instance Gas Infrastructure Europe (GIE) (2010) and see EWI (2010b) and EWI (2010a) for more details)

Appendix B. Parameterization and data sources

The TIGER model's input parameters for the simulations of this paper are based on the sources presented in the following table:

Assumptions made on storages as discussed above in the context of the storage constraint were developed with storage operators and are discussed in EWI (2010b).

Disruption costs are the most cost-intensive option to keep the node balance. The concrete level of disruption costs does not impact the model results in terms of disrupted volumes as long as these costs are higher than for alternative supply options. Disruption costs vary between countries depending on their demand structure and type of demand (household, industry or power demand), on weather conditions and substitutive energy carriers. Further comprehensive research is necessary to reflect these aspects in precise disruption cost estimations for the European gas market which was out of range within this study. Therefore only the disrupted volumes are evaluated and not the costs of such gas demand reductions.