

Holz, Franziska; Richter, Philipp M.; Egging, Ruud

Article — Manuscript Version (Preprint)

The Role of Natural Gas in a Low-Carbon Europe: Infrastructure and Supply Security

The Energy Journal

Provided in Cooperation with:

German Institute for Economic Research (DIW Berlin)

Suggested Citation: Holz, Franziska; Richter, Philipp M.; Egging, Ruud (2016) : The Role of Natural Gas in a Low-Carbon Europe: Infrastructure and Supply Security, The Energy Journal, ISSN 0195-6574, International Association for Energy Economics, Cleveland, Vol. 37, Iss. SI37, pp. 33-59, <https://doi.org/10.5547/01956574.37.SI3.fhol> , <https://www.iaee.org/energyjournal/article/2827>

This Version is available at:

<https://hdl.handle.net/10419/214193>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.

The Role of Natural Gas in a Low-Carbon Europe: Infrastructure Requirements and Supply Security

Franziska Holz^{a)}

Philipp M. Richter^{b)}

Ruud Egging^{c)}

August 15, 2018

Abstract

In this paper, we use the Global Gas Model to analyze infrastructure requirements of the European natural gas market in the transition to a future low-carbon energy system until 2050. Three pathways of natural gas consumption are investigated: i) a decreasing natural gas consumption, following the scenarios of the EU Energy Roadmap 2050; ii) a moderate increase of natural gas consumption, along the lines of the IEA's New Policies Scenario; and iii) a temporary increase of natural gas use as a "bridge" technology, followed by a strong decrease after 2030. Our results show that import infrastructure and intra-European transit capacity currently in place or under construction are by and large sufficient to accommodate future import needs. This is despite a pronounced reduction of domestic production and a strong increase in import dependency. However, due to strong demand in Asia which draws LNG and imports from Russia, Europe has to increasingly rely on exports from Africa and the Caspian region leading to new pipeline capacity requirements from these regions. Moreover, pipeline investments open up new import and transit paths, including reverse flow capacity, which improve the diversification of supplies. When natural gas serves as bridging technology, short-term utilization rates of LNG import capacity are increased rather than pipelines expanded at large scale.

Keywords: natural gas, Europe, decarbonization, infrastructure

JEL codes: Q41, L71, C61

Highlights:

- The future role of natural gas depends on climate policy
- Increasing European natural gas imports can be accommodated by existing pipeline capacities
- Selected pipeline expansions will help to diversify the supply and allow a more efficient distribution within Europe
- Natural gas as bridge technology leads to a high reliance on LNG imports rather than large pipeline expansions

a) Corresponding author. German Institute for Economic Research (DIW Berlin), Mohrenstraße 58, 10117 Berlin, Germany; and Hertie School of Governance, Berlin, Germany. Mail: fholtz@diw.de, Phone: +49 30 89789-337.

b) German Institute for Economic Research (DIW Berlin), Mohrenstraße 58, 10117 Berlin, Germany. Mail: prichter@diw.de.

c) SINTEF Technology and Society, Trondheim, Norway and NTNU Industrial Economics and Technology Management, Trondheim, Norway. Mail: rudolf.egging@iot.ntnu.no.

1 Introduction

The role of natural gas in the transition to a decarbonized European energy system is yet unclear. There is a broad range of perspectives of natural gas in the future European energy mix: Natural gas could play the role of a “bridging fuel” during a transition phase, or serve as the main backup fuel for intermittent renewable power generation. However, it could also be steadily phased out and substituted for by non-fossil fuel alternatives which would quickly become economic under stringent climate policies.¹ While the European Energy Roadmap to 2050 suggests a development in the latter direction with a decreasing natural gas consumption over the next few decades (EC, 2011a), the International Energy Agency (IEA, 2014) sees a consistently large role for natural gas in the next decades in its New Policies Scenario.

In this paper we focus on potential infrastructure needs within the European natural gas sector and investigate to what extent the current natural gas infrastructure is capable to accommodate the transition towards a low-carbon energy system.² Even in case of a stabilisation of the European natural gas consumption at current levels, due to depleting domestic reserves and decreasing production European net imports increase and, hence, more infrastructure is potentially needed to facilitate those imports. Since Van Oostvoorn et al. (2003), several academic and policy studies have argued that more interconnection in the European natural gas network may be necessary (Lise and Hobbs 2008; EC, 2006). The European Commission has recognized the need to strengthen infrastructure in a transitioning system to a climate-friendly economy in its proposal for a “Connecting Europe Facility” (EC, 2011b), after already giving support in its TEN-E program (EC, 2006) and in the European Economic Recovery Plan (EU, 2009). Especially Central East and South East Europe are still not well enough connected to other parts of Europe and to other exporters than Russia to diversify their supplies. Moreover, it is argued that additional infrastructure is needed to facilitate a level playing field for all market participants and to reach a competitive market in the EU (e.g. EC, 2011c). Following the “dash for gas” of the past decade and with the European Commission and Member States aiming at improving supply security after several disruption episodes (e.g. Stern 2010, Richter and Holz 2015), many infrastructure projects have been agreed or were started and are due for completion before 2020.

In order to investigate the need for further investments after 2020 we rely on a numerical modeling analysis following a long tradition. Applied modeling approaches of natural gas markets can basically be divided into optimization models and complementarity (equilibrium) models. Optimization models are often set up as linear programs including a great level of technical detail (in linearized functions). The EUGAS model (Perner and Seeliger, 2004) and the TIGER model (e.g., Lochner and Bothe, 2007, Dieckhöfner, 2012) are two of the most detailed optimization models of the European natural gas sector, where dispatch is optimized in a network based on a complete representation of European pipelines of

¹ See Holz et al. (2015) for a discussion of the future of natural gas in a global context with a particular focus on resources, climate policies and uncertainties.

² Research for this paper was initiated during the Energy Modeling Forum (EMF) no. 28, which investigated greenhouse gas (GHG) mitigation pathways for the EU until 2050 (see Knopf et al. 2013).

different pressure-levels. André et al. (2009) present an infrastructure analysis based on nonlinear optimization. Midthun et al. (2012) develop a systems optimization approach taking into account the impact of pressure drops on network capacities. Complementarity modeling (also called equilibrium modeling), on the other hand, allows to include imperfect market structures that well characterize the European natural gas market (cf. Holz et al., 2008). This literature stream was initialized by Mathiesen (1987) and, after improvements of the computational capacities and the solvers, carried forward by Boots et al. (2004). Lise and Hobbs (2008) provided an extension of this model (the GASTALE model), while Egging and Gabriel (2006) as well as Egging et al. (2008) developed an alternative model with a detailed player set-up (European Gas Model). Egging et al. (2010) introduced a multi-period optimization in the World Gas Model, allowing for endogenous investment decisions in infrastructure variables.

In this paper we employ the Global Gas Model (GGM), a complementarity model of the world natural gas market with a detailed representation of Europe, in order to investigate the perspectives of natural gas in the transition to a low-carbon European energy system. Three pathways for the future role of natural gas in Europe are conceivable and shall be the frame for this paper:

- i) natural gas will gradually be used less in the energy mix, which is dominated by low-CO₂ alternatives such as renewable electricity, nuclear or coal with CCS;
- ii) natural gas will increasingly be used, substituting other fossil fuels with a relatively higher carbon content per generated unit of energy, particularly coal. This effect may be intensified by the advantageous balancing properties of natural gas-fired power generation in an increasingly intermittent electricity system in which natural gas acts as a “backup fuel”. Other sectors than electricity generation, i.e. transportation and heating may be affected as well;
- iii) natural gas will play a vital role during a transition period until CO₂-free technologies are economically available: natural gas as a “bridging fuel”. The relatively low carbon intensity of natural gas and the flexibility of gas-fired power generation lead to a short-term increase of natural gas consumption followed by a phase out in the long-term.

In the first part of this paper, we base our analysis on two EU Energy Roadmap 2050 scenarios, one scenario in compliance with EU 2020 targets, one more stringent climate scenario in line with EU 2030 targets. Both scenarios see a decreasing importance for natural gas in the European energy system (pathway i). We then define two alternative scenarios to investigate other possible developments of the European natural gas sector (pathways ii and iii): the first alternative scenario serves to investigate infrastructure needs in an environment of increasing natural gas consumption, while the second alternative scenario focuses on natural gas as “bridging fuel” towards a decarbonized European energy system.

Our results suggest that the pipeline and LNG capacities already in place or currently under construction could be largely sufficient to accommodate the European demand for natural gas in most of the scenarios. This particularly holds for scenarios with stringent climate policies. However, allowing for a more diverse natural gas supply, and taking into account the competition for Russian gas with Asia, new connections are advisable. In particular, pipeline connections from Africa and the Caspian region towards central Europe are significantly expanded. Moreover, within Europe there is need only for small but important infrastructure investments for improved interconnection between regions (e.g. between

the Iberian Peninsula and the rest of Western Europe) and for reverse flows (West-East direction). These small additional capacities will not only serve to import additional volumes but they will also improve supply security considerably as they allow for a diversification of flows. Naturally the increasing natural gas consumption scenario (*Back-Up*) is characterized by the most significant pipeline expansions. The *Bridge* scenario results in lower investments in pipelines but higher expansions of LNG facilities to accommodate the (solely) short-term increase in consumption.

The remainder of this paper is organized as follows: in Section 2 the GGM and its underlying dataset are presented. We present results for pathway i, a decreasing European natural gas consumption, in Section 3. The two alternative scenarios on pathways ii and iii are discussed in Section 4. Section 6 concludes.

2 The Global Gas Model

The Global Gas Model (GGM) is a partial equilibrium model of the natural gas market that numerically simulates regional production, consumption and trade patterns of natural gas.³ The model allows a high level of detail featuring demand seasonality, potential market power of trading agents as well as endogenous investment in storage and transport capacity both of pipelines and along the LNG supply chain. While Egging (2013) presents a stochastic version of the model, in this paper we use a deterministic version with a particular focus on and a more detailed representation of Europe. Twenty five of the EU member states are incorporated individually in the global total of 45 nodes.⁴

Figure 1 illustrates the supply chain structure incorporated in the GGM for two trading countries, highlighting the interaction between different market players, namely producers, traders, storage system operators (SSO) and transmission system operators (TSO). All agents are price takers, except for selected traders who can exert market power à la Cournot by taking into account the effect of their supplied quantities on market prices. All agents operate under complete information and maximize their discounted net present value of revenues over the full model horizon under operational constraints (such as production capacity limits) and technical and infrastructure restrictions (such as pipeline capacities and loss rates).

³ See Egging (2013) for the mathematical formulation of the GGM.

⁴ Cyprus and Malta did not consume any natural gas in 2010 and are left out. Croatia only acceded the European Union after our base year 2010. Hence, the region “EU” in this paper refers to the EU-27. Furthermore, our dataset separately includes ten East European countries as well as Russia, Turkey, Norway and Switzerland. All other countries are combined in the six regions Africa (AFR), Asia-Pacific (ASP), the Caspian Region (CAS), the Middle East (MEA), North America (NAM) and South America (SAM) to represent all production, consumption and trade, in the global natural gas market. See the Appendix for a list of country and regional abbreviations.

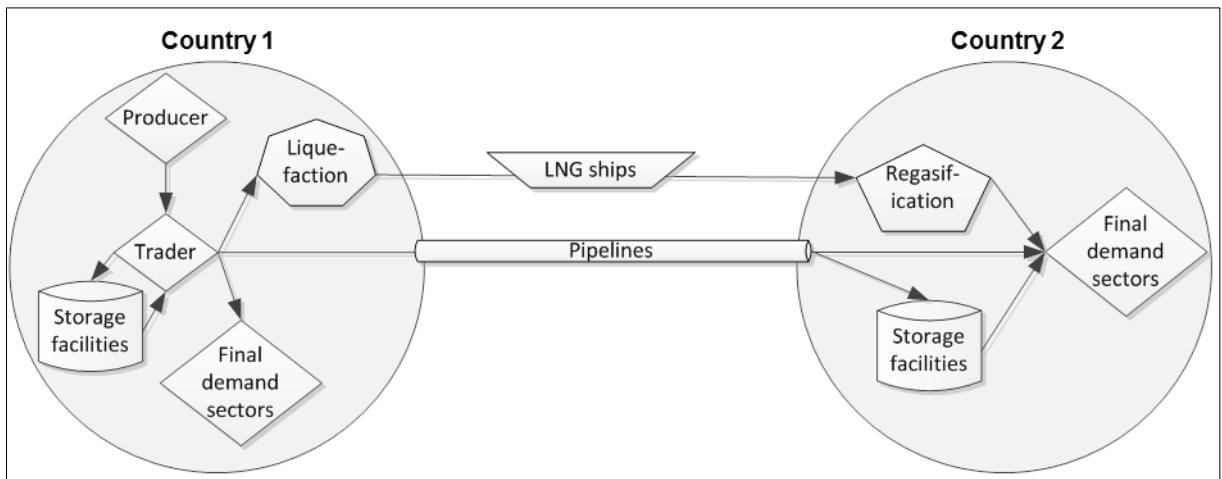


Figure 1: Representation of the natural gas market and supply chain in GGM

Producers maximize discounted profits of selling natural gas to assigned traders, bearing the costs of extraction. Production cost functions are defined as proposed by Golombek et al. (1995), with a constant per unit term, a linearly increasing term and a third term inducing a steep cost increase whenever production approaches the maximum capacity. Traders, in turn, generate revenues by selling natural gas to consuming sectors, and bear costs for purchasing natural gas, as well as rents for using storage and transportation services. The TSO manage the transportation network and rent out capacity to traders. This can be pipelines, or liquefaction, shipping and regasification infrastructure. The TSO maximize profits from congestion rents on transportation capacities minus incurred investment costs. Similarly, the SSO manage the storage facilities that traders can rent to arbitrate between seasonal price variations. To relieve the pressure of infrastructure bottlenecks, the TSO and SSO can endogenously invest in additional transportation and storage capacities respectively, and will do so whenever profitable. Furthermore, marketers serve to balance natural gas supply with the combined demand of three different sectors (residential/commercial, industrial and power generation). Consumption within the different sectors is represented by an aggregate inverse demand function for each country node.⁵

This “multi-agent economic game on an underlying transportation network” (Egging, 2013) is formulated as mixed complementarity problem (cf. Facchinei and Pang, 2003), programmed in GAMS (Brooke et al., 2008) and solved using the PATH solver (Ferris and Munson, 2000). The model is fully parameterized regarding production capacities and costs, reference prices and consumption levels, transportation and storage capacities, costs and losses. The base year is 2010, the reporting horizon is 2050, including every fifth year in between.⁶

⁵ It can be shown that if the model outcome for the price in a country is lower than the intercepts of the inverse demand curves in all separate sectors, the country level aggregation results in the same prices and consumed values as representing each sector separately would. We therefore opt for using one single aggregated demand function for each country.

⁶ The actual model horizon is 2060 to allow a payback period for investments towards the end of the time horizon.

Reference demand and price levels as well as production costs and capacities are based on qualified assumptions and results of various energy system models, namely BP (2011), the World Energy Outlook (IEA, 2012) or EMF28 model results with the EPPA model.⁷ In our base (called *Reference scenario*) case we use PRIMES results underlying the “Reference Case” of the EU Energy Roadmap 2050 as data inputs for reference demand and production levels for each EU member state. These are then varied across our scenarios (see the following sections). Production capacities are set exogenously at a level between 1.5% and 15% higher than projected production levels depending on the production region. The inverse demand curves are based on reference consumption levels and data on sector shares in the year 2010. The fixed price elasticities for each sector are chosen as follows: for the residential sector as -0.25, the industrial sector as -0.4, and for the power sector as -0.75 (cf. van Oostvoorn et al., 2003).

Initial pipeline capacities within Europe are to a large extent based on GTE (2011). Initial liquefaction and regasification capacities are taken from GIIGNL (2011). Infrastructure projects under construction are accounted for in the year 2015 and some planned projects are included in 2020. We limit endogenous investments in infrastructure—both in pipelines and along the LNG chain—in the first two periods. After 2020, however, investments in transportation are unrestricted in order to allow the most economically efficient network configuration in the long run. Transportation losses and costs for the pipeline and the LNG technology are distance-related. Similarly, investment costs for pipelines depend on the total length but also on the length of onshore and offshore segments of the pipeline. All costs are inflated by 2.75% annually and the discount rate is set to 10%.

Our analysis on the European natural gas sector in transition towards a decarbonized energy system takes place in the context of global consumption and production of natural gas growing by 67% between 2010 and 2050. In all regions but Europe, consumption is projected to rise, particularly in the Asia-Pacific region that is projected to see the largest growth with a doubling by 2025 and an increase by almost three times until 2050. In most regions, natural gas production is projected to develop along roughly the same trajectories as the respective consumptions (North and South America, Middle East and Africa). However, for Russia and especially the Caspian region the increase in production is projected to be significantly larger than the rise in consumption. Russian production increases by about two thirds until 2035, while production in the Caspian region doubles in the following decades until 2050.

3 Natural gas in the EU Energy Roadmap 2050

This section takes a closer look at two Energy Roadmap 2050 scenarios (EC, 2011a) and their implications for the European natural gas market. We use the GGM to take a deeper look at resulting trade flows through pipelines and via LNG transports and potential infrastructure expansions. For both scenarios analyzed in this section, reference demand and production levels for European countries are based on the energy system model PRIMES. PRIMES results—calculated for the EU Energy Roadmap

⁷ See Knopf et al., 2013, for a comparison of EPPA results to other models in the model comparison EMF28 “Technology scenarios for transforming the European energy system”. EPPA is the only top-down model in EMF28 that provided detailed data for the natural gas sector.

2050 (EC, 2011) and provided for the EMF28 (see Knopf et al., 2013)— reflect the optimal choice between different technologies in an environment of aggregate EU GHG constraints.

The first scenario, our *Reference* scenario, is defined by a moderate climate policy. It incorporates the two binding EU 2020 targets of a 20% GHG emission reduction relative to 1990 levels and a 20% share of renewable energy in final consumption. The long-term emissions reduction path of the EU economies reaches a GHG level in 2050 that is 40% lower than the 1990 level. Both carbon capture and storage (CCS) and nuclear power are options in decarbonizing the future energy mix. Energy efficiency and renewable energies will improve following current learning-curves without any significant breakthroughs. Our second scenario, the *HRes* scenario, is defined by a stricter climate policy incorporating the EU 2030 targets of a 40% GHG emissions reduction relative to 1990 and a 30% share of renewable energy in final consumption. It further is constructed such that a 80% GHG emission reduction is reached until 2050. Again the set of available technologies is not restricted but shifted to an important role of renewable energies. This second scenario is based on the “High RES” scenario of the EU Energy Roadmap 2050 (EC, 2011a).

3.1 Reference scenario: 40 % GHG emissions reduction until 2050

3.1.1 Consumption, production and trade flows

In the energy system model PRIMES, the 40% reduction of GHG emissions until 2050 comes with a reduction of the role of natural gas in the European energy mix. This trend is heterogeneous among EU member states with some countries seeing a major decrease of the natural gas share and consumption level and some other countries actually increasing their natural gas use. However, the overall EU trend unambiguously points to a reduced importance of natural gas: 19 % less natural gas consumption in 2050 compared to 2010 leading to a reduction of the share of natural gas in the primary energy consumption from about 25% to 20%.

Figure 2 shows that EU natural gas consumption steadily decreases to a level well below 395 bcm/y by the mid-2040s.⁸ This aggregate reduction is unevenly spread across the member states. The strongest decrease in natural gas consumption takes place in the Netherlands (-41% between 2010 and 2050), the UK (-35%), France (-35%), and Germany (-27%). By contrast, some countries increase their natural gas consumption in a shift away from coal, e.g. Greece (+126%), Spain (+30%) and Bulgaria (+26%). Accordingly, Spain becomes a more important natural gas consumer with a higher consumption level by 2025 than France and the Netherlands. The changes in natural gas consumption are mostly triggered by a change in the role of natural gas for electricity generation and for household heating; industry consumption varies hardly over time.

⁸ Bcm or billion cubic meters is a unit of volume, where one unit approximately corresponds to 35.31 billion cubic feet (bcf).

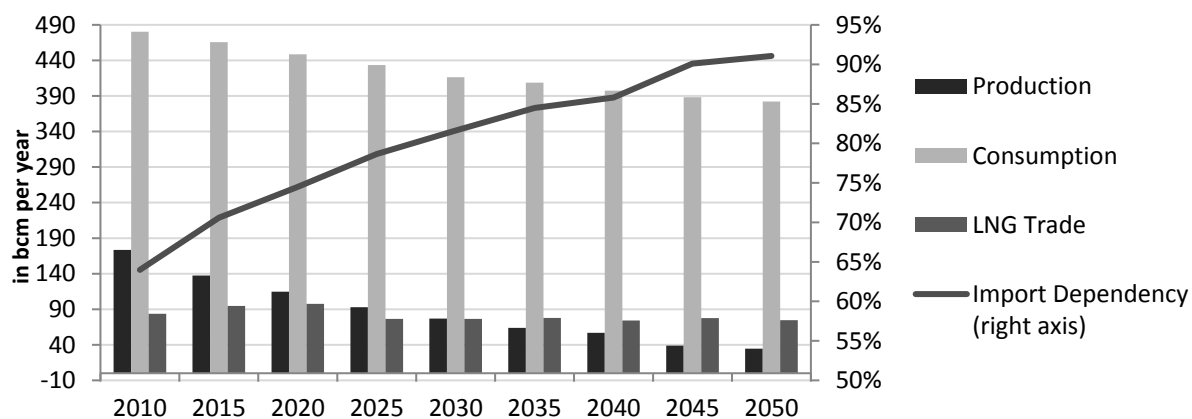


Figure 2: GGM results for EU production, consumption, LNG trade and import dependency (right axis) in the *Reference* scenario (in bcm/y and percentages)

EU natural gas production decreases even more strongly, namely by 56% to 76 bcm/y in 2030 and by 80% to 34 bcm/y in 2050. Except for the Netherlands and Romania all producing countries stop extracting natural gas after 2040 at the latest. Domestic production levels decreasing at a faster rate than consumption necessarily leads to an increasing import dependency. While in 2010 64% of EU natural gas consumption was covered by imports, this rate goes up to 82% by 2030 and above 90% by 2050 (see Figure 2, right axis).⁹ As EU consumption decreases by less than production not only in relative terms but also in absolute terms net imports increase over time; by 10% to 339 bcm/y until 2030 and by 13% to 347 bcm/y until 2050 compared to 2010 levels.

Underlying these increasing EU-wide import needs, large country heterogeneity can be observed (see Figure 3). In particular those countries with an overall increasing demand experience a significantly higher than average increase in net imports, e.g. Spain, Greece, Belgium and Bulgaria. Furthermore, countries with initially large domestic production become more and more dependent on imports such as the UK (+36% net imports between 2010 and 2030). Eventually the Netherlands produce at a level just above self-sufficiency—a shift from a significant net exporter in 2010 to a transit country by 2050 with significantly increasing imports, partly from LNG. Italy and particularly Austria become more and more important in the inter-European transit of natural gas. Some large natural gas consumers such as Germany and France experience a significant reduction of net imports over time, in line with their declining consumption rates.

⁹ Note that these figures are import dependencies for EU-27, excluding Croatia, Norway and Turkey. This holds for all given aggregate EU data.

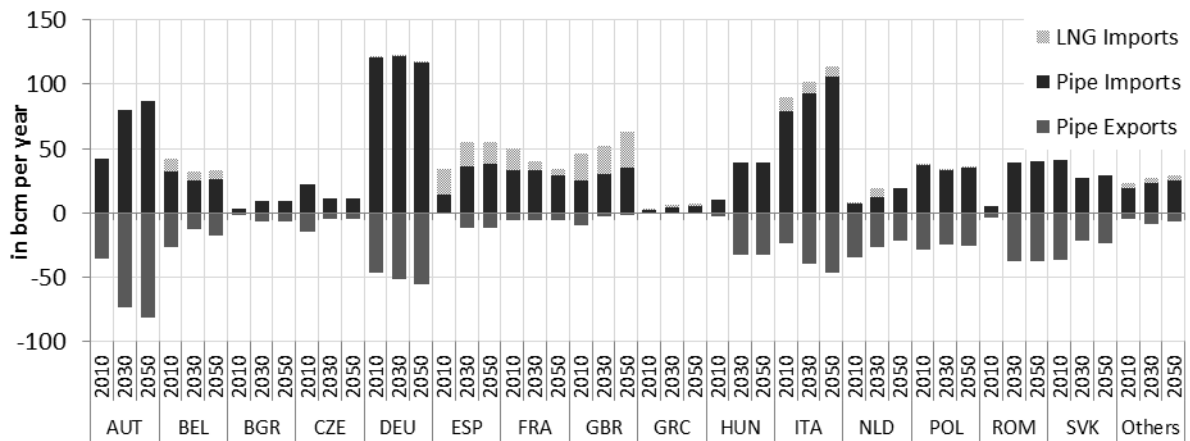


Figure 3: Imports and exports by country and type (pipeline natural gas or LNG) in 2010, 2030, and 2050 in the Reference scenario (in bcm/y)

Most imports are delivered by pipelines to the EU, both today and in the coming decades. LNG imports stay below a 30% share of total net imports (fluctuating around 79 bcm/y over time as depicted in Figure 2) with the highest share in 2020 and declining thereafter. Most of the imported LNG remains to originate from the Middle East and Africa (jointly more than 70% in 2050). However, African LNG exports to the EU decline after 2020, whereas LNG supply from Russia and South American rises to almost 30% of EU LNG imports in 2050.

Overall, European natural gas imports — in form of LNG or transported through pipelines — are mainly satisfied by African, Russian and Norwegian supplies and to a lesser extent from the Caspian region and the Middle East. Particularly the share of Africa increases significantly (by pipeline exports) while Norwegian exports to Europe become smaller over time. A notable divergence from current trade flows are Russian exports: throughout the entire model horizon, Russian exports to Europe and Ukraine are considerably lower than in 2010. This is due to increased competition for Russian gas with the domestic Russian market as well as the strong import demand in Asia-Pacific where a limited number of alternative suppliers is available. Consequently, Russia does not completely use the large export capacity towards Europe that is currently in place and under construction.

Similarly, the stagnating European LNG imports must be seen in the context of a globally increasing demand for natural gas which triggers a considerable increase of LNG imports in other regions than Europe. In particular the Asia-Pacific region with a projected boom in natural gas consumption in China and India, and the ever-strong demand in Japan increases its role in the world markets substantially. Asia-Pacific sees a threefold increase of consumption between 2010 and 2050 and an increase of its share in world consumption from 18% to 30%. A large share of this demand is satisfied by LNG from the other world regions.

More than half of European LNG imports are shipped to the UK and Spain. In particular the UK imports more LNG over time due to decreasing domestic production levels and little interconnection with the continental pipeline network. Spain's LNG imports steadily decline over time while African pipeline gas becomes more important. Similarly in Italy where additional pipeline gas imports from Africa and the Caspian replace imports of LNG. Moreover, France's LNG imports from Africa are phased-out over time due to unfavorable costs. In contrast, Ireland, Poland, Germany and the Netherlands start importing LNG.

3.1.2 Infrastructure expansions

The model determines levels of consumption, production and trade simultaneously with the decisions on infrastructure expansions. On the one hand, a change in trade pattern determines the necessity of additional pipeline capacities and LNG infrastructure. On the other hand, the existing infrastructure as well as the costs and restrictions on further expansions determine to which extent trade between two regions is possible. We identify two main drivers for infrastructure expansions: an increase in total imports due to strongly decreasing EU production levels and the profit-seeking motives of new suppliers to the European market.¹⁰

Figure 4 depicts all major interconnecting pipelines towards Europe as well as the regasification infrastructure, comparing capacities in 2030 with those already existing in 2010. The largest cross-border pipelines in 2030 are projected to run from Russia to the Ukraine (118 bcm/y via the already existing Brotherhood system) and to Germany (61 bcm/y via Nord Stream), between Africa and Italy (63 bcm/y via TransMed, Greenstream and GALSI) and Spain (32 bcm/y via MEG and Medgaz), and from Norway to the UK (47 bcm/y via Langeled) and to Germany (42 bcm/y via Europipe and Norpipe). The model results show a newly built pipeline between the Caspian region and Romania (34 bcm/y in White Stream) and a link between Russia and Bulgaria (16 bcm/y via South Stream),¹¹ and a subsequent pipeline between Bulgaria and Serbia (5 bcm/y).

¹⁰ Even in the absence of additional import needs, a costly infrastructure expansion can be rational as different actors with individual maximization problems and the ability to exert market power may have an incentive to pay for an expanded transmission system in order to supply their gas to selected regions.

¹¹ Construction of the offshore section of South Stream started in December 2012, but the project was abandoned during the Russian-Ukrainian crisis in December 2014. It is yet unclear whether the project is still a viable option as future export route of Russian natural gas to Europe.

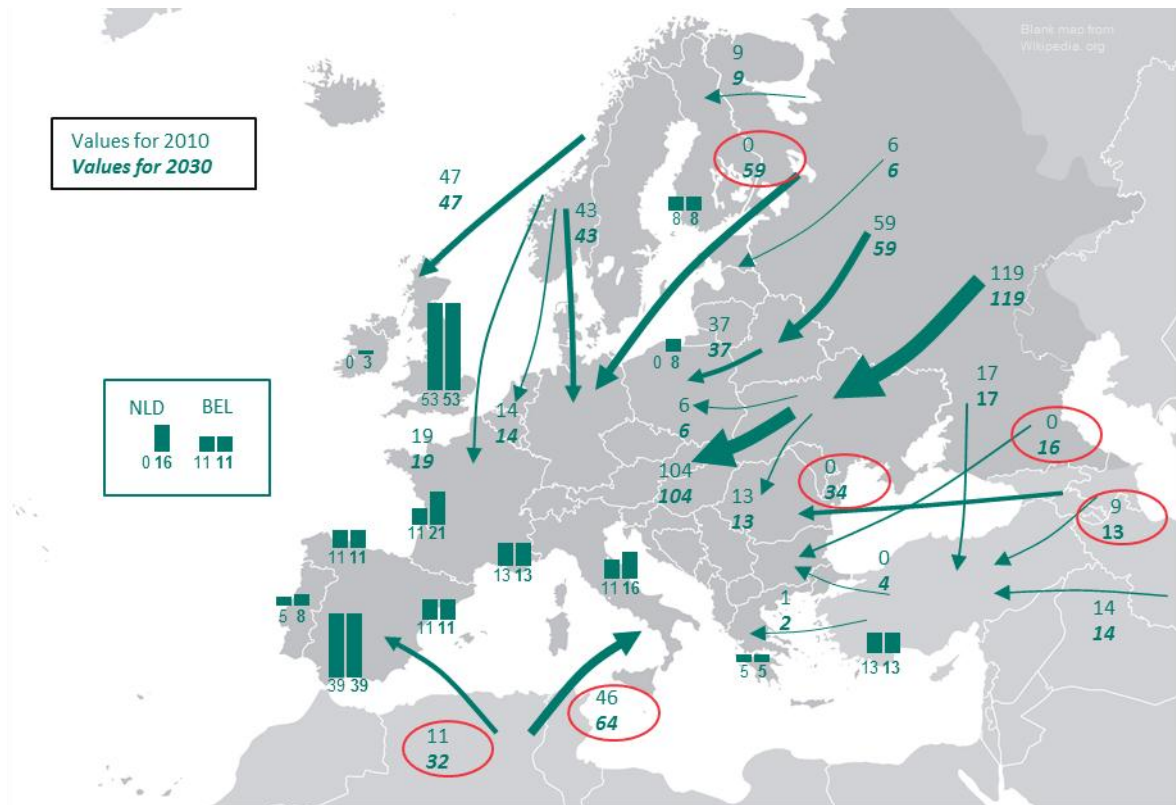


Figure 4: Pipeline and regasification capacities to Europe in the Reference scenario in 2010 and 2030 (in bcm/y)

Note: Only expansions are depicted that reach a level of at least 0.03 bcm/y. The size of a particular arrow in the illustration corresponds to the respective capacity of this interconnector in 2030.

Rising LNG imports to the UK can be satisfied by the existing regasification capacity. In contrast, in Ireland, Poland, Germany and the Netherlands new LNG regasification terminals are built (together 26 bcm/y until 2050).¹² In other countries like Spain, France, Italy or Portugal the model suggests that it is not economically sensible to build additional capacities. Currently planned—and therefore included—expansions in these countries will not be utilized.

Figure 5 presents cumulative expansions of all all major pipelines towards EU member states, indicating the time a pipeline expansion is operational. Five major pipeline projects can be identified: First, the exogenously included Nord Stream pipeline from Russia to Germany (59 bcm /y) is built until 2015; but will not be further expanded. Second, the White Stream pipeline is endogenously added to the European pipeline system in order to bring Caspian natural gas to Romania and central Europe starting in 2020. This means a major expansion between the Caspian region and Romania (by 34 bcm /y), from Romania to Hungary (by 31 bcm/y) and further to Austria (by 28 bcm/y). From there, additional pipeline capacity to Germany (plus 33 bcm/y) is needed while the existing one from Austria towards Italy is sufficient. Third, capacity is added endogenously from Africa to Italy (GALSI pipeline with 29 bcm/y) to satisfy Italian demand and to further transport it to Western and Central Europe via Austria. This result in an expansion from Italy to Austria (by 7 bcm/y) and also explains the significant expansion between

¹² For Poland and the Netherlands these expansions have been already scheduled and are incorporated exogenously in the model.

Austria and Germany (see above). The fourth major expansion project towards Europe can be seen between Africa and Spain (Medgaz pipeline with 25 bcm /y). This endogenous expansion is partly explained by African exports to France, which is reflected in additional capacity from Spain towards France (11 bcm/y). Finally, the first section of South Stream is included with exogenous expansions between Russia and Bulgaria (16 bcm/y) and from Bulgaria towards Serbia (5 bcm/y). Since it is only sparsely used, endogenous expansion originating in Serbia (to Hungary) is little.

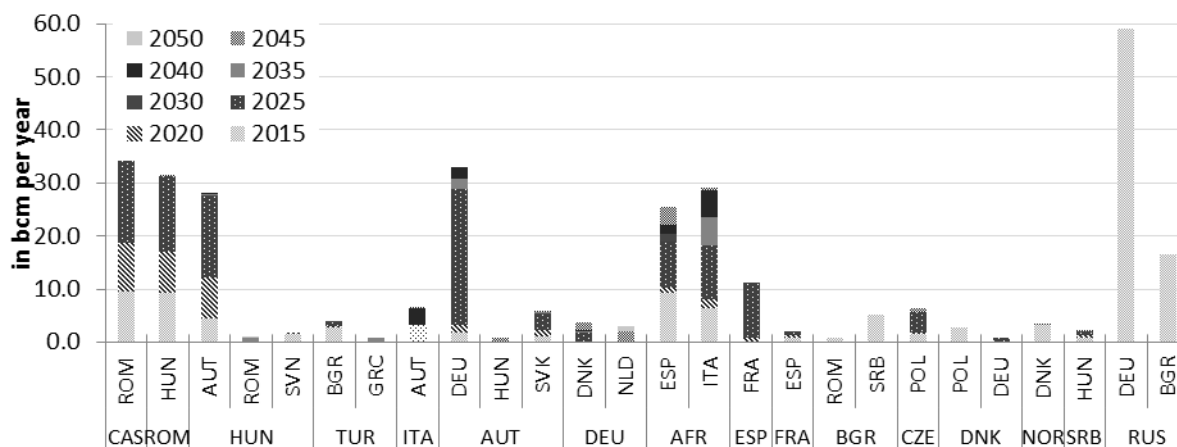


Figure 5: Pipeline expansions in the Reference scenario with destination within the EU member states (lower part of horizontal axis is the pipeline's origin; in bcm/y)

Most of the described expansions take place before 2030. Exceptions are a further increase of pipeline capacity from Africa to Italy (by 11 bcm/y) and to Spain (by 5 bcm /y) as well as from Italy to Austria (by 7 bcm/y) and from Austria to Germany (by 4 bcm/y) (see Figure 5). Given our assumptions on pipeline length and expansion costs and taking into account investments into additional LNG infrastructure, total investment costs for the EU can be estimated at around € 25 bn. until 2050.¹³ More than 65% of these costs fall due before 2020, more than 94% before 2025.

It is notable that some major projects currently under discussion are not endogenously built in the base case. Neither Nabucco, nor TAP (Trans-Adria Pipeline) or ITGI (Interconnector Turkey-Greece-Italy) are needed to bring Caspian natural gas to Central Europe. In a nutshell, South Stream, Nord Stream, White Stream, Blue Stream, Greenstream, Medgaz, GME, GALSI and major LNG import capacities in Spain, the UK, the Netherlands, France, Belgium, Italy, Portugal and Poland are sufficient to satisfy the natural gas demand in the EU. However, new infrastructure capacities contribute to an increased diversification of supplies as new import paths and transit routes open up. Accordingly, the infrastructure investments lead to an improvement of supply security and an increase in competition.

3.2 Ambitious climate policy: 80% GHG emissions reductions

In this section, we discuss the GGM results of the more ambitious 80% GHG reduction scenario. The scenario input is again based on the PRIMES results of the respective scenario ("High RES" in EC,

¹³ This figure includes the total costs of investments in regasification facilities and of all inter-country pipeline expansions within the EU. Expansion costs of pipelines which start or end in the EU are accounted for with half of the project's costs. For instance, half of the investment costs of the interconnection between Turkey and Greece is added to the EU's investment figure.

2011). Aggregate natural gas consumption is significantly lower in the *HRes* scenario than in the *Reference* scenario (see Figure 6). This has important implications on EU imports of natural gas and infrastructure expansion needs. While in the *Reference* scenario EU net imports increase over time, they only slightly increase in the first periods in *HRes*, before starting to decrease strongly as of 2025.

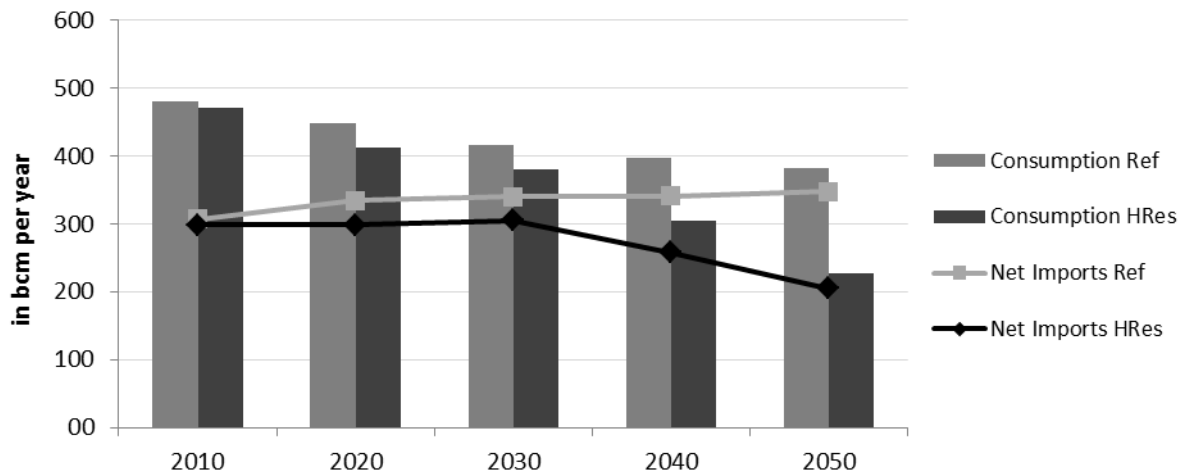


Figure 6: EU consumption levels and net imports by scenario (in bcm/y)

Transportation network expansions can consequently be expected to be of a small scale.

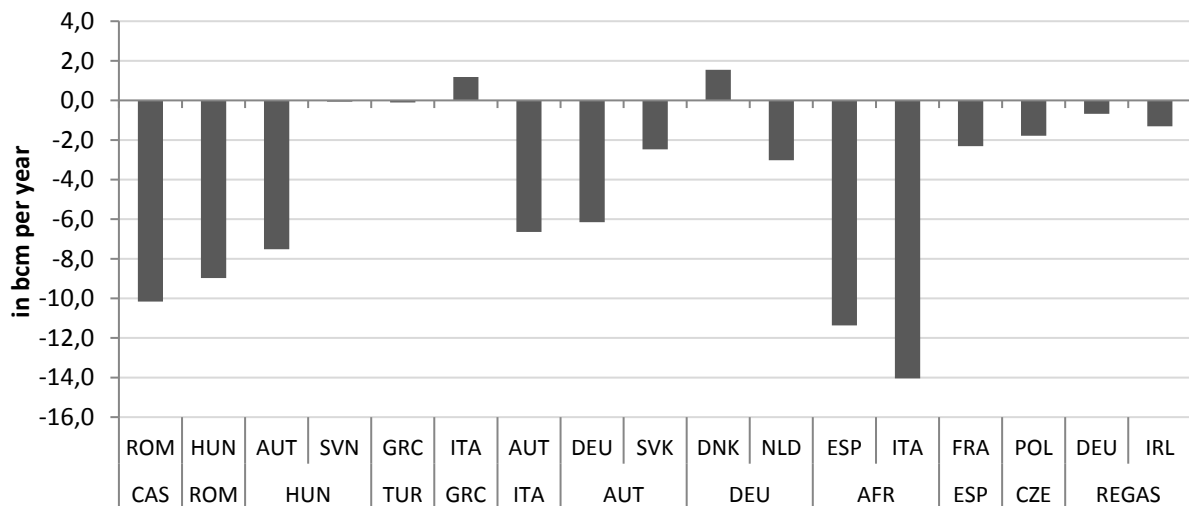


Figure 7 depicts the absolute deviations of cumulative infrastructure expansions until 2050 relative to the *Reference* case. As expected, expansions are generally smaller. In particular the connections from Africa to Italy and Spain are expanded by much smaller amounts. Likewise, White Stream with all subsequent pipeline sections is built but only with a significantly lower capacity. This further translates into fewer expansions between Italy and Austria and from Austria to Germany. There are only two minor exceptions: small amounts of additional capacity are built between Germany and Denmark to satisfy a considerably higher Danish demand, and between Greece and Italy to compensate for the faster phasing-out of Italian production. Regasification facilities are endogenously built only in Ireland, but with smaller capacity than in the *Reference* scenario leading to a new capacity of only about 3 bcm/y in 2030.

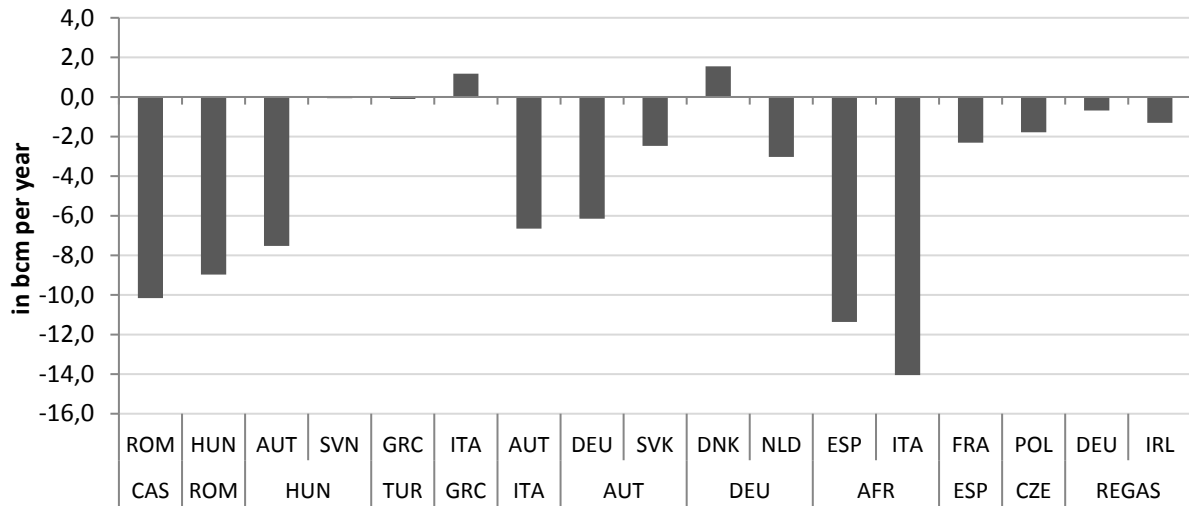


Figure 7: Cumulative infrastructure expansions until 2050 with EU destination in *HRes* relative to the *Reference* scenario (absolute deviations in bcm/y)

4 Alternative perspective: Growing importance of natural gas in a climate-friendly Europe

The two EU Energy Roadmap 2050 scenarios discussed in the previous section are characterized by a decrease in EU natural gas consumption. In the political and public debate, however, natural gas is often perceived as an important energy carrier on the way to a low carbon economy, i.e. as a “bridge technology”.¹⁴ Compared to other fossil fuels natural gas has the lowest carbon content per unit of energy and is additionally highly flexible to be used as a backup for intermittent renewable power generation. This discrepancy between the scenarios analyzed above and the advantages of natural gas has led us to investigate projections from other model frameworks that project an increasing natural gas consumption in the EU.

In this respect we have constructed two alternative scenarios in which natural gas plays a vital role—at least in the short-run—for the transition to a low-carbon European economy. The first scenario, *Back-Up* (discussed in Section 4.1), is based on the World Energy Outlook 2012 by the IEA (2012) providing projections for the global energy system until 2035. Particularly we argue that the WEO’s New Policy Scenario (NPS) can consistently be compared to the 40% reduction Energy Roadmap scenarios. In the NPS, the underlying moderate EU climate policy leads to an overall reduction in the use of fossil fuels with a shift from coal and oil to renewables and natural gas. Accordingly, natural gas consumption is projected to increase steadily until 2050 because it is employed as a backup technology for intermittent renewables. The second scenario, *Bridge* (see Section 4.2), is based on results of the PET model for the EMF 80%noCCS scenario (see Labriet et al., 2012, for the model description and Knopf et al., 2013, for an overview of different models’ results in the EMF 28 group), i.e. a scenario characterized by

¹⁴ For instance, see the speech of the former European Commissioner for Energy, Günther Oettinger, in October 2012 on the “energy partnership” of natural gas and renewable energies: http://ec.europa.eu/commission_2010-2014/oettinger/headlines/speeches/2012/10/doc/20121031_energy_partnership.pdf

a 80% GHG emissions reduction in the EU by 2050 similar to the *HRes* scenario discussed in the previous section. While natural gas consumption increases slowly until 2030, it decreases sharply afterwards. This scenario comes closest to the described “bridge into a low carbon future” and is hence worth to be analyzed with respect to infrastructure expansions.¹⁵

4.1 An increasing role for natural gas within a 40% reduction scenario: the *Back-Up* scenario

The NPS is based on “[...] broad policy commitments and plans that have already been implemented to address energy-related challenges as well as those that have been announced” (IEA (2012), p.629). It includes the EU 2020 targets of 20% GHG reduction relative to 1990 and a 20% share of renewables in the energy demand. The nuclear phase-out in Germany by 2022 is taken into account and CCS is assumed to be potentially employed only on a limited scale.

For the EU, projections show a steady increase in the consumption of natural gas, namely by 14.7% in 2035 relative to 2010. This stands in sharp contrast to a reduction of 14.9% in our base case. The NPS shows that this can still be consistent with moderate climate policies projecting a reduction of EU CO₂ emissions by 32.6% until 2035 compared to the 1990 level, even without CCS in natural gas electricity generation. The emissions reduction can be decomposed into a scale and a substitution effect: On the one hand, the total consumption of the three fossil energy carriers, oil, coal and natural gas, is projected to steadily decline between 1990 and 2035 (the scale effect). On the other hand, the relatively carbon intensive fossils coal and oil are substituted for by natural gas, whose combustion generates less CO₂ per unit of energy (the substitution effect). In particular, the use of coal in the power generation is significantly reduced (-70% relative to 1990). About two thirds of the overall emission reduction until 2035 can be attributed to the scale effect, the remaining one third to the substitution effect. The NPS emissions reduction path is comparable to the assumed path of the 40% reduction Reference scenario. Both projections reach a similar level of CO₂ emissions in 2035 which is about 30% lower than the level of 1990.

The general setting and aggregate differences are summarized by Figure 8 **Fehler! Verweisquelle konnte nicht gefunden werden.** While EU production levels are only marginally larger than in the *Reference* scenario, in the *Back-Up* scenario the EU consumption of natural gas lies well above levels of the *Reference* scenario. In 2030 about 526 bcm/y are consumed (27% more than in the *Reference* scenario) increasing to 579 bcm/y in 2050 (52% more). Consequently, the discrepancy between falling production and steadily increasing consumption leads to an even higher import dependency, reaching up to 94% in 2050.

¹⁵ See also Paltsev (2011) for a scenario analysis with a short-term increase in natural gas consumption followed by a sharp decrease as of the mid-2030s.

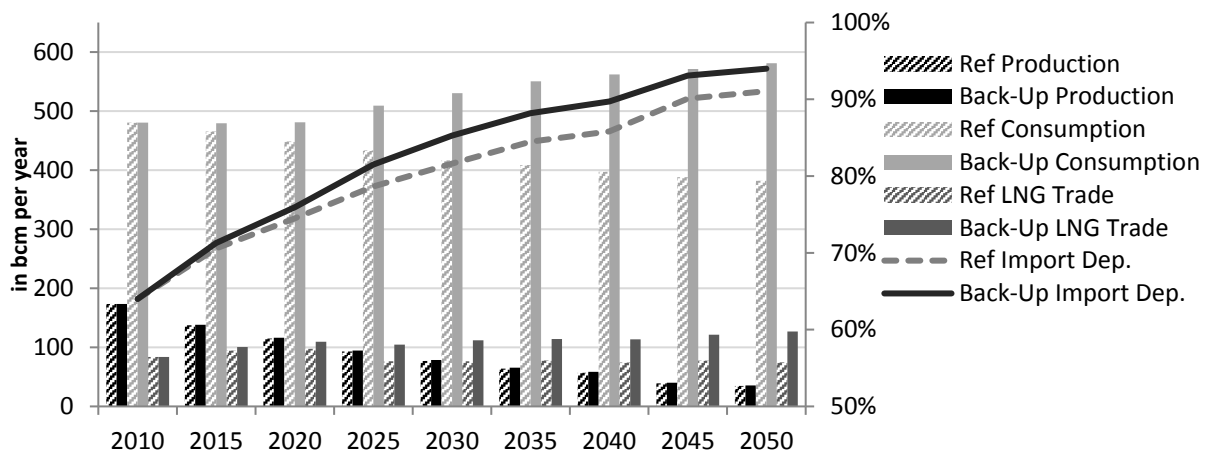


Figure 8: Volumes and import dependency of the EU in the *Back-Up* and *Reference* scenarios (in bcm/y)

Obviously, the EU share in total world consumption is higher in the *Back-Up* scenario than in the base case since the Rest of World assumptions (with strong consumption increases) are left unchanged between both scenarios: the EU share in global consumption decreases from 15% in 2010 to 7% in 2050 in the *Reference* scenario; while it decreases to only 11% in the *Back-Up* scenario. The increased consumption levels in 2030 relative to the base case are spread across all EU member states with significant higher levels in Germany, Italy, the UK and Poland due to a significant substitution of natural gas for coal in power generation.¹⁶

In 2030 total net imports into the EU (447 bcm/y) are 33% higher than in the base case rising to a 57% higher level (553 bcm/y) in 2050. All major flows from the *Reference* scenario take place and are further intensified in the *Back-Up* scenario (see Figure 9 for a 2030 comparison). More trade takes place via the (newly built) White Stream pipeline and through imports from Africa. The role of Austria, Hungary, Romania and Slovakia as transit countries is also more pronounced in the *Back-Up* scenario.

¹⁶ On a country-level, the more coal is used in power generation in the starting year, the higher the additional natural gas consumption over time (through coal "phase-out").

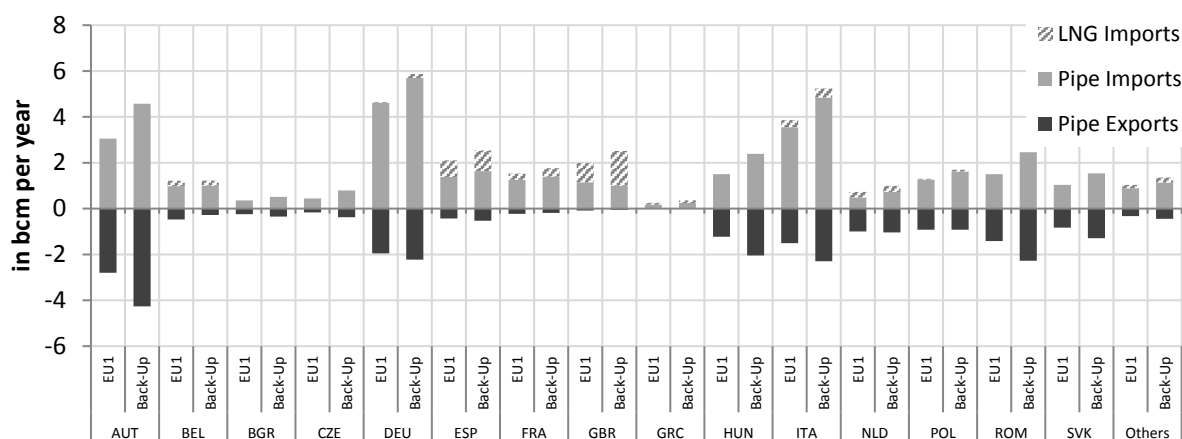


Figure 9: Imports and exports through pipelines and in form of LNG in 2030; *Back-Up* vs *Reference* scenario (in bcm /y)

LNG imports oscillates around a 25% share of total EU net imports. Accordingly, almost 132 bcm/y of LNG is projected to be imported by the EU in 2050. LNG imports from the Middle East increase over time, however its market share declines. Both South America and Russia are projected to gain a larger share in the European LNG market. North American LNG will be exported to the EU as of the mid-century. The higher LNG imports relative to the *Reference* scenario lead to a small increase in the expansion of regasification facilities in the EU. Until 2050 a capacity of 50 bcm/y is built up compared to only 45 bcm/y in the base case (thereof around 39 bcm/y exogenously given in both scenarios). The expansion is higher in Ireland and Germany (about +3 bcm/y until 2050 each). In Poland there is no additional investment to the scheduled (exogenous) expansion in either scenario.

A larger difference between the two scenarios can be observed in the expansion of the pipeline network directed towards Europe. Figure 10 contrasts cumulative pipeline expansions for selected connections until 2050 in the *Back-Up* scenario with the *Reference* scenario. There is a significant expansion of pipeline capacity both in the Southern corridor from the Caspian region via Romania, Hungary and Austria to central Europe and from Africa towards Spain and especially Italy. In particular relative to the *Reference* scenario, pipeline expansion from the Caspian region to Asia is diverted towards Europe. One additional import pipeline to Europe is constructed from the Middle East (e.g. Iran) to Turkey and then on to Greece and Italy via the Trans Adria Pipeline (TAP) as well as to Bulgaria. As in the base case, existing or scheduled pipelines from Russia and Norway are sufficient to meet the increasing import demand of the EU27 from these production regions. The absence of additional expansion from Russia towards Europe shows an effective restriction in its production capacity as well as the growing competition of the EU with Asia-Pacific and the Russian domestic consumption. Total EU infrastructure investments in the *Back-Up* scenario are projected to be almost twice as high as in the *Reference* scenario. They reach almost 43 bn € until 2050, with investments before 2025 being already significantly higher than total expenditures in the *Reference* scenario.

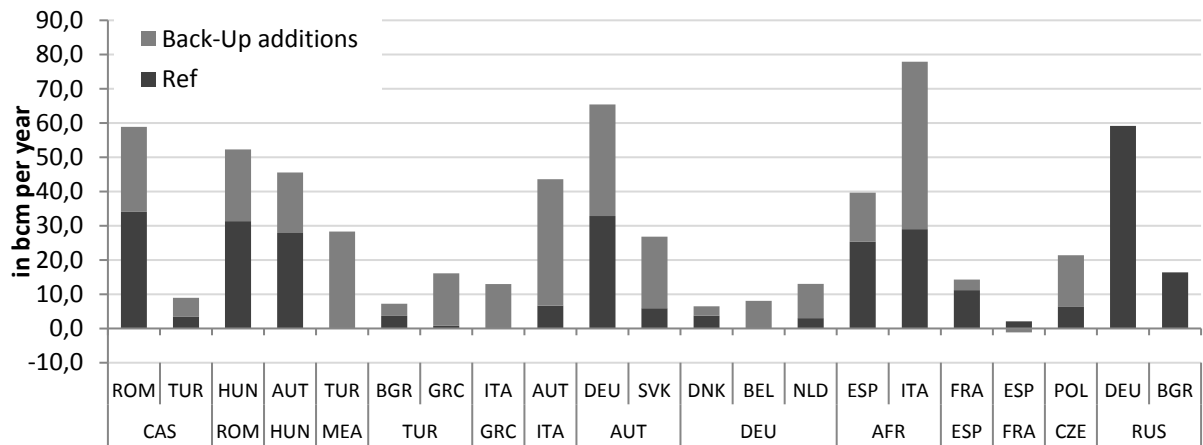


Figure 10: Cumulative pipeline capacity expansions worldwide (in bcm/y)

4.1.1 Regional Focus: Perspectives of Central and Eastern Europe

Central and Eastern Europe (CEE) currently suffers from a strong dependency on Russian natural gas exports. The only direction of pipeline flows is from the East (Russia and subsequent transit countries) westwards. Some countries currently have a small domestic production (Romania, Poland, Czech Republic, and Hungary), but this will phase out until 2040 (expect in Romania).¹⁷ While natural gas is usually not the dominant fuel in the energy systems of the CEE countries, it is often the input fuel for peak power generation (e.g. on high-demand winter days). This makes these countries vulnerable to unilateral disruptions by Russia such as in the winters 2008/2009 (gas dispute between Russia and Ukraine), 2011/2012 (strong winter and gas dispute), and particularly the 2014 Russia-Ukraine-EU crisis.¹⁸ They would benefit from a diversification of supplies, even if it affects only small shares of total imports. Instruments such as reverse flow capacity, LNG terminals in coastal countries, and increasing storage capacity have been discussed in the last years to improve the supply security by increasing the number of potential exporters to the CEEC.

Figure 11 shows all major pipeline expansions in this region for the *Back-Up* scenario compared to the *Reference* scenario. Let us highlight some major observations. First, Caspian natural gas finds its way to central Europe via a significant pipeline expansion through Bulgaria, Romania and Hungary to Austria. This leads to a finer meshed pipeline network towards and within CEE than is currently the case, resulting in a potentially higher diversification and a reduction of the dependence on Russian natural gas. This goes hand in hand with a relatively small expansion from Russia towards Bulgaria (South Stream). Second, the White Stream project is preferred endogenously to other projects in the Southern corridor. In particular, there are no investments along the original route of the Nabucco project via Turkey and Romania towards central Europe. A similar pipeline route from Turkey to Bulgaria and further on via Serbia to Hungary is expanded by a small amount, though. The model outcome of the

¹⁷ Note that we do not include the possibility for shale gas production in Europe in our data set, due to the lack of reliable data. However, given the high costs that shale gas production in Europe would likely have and the overall reduction of natural gas consumption in most scenarios, shale gas hardly seems to have a perspective in Europe anyways.

¹⁸ See Richter and Holz (2015) for a specific analysis of such disruption crises of Russian natural gas supplies to Europe.

high-demand scenario (*Back-Up*) suggests a more attractive interconnection from Turkey via Greece to Italy (the TAP). Third, both expanded pipeline routes to Austria—White Stream from the Caspian Region as well as the connection between Italy and Austria—lead to a further capacity expansion towards Germany. In the *Back-Up* scenario this expansion accounts for almost 66 bcm/y.¹⁹ Fourth and importantly, a West-East natural gas transfer (reverse flow) becomes possible due to some new pipelines. Poland can import more natural gas via Denmark and the Czech Republic; the pipeline from Austria in direction to Slovakia is built, as well as the pipeline from Austria to Hungary and further on to Romania and from Italy to Slovenia. Fifth, the figure shows that no additional pipeline capacity towards Switzerland is needed. Despite an increasing demand in the *Back-Up* scenario by around 20% between 2010 and 2050 due to the scheduled nuclear phase-out, existing capacities from France, Italy and Germany are sufficient without any need for expansions. Remarkably, the Caspian region and Africa become more and more important origins of Swiss supplies. Finally, there will be no LNG regasification capacity construction in addition to the small Polish terminal currently under construction. Pipeline supplies, including reverse flows, will remain the preferred way of import, even for coastal countries.

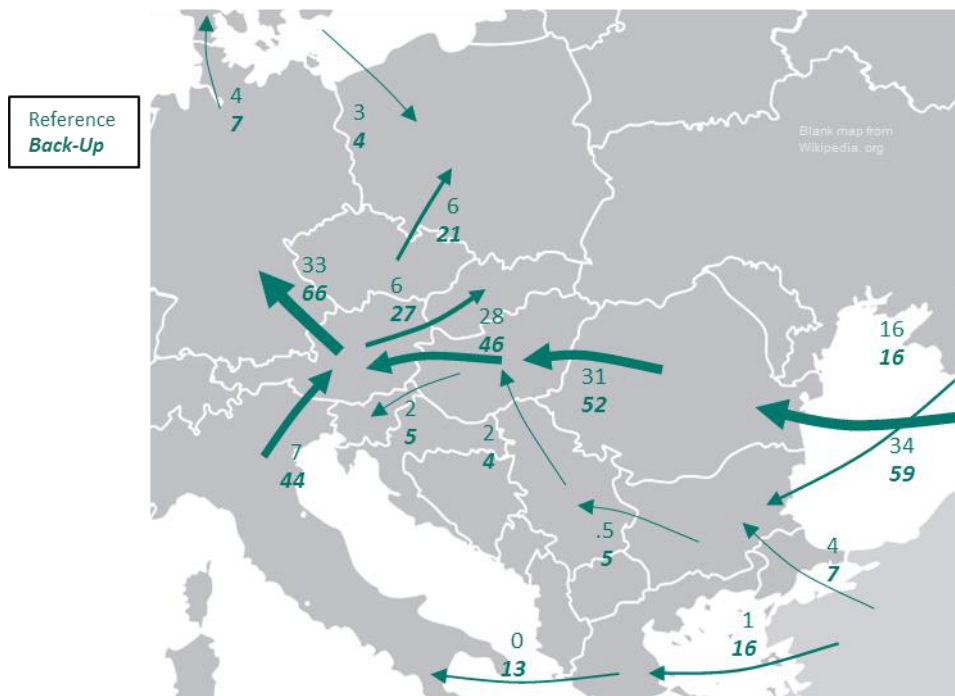


Figure 11: Major cumulative pipeline expansions in Central and South East Europe until 2050 in the *Reference* and the *Back-Up* scenarios (in bcm/y)

Note: Only expansions are depicted that reach a level of at least 3 bcm/y. The size of a particular arrow in the illustration corresponds to the respective capacity of this interconnector in the Back-Up scenario.

¹⁹ Originating in Germany pipelines towards the Netherlands, Denmark and Belgium are expanded in the *Back-Up* scenario between 7 and 13 bcm/y each.

4.2 Natural gas as bridge fuel towards 80% GHG emission reduction: the *Bridge* scenario

In this section we take a closer look at the *Bridge*. In particular the comparison with the “Back-Up” scenario reveals some interesting insights concerning infrastructure expansions. Until 2030 one can observe similar paths between these two scenarios concerning production, consumption and trade patterns for the EU aggregate. After 2030, however, the scenarios substantially diverge (see Figure 12). In 2030 the EU aggregate consumption levels are almost the same for both cases being about 10% higher relative to 2010 levels. However, while consumption increases steadily further in the *Back-Up* scenario it decreases fast in the *Bridge* scenario. In 2035 the latter is 23%, in 2050 74% below the *Back-Up* consumption level and 69% below the 2010 consumption level. Both absolute imports (LNG and via pipelines) and the import dependency are close but higher in the *Bridge* scenario until 2030. LNG imports in this scenario reach a level of more than 132 bcm/y in 2020—a share of up to 32% of net imports.

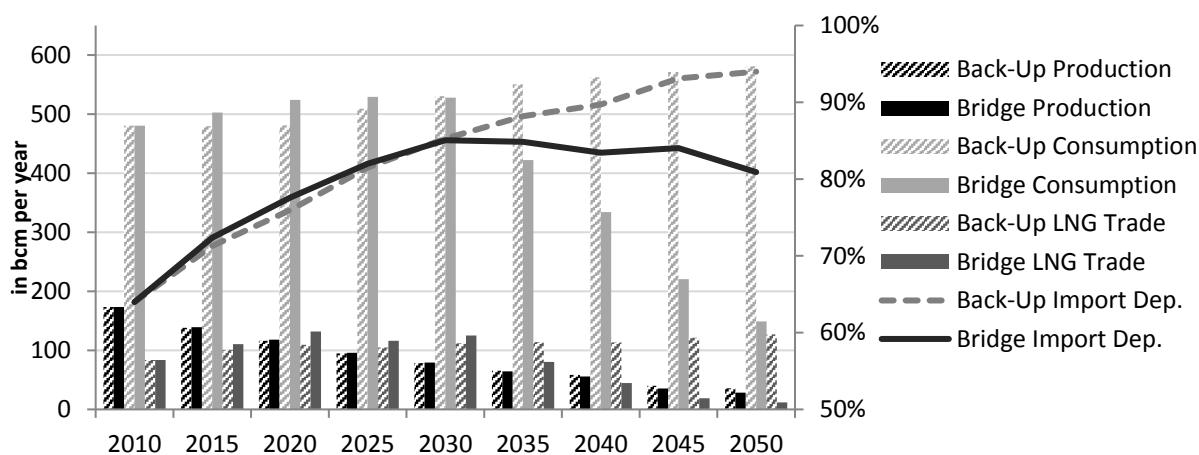


Figure 12: Comparison between the *Back-Up* and the *Bridge* scenario (in bcm/y and percentage)

Indeed, there is spare LNG capacity in the Energy Roadmap scenarios discussed in section 3 and the *Back-Up* scenario which is entirely used in the *Bridge* scenario until 2030 as it can flexibly satisfy the additional demand for the limited time period. As demand is not sustained in the long-term, many infrastructure expansions in the pipeline network are hardly economically justifiable and LNG regasification is the utilized alternative short-term option to serve the high demand.

Pipeline expansions in the *Bridge* scenario are close to the *Reference* scenario but generally smaller (with a few exceptions) than under the other 80% scenario, *HRes* (see Section 3). In contrast, expansions of regasification facilities are highest in the *Bridge* scenario (56 bcm/y compared to 50 bcm/y in the *Back-Up* scenario). The expected decline in demand after 2030 in the *Bridge* scenario reduces total infrastructure investments and shifts pipeline expansions towards short-term economical and more flexible LNG facility expansions. Until 2025 the two alternative scenarios follow a similar expansion path, slightly higher than expansions of the *Reference* scenario. After 2025, only in the *Back-Up* scenario cumulative expansions increase gradually up to a significantly higher level.

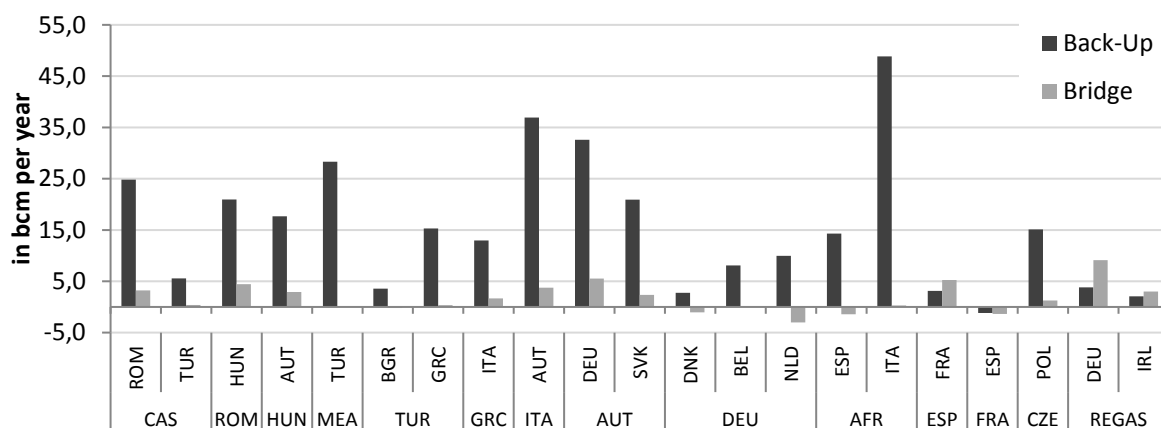


Figure 13: Deviations of *Back-Up* and *Bridge* scenarios from the reference case 40%DEF of selected cumulative expansion until 2050 (in bcm/y)

Total EU infrastructure investments in the *Bridge* scenario are about € 26 bn., close to the expenditure figures in the base case but well below the investment costs in the *Back-Up* scenario. Among all three scenarios, the *Bridge* scenario is characterized by the highest investment levels in the first two model periods. Moreover, in this scenario 99% of all investments are made before 2025 compared to only 69% in the *Back-Up* scenario.

5 Conclusions

In this paper we take a closer look at the natural gas sector within the decarbonization process of the European energy sector, with a particular focus on infrastructure needs to accommodate the transition to a low-carbon economy. To this end, we employ the Global Gas Model, a complementarity model of the world natural gas market, and analyze three potential and quite opposite pathways for the role of natural gas in Europe: First, a continuously decreasing consumption of natural gas in the EU, second, a slightly increasing consumption path and third, the role of natural gas as a bridge fuel to a low-carbon Europe.

In a first step we analyze two climate scenarios from the EU Energy Roadmap 2050. These scenarios are characterized by a decreasing natural gas consumption—the more stringent the climate policy the lower the level of consumption. Consequently, in the 80% GHG reduction scenario there is no need for large-scale pipeline expansions. In the moderate climate policy scenario, however, the decline in European domestic production and the increasing reliance on African and Caspian exports lead to some expansions from Africa to Spain and Italy, and from the Caspian region via the White Stream project to Central and East Europe. Russia is oriented towards its domestic market and the Asia-Pacific region and there are no further expansions except for the already scheduled Nord Stream and a small part of South Stream. Similarly, European LNG imports stagnate and even fall after a peak in 2020 because of the strong demand in the Asia-Pacific region. The availability of shale gas, both as LNG exports from North America as well as with increased production capacity in some major demand regions of the world (e.g., China, Poland) could change this picture somewhat, by reducing the demand pressure from Asia-Pacific on the current large exporters. Russia would in that case export more to Europe and the LNG imports into Europe would also be higher.

In an alternative moderate climate policy scenario a continuously increasing natural gas consumption is analyzed. Expansions are significantly higher than in the *Reference* scenario, especially on the connections from Africa and the Caspian region to central Europe, and a new pipeline from the Middle East towards Turkey, Greece and Italy is invested in. The results of the *Bridge* scenario show that long-term trade relations are needed to economically justify pipeline infrastructure construction. Instead of large scale pipeline expansion, the existing idle LNG import capacities are used during years of high demand, supported by some additional expansions in regasification facilities.

The results of all scenarios show a potential improvement of the import diversification in the build-up of West-East (reverse flow) capacity that is still lacking in today's market. This is the result of an economic cost minimization mechanism in a capacity-constrained market with market power but with no explicit consideration of supply security considerations. In other words, supply security would benefit from relaxing the (institutional, political, and technical) constraints on investments as we assume for the period after 2020. The next decade will show if the tendency of lowering natural gas consumption in Europe as indicated by the Energy Roadmap will realize. In contrast, a stronger reliance on natural gas may be a probable energy future and our alternative scenarios indicate the economic feasibility of such a pathway.

Future research should include a more detailed look at the developments in the other world regions than Europe to capture all global dynamics. In particular, in the Asia-Pacific region one can expect strongly increasing demand in the emerging natural gas markets of China, India, Thailand and others, booming natural gas production and LNG exports in Australia and a sustained high demand in Japan and Korea. Climate and energy policies in this region would impact the trade flows in the entire global natural gas market and merit a more detailed modeling analysis. Moreover, there is uncertainty on the development of a number of factors in natural gas markets and stochastic modeling may be an alternative to the deterministic scenario analysis presented in this paper. Fodstad et al. (in this issue) present the results of using a stochastic model.

Acknowledgements

This work has been carried out in the framework of the EMF28 on the Effects of Technology Choices on EU Climate Policy. Franziska Holz and Philipp M. Richter gratefully acknowledge funding from the German Ministry of Education and Research in the research project "RESOURCES: International Energy Resource Markets under Climate Constraints - Strategic Behavior and Carbon Leakage in Coal, Oil, and Natural Gas Markets". Rudd Egging gratefully acknowledges funding from the Centre for Sustainable Energy Studies - FME CenSES under grant 209697 from the Research Council of Norway. We thank Hanna Brauers, Daniela Griese, Daniel Huppmann, Christian von Hirschhausen and the participants of the 8th ENERDAY conference on energy economics and technology in Dresden 2013. All remaining errors are ours.

References

- André, J., Bonnans, F., Cornibert, L. (2009). "Optimization of Capacity Expansion Planning for Gas Transportation Networks." *European Journal of Operational Research*, Vol. 197, No. 3, pp. 1019-1027.
- Boots, M.G., Rijkers, F.A.M., Hobbs, B.F. (2004). "Trading in the Downstream European Gas Market: A Successive Oligopoly Approach." *The Energy Journal*, Vol. 25, No. 3, pp. 73-102.
- Brooke, A., Kendrick, D., Meeraus, A., Raman, R. (2008). *GAMS: A User's Guide*, <http://www.gams.com/dd/docs/bigdocs/GAMSUsersGuide.pdf>
- BP (2011). Statistical Review of World Energy, <http://www.bp.com/statisticalreview>.
- Dieckhöfner, C. (2012). "Simulating Security of Supply Effects of the Nabucco and South Stream Projects for the European Natural Gas Market." *The Energy Journal*, Vol. 33, No. 3, pp. 153-181.
- EC (European Commission, 2006). Decision No. 1364/2006/EC of 6 September 2006 laying down guidelines for trans-European energy networks.
- EC (2011a). Energy Roadmap 2050. COM(2011) 885 final. Brussels, 15 December 2011.
- EC (2011b). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the Connecting Europe Facility. COM(2011) 665 final. Brussels, 19 October 2011.
- EC (2011c). 2009-2010 Report on progress in creating the internal gas and electricity market. Commission Staff Working Document. Brussels, 9 June 2011.
- Egging, R. 2010. *Multi-Period Natural Gas Market Modeling - Applications, Stochastic Extensions and Solution Approaches*. College Park: University of Maryland.
- Egging, R. and Gabriel, S.A. (2006). "Examining Market Power in the European Natural Gas Market," *Energy Policy*, Vol. 34, No. 17, pp. 2762-2778.
- Egging, R., Gabriel, S.A., Holz, F., Zhuang, J. (2008). "A Complementarity Model for the European Natural Gas Market." *Energy Policy*, Vol. 36, No. 7, pp. 2385-2414.
- Egging, R., Gabriel, S.A., Holz, F. (2010). "The World Gas Model – a multi-period mixed complementarity model for the global natural gas market," *Energy*, Vol. 35, No. 10, pp. 4016-4029.
- Egging R., Holz, F., Gabriel, S.A., von Hirschhausen, C. (2009). Representing GASPEC with the World Gas Model, *The Energy Journal, Special Issue World Natural Gas Markets and Trade: A Multi-Modeling Perspective*, pp. 97-117.
- Egging, R. (2013). "Benders Decomposition for Multi-Stage Stochastic Mixed Complementarity Problems – Applied to a Global Natural Gas Market Model." *European Journal of Operational Research*, Vol. 226, No. 2 pp. 341–353.
- EU (2009). Regulation (EC) No 663/2009 of the European Parliament and of the Council of 13 July 2009 establishing a programme to aid economic recovery by granting Community financial assistance to projects in the field of energy.
- Facchinei, F. and Pang, J.-S. (2003). *Finite-Dimensional Variational Inequalities and Complementarity Problems*. Vol. 1 and 2, Springer, New York.
- Ferris, M.C., Munson T.S. (2000). "Complementarity Problems in GAMS and the PATH Solver." *Journal of Economic Dynamics and Control*, Vol. 24, No. 2, pp. 165-188.
- Fodstad, M., Midthun, K., Egging, R., Tomasgard, A.: Natural Gas Infrastructure in Europe: Stochastic Modeling of an Uncertain Demand. This issue.
- Groupe International des Importeurs de Gaz Naturel Liquéfié (GIIGNL) (2011). *The LNG Industry*. <http://www.giignl.org/fr/home-page/lng-industry/>

- Golombek, R., Gjelsvik, E., Rosendahl, K.E. (1995). "Effects of Liberalizing the Natural Gas Markets in Western Europe." *Energy Journal*, Vol. 16, No. 1, pp. 85-111.
- GTE (2011). The European Natural Gas Network (Capacities at cross-border points on the primary market). August 2011. <http://www.entsog.eu/maps/transmission-capacity-map/2011>
- Holz, F., von Hirschhausen, C., C. Kemfert (2008). "A Strategic Model of European Gas Supply (GAS-MOD)." *Energy Economics*, Vol. 30, No. 3, pp. 766-788.
- Holz, F., P.M. Richter, and R. Egging, 2015. A global perspective on the future of natural gas: Resources, trade, and climate Constraints. *Review of Environmental Economics and Policy* 9(1), pp. 85-106.
- International Energy Agency (IEA) (2012). *World Energy Outlook 2012*. OECD/IEA, Paris.
- International Energy Agency (IEA) (2014). *World Energy Outlook 2014*. OECD/IEA, Paris.
- Knopf, B., Chen, Y.-H.H., De Cian, E., Förster, H., Kanudia, A., Karkatsouli, I., Keppo, I., Koljonen, T., Schumacher, K., van Vuuren, D.P. (2013). "Beyond 2020 - Strategies and costs for transforming the European energy system." *Climate Change Economics*, Vol. 4, Suppl. 1 (Special Issue on "The EMF28 Study on Scenarios for Transforming the European Energy System"): 1340001 (38 pages).
- Labriet, M., Kanudia, A., Loulou, R. (2012). "Climate mitigation under an uncertain technology future: A TIAM-World analysis." *Energy Economics*, Vol. 34, Supplement 3, pp. S366-S377.
- Lise, W. and B.F. Hobbs (2008). "Future Evolution of the Liberalised European Gas Market: Simulation Results with a Dynamic Model." *Energy*, Vol. 33, No. 7, pp. 989-1004.
- Lochner, S. and D. Bothe (2007): *From Russia with Gas – An Analysis of the Nordstream Pipeline's Impact on the European Gas Transmission System with the TIGER-Model*. EWI Working Paper No. 07.02, Institute of Energy Economics at the University of Cologne (EWI).
- Mathiesen, L., Roland, K., Thonstad, K. (1987). "The European Natural Gas Market: Degrees of Market Power on the Selling Side." In *Natural Gas Markets and Contracts*, edited by Rolf Golombek, Michael Hoel and Jon Vislie. North-Holland, pp. 27–58.
- Midthun, K. T., Bjorndal, M., Tomasgard, A. (2012). "Modeling optimal economic dispatch and system effects in natural gas networks." *The Energy Journal*, Vol 30 No. 4, pp. 155-180.
- Oostvoorn, F. v. (2003). Long-Term Gas Supply Security in an Enlarged Europe. ECN, Amsterdam. Available online: <ftp://www.nrg-nl.com/pub/www/library/report/2003/c03122.pdf>
- Paltsev, S. (2011). Russia's Natural Gas Export Potential up to 2050. MIT Joint Program on the Science and Policy of Global Change. Report No. 201.
- Perner, J. and A. Seeliger (2004). "Impact of a Gas Cartel on the European Market – Selected Results from the Supply Model EUGAS." *Utilities Policy*, Vol. 12, No. 3, pp. 291-302.
- Richter, P.M. and F. Holz (2015): All quiet on the Eastern front? Disruption scenarios of Russian natural gas supply to Europe. *Energy Policy*, Vol: 80, pp: 177-180.
- Stern, J. (2010). The new security environment for European gas: Worsening geopolitics and increasing global competition for LNG. In: Lévêque, F., Glachant, J.-M., Barquín, J., Hirschhausen, C.v., Holz, F., Nuttall, W.J. (Eds.), *Security of Energy Supply in Europe: Natural Gas, Nuclear and Hydrogen*. pp. 56-90. Edward Elgar Publ.

Appendix

Table 1: Abbreviations for countries and regions

EU		South East Europe	
Austria	AUT	Albania	ALB
Belgium	BEL	Belarus	BLR
Bulgaria	BGR	Bosnia and Herzegovina	BIH
Czech Republic	CZE	Croatia	HRV
Denmark	DNK	Kosovo	KOS
Estonia	EST	Macedonia	MKD
Finland	FIN	Moldavia	MDA
France	FRA	Montenegro	MNE
Germany	DEU	Serbia	SRB
Greece	GRC	Ukraine	UKR
Hungary	HUN		
Ireland	IRL	Other country nodes	
Italy	ITA	Norway	NOR
Latvia	LVA	Russia	RUS
Lithuania	LTU	Switzerland	CHE
Luxembourg	LUX	Turkey	TUR
Netherlands	NLD		
Poland	POL	Other regional nodes	
Portugal	PRT	Africa	AFR
Romania	ROM	Asia-Pacific	ASP
Slovakia	SVK	Caspian Region	CAS
Slovenia	SVN	Middle East	MEA
Spain	ESP	North America	NAM
Sweden	SWE	South America	SAM
UK	GBR		