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2013

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ISSN print edition 1433-0210
ISSN electronic edition 1619-4535

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

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March 11, 2013

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Abstract

In this paper, we use the Global Gas Model to analyze the perspectives and infrastructure needs of the European natural gas market until 2050. Three pathways of natural gas consumption in a future low-carbon energy system in Europe are envisaged: i) a decreasing natural gas consumption, along the results of the PRIMES model for the EMF decarbonization scenarios; ii) a moderate increase of natural gas consumption, along the lines of the IEA (2012) World Energy Outlook’s New Policy 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 largely sufficient to accommodate the import needs of the EMF decarbonization scenarios, despite the reduction of domestic production and the increase of import dependency. However, due to strong demand in Asia which draws LNG and imports from Russia, Europe has to increasingly rely on pipeline exports from Africa and the Caspian region from where new pipelines are built. Moreover, pipeline investments open up new import and transit paths, including reverse flow capacity, which improves the diversification of supplies. In the high gas consumption scenario similar pipeline links are realized—though on a larger scale, doubling the costs of infrastructure expansion. In the bridge technology scenario, the utilization rates of (idle) LNG import capacity can be increased for the short period of temporary strong natural gas demand.

Keywords: natural gas, climate change, infrastructure, equilibrium modeling

JEL Classification: Q31, Q47, Q54, C61, D43

1 Introduction

The role of natural gas in a future decarbonized European energy system is yet unclear. There is a great range of perspectives on the importance of natural gas a few decades into the future—both regionally and globally. 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. 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 New Policy Scenario of the International Energy Agency sees a consistently large role for natural gas in the next decades (IEA, 2012).

This paper is written within the framework of the Energy Modeling Forum (EMF) no. 28, which particularly investigates GHG mitigation pathways for the EU until 2050. Focusing on the natural gas sector we pose the question if the current infrastructure is capable to accommodate the identified low-carbon energy system. Even if natural gas consumption stabilizes at current levels in Europe, due to depleting reserves and decreasing domestic production in Europe net imports would increase and, hence, more infrastructure is likely needed to facilitate those imports.

Since Van Oostvoorn et al. (2003), several academic and policy studies have pointed to the fact that more interconnection in the European natural gas network is necessary (Lise and Hobbs 2008; EC, 2006 TEN-E Communication). 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-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), many infrastructure projects have been agreed or started and are due for completion before 2020.

In order to investigate the need for further investments after 2020 we rely on numerical modeling analysis. An earlier EMF, no. 23 on "World Natural Gas Markets and Trade", dealt specifically with the modeling of natural gas markets on a global and regional scale; Huntington (2009) summarizes the results. Several modeling approaches can be found in the literature, of which the most common are 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, Dieckhöhner, 2012) are two of the most detailed optimization models of the European natural gas sector. They include a complete data set of European pipelines of different pressure-levels and dispatch is optimized in the given network. André et al. (2009) presents an infrastructure analysis based on nonlinear optimization. Midthun et al. (2009) develop a systems optimization approach taking into account the impact of pressure drops on network capacities.

In contrast to optimization, complementarity modeling (also called equilibrium modeling), allows to include imperfect market structures in the representation of the market. Since there is a limited number of suppliers in many European countries, oligopolistic behavior with strategic withholding is a common strategy in the natural gas market (Holz et al., 2008). Hence, a model including market power and allowing for the simultaneous solution of optimization problems of several players is preferable. 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) provide an extension of this model (the GASTALE model), while Egging and Gabriel (2006) as well as Egging et al. (2008) develop and improve an alternative model with a detailed player set-up (European Gas Model). Egging et al. (2010) introduce a multi-period optimization in the World Gas Model, allowing for endogenous investment decisions in infrastructure variables. Smeers (1997, 2008) provides a critical assessment of the use of complementarity models for natural gas markets, in particular for market structure analyses, all by acknowledging its advantages in terms of realism.

In this paper, we employ a complementarity model of the world natural gas market with a detailed representation of Europe 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 and less in the energy mix, which is dominated by low-CO_2 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 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 CO_2-free technologies are economically available (naturally 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 this paper we focus on potential infrastructure needs within the natural gas sector in the setting of a future low-carbon European energy system. We use the Global Gas Model (GGM) to compute the major variables of the European and global natural gas markets: consumption and production, international trade and infrastructure expansion. In the first part, we base our analysis on the EMF-28 decarbonization scenarios as run by the PRIMES model. These results suggest 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 or iii, respectively). One pathway (ii, “Back-Up”) serves to investigate infrastructure needs in an environment of increasing natural gas consumption, while the second alternative (pathway iii) focuses on the outcome where natural gas plays the role of a “bridge fuel”.

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 in our results. Moreover, within Europe there will be 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 Global Gas Model (GGM) and used data sources are described. By means of the GGM we analyze the impact of the PRIMES-based EMF scenarios in Section 3 on the European natural gas sector. The two alternative, high-gas scenarios are presented in Section 4. In Section 5, we take a closer look at the particular perspectives of South-East Europe. 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 global natural gas production, consumption and trade flows. Egging (2013) provides a description of the main model setup and features. 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 along the LNG supply chain and regarding pipeline connections. Future reference demand and price levels as well as production costs and capacities are based on qualified assumptions and with reference to energy system models. While Egging (2013) presents a stochastic model, in this paper we use a deterministic version, with a particular focus on, and more detailed representation of Europe and an updated data set. Twenty five of the EU27 countries are incorporated individually in the total of 45 country or regional nodes.[1] Figure 1 illustrates the supply chain structure incorporated in the GGM, highlighting the interaction between different players: producers, traders, storage system operators (SSO) and transmission system operators (TSO) at two different region nodes.

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[1] Cyprus and Malta did not consume any natural gas in 2010 and are left out. Furthermore, the model 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 Table 2 in the Appendix for more detail.

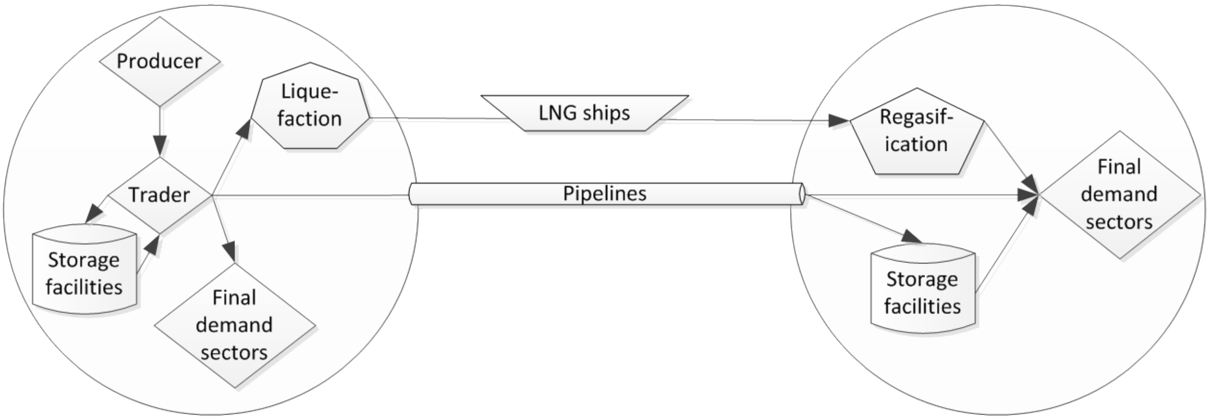

Figure 1: Representation of the natural gas market and supply chain in GGM

Producers extract natural gas and sell it to traders. Traders sell the natural gas in the domestic nodes, or rent transportation capacity from the TSO to export the natural gas to other nodes. This can be pipelines, or liquefaction, shipping and regasification infrastructure. Traders can rent storage capacity to arbitrate between seasonal price variations. 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.[2] The Transmission System Operator (TSO) manages the transportation network and rents out capacity to traders. Similarly, the Storage System Operator (SSO) manages the storage capacity.

In the model, all agents are price takers, except for traders who can be assumed to exert market power. All agents operate under complete information and maximize their discounted net present value 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). To relieve the pressure of (future) infrastructure bottlenecks, the TSO and SSO can endogenously invest in additional transportation and storage capacities respectively.

Producers maximize discounted profits of selling natural gas to an assigned trader, bearing the costs of extraction. Traders generate revenues by selling natural gas to consuming sectors, and bear costs for purchasing natural gas, as well as costs for using storage and transportation services. Exogenously set parameters define a market power level for some traders, depending on origin and destination. This means that they exert market power à la Cournot and take into account the effect of their supplied quantities on the market prices. The TSO maximize profits from congestion rents on transportation capacities minus incurred investment costs. As price takers, the TSO will invest as much in additional capacity of a specific arc (connection), that the discounted congestion rents equal the marginal investment costs. In a similar way the SSO are in charge of the storage facilities.

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[2] It is easily 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.

This “multi-agent economic game on an underlying transportation network” (Egging, 2013) is developed as a mixed complementarity problem (cf. Facchinei and Pang, 2003), implemented 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. Currently, the base year is 2010, the reporting horizon is 2050, and each fifth year in the horizon is included.[3] Production cost functions used are the ones 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 close to capacity. Production capacities are set exogenously for all periods, based on production forecasts for European member states by the PRIMES model (EMF 28 results), BP (2011), other EMF 28 model runs (e.g. the EPPA model’s EU1 results, see Knopf et al., 2013, for an overview of the EMF 28 results) and other forecasts such as the World Energy Outlook (IEA, 2011). We assume that the production capacities are between 1.5% and 15% higher than the production forecast levels. The inverse demand curves for consumption are based on reference consumption levels from the same sources as the production references and the sectors shares in the year 2010. The fixed price elasticities for each sector are: residential -0.25, industry -0.4, power -0.75 (cf. van Oostvoorn et al., 2003). More detail of the input data for production and consumption modelling can be found in the Appendix in Tables 3 and 4.

Initial pipeline capacities within Europe are to a large extend based on GTE (2011). Pipelines currently under construction have been included starting 2015. Liquefaction and regasification capacities are based on GIIGNL (2011). Projects under construction mentioned in GIIGNL (2011) are accounted for in the year 2015 and some considered projects are included in 2020. We have limited the possible endogenous capacity expansions in the first two periods, but as of 2020 investments in transportation—both in pipelines and along the LNG chain—are unrestricted to allow the most economic 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 length but also on the onshore or offshore nature of the pipeline (segments). All costs are inflated by 2.75% annually and the discount rate is set to 10%. More detail of the input data for the transportation segment of the model can be found in the Appendix in Tables 5 and 6.

In the baseline scenario EU1, reference global consumption and production grow by 67% between 2010 and 2050. The natural gas consumption in North America gradually increases until 2035 and stabilizes at +20% relative to 2010 consumption. In South America, natural gas consumption doubles from 2010 to 2040, and stagnates thereafter. In the European Union, natural gas consumption gradually decreases (-20% by 2050), but there are large variations from one country to the next (see Section 3). In neighbouring European countries, including Turkey, natural gas consumption decreases, but with smaller percentages than the EU average. African natural gas consumption doubles by 2035 and continues growing thereafter but at a lower rate (+153% by 2050). Russian and Caspian natural gas consumption gradually grows with about 40% by 2050. In the Middle East, natural gas consumption approximately doubles by 2035, and continues growing at a lower pace (+128% by

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

2050). Lastly, the Asia-Pacific region is projected to see the largest growth, with a doubling by 2025, and eventually +186% by 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, in the EU27, production is projected to halve between 2025 and 2030 and continues declining to -80% by 2050. In neighbouring European countries, including Turkey, natural gas production decreases, but by just a bit over 1/4. Russia and especially the Caspian region are projected to have a much larger production than consumption increase. Russian production is about 2/3 more by 2035 and in later periods, and the Caspian region doubles its production by 2035 and grows further to +128% by 2050.

3 EMF Decarbonization Scenarios

This section takes a close look at the implications on the European natural gas market of the EMF decarbonization scenarios that are defined by a technology and a policy dimension. For all scenarios analyzed in this section, reference demand and production levels of natural gas for European countries are based on the PRIMES results of the same scenarios. The PRIMES energy system model forecasts reflect the optimal choice between different technologies in an environment of aggregate EU GHG constraints. The Global Gas Model then allows a deeper look at the sectoral level, in particular at the resulting trade flows through pipelines and via LNG transports. Capacity constraints are taken into account in GGM and potential infrastructure expansions can be analyzed.

In the following analysis we first discuss scenario EU1 that we use as the base case. It is characterized by a moderate climate policy (with a reduction target of -40% GHG emissions by 2050 compared to 1990), no restrictions in technology availability and current learning curves (see Table 1 which summarizes the scenario assumptions). We then highlight model results for variations in the two scenario dimensions. Scenario EU4 represents a change in the set of technologies; scenario EU6 reflects the effects of a stricter climate policy (80% GHG emission reduction) given the same set of technologies as in the base case; scenarios EU7 to EU10 also represent a strict climate policy (80% GHG emission reduction) with varying technology assumptions; EU11, in contrast, is a no climate policy scenario where there is no GHG emission reduction objective. The availability of PRIMES results for specific EMF scenarios determines our choice of EMF scenario runs (highlighted in grey in Table 1).

Table 1: EMF 28 Scenario matrix

		Technology dimension				
		Default w CCS	**Default w/o CCS**	**Pessimistic**	**Optimistic**	**Green**
CCS		on	off	off	on	off
Nuclear energy		ref	ref	low	ref	low
Energy efficiency		ref	ref	ref	high	high
Renewable energies		ref	ref	ref	opt	opt
Policy dimension for the EU	**Policy dimension for the Rest of the World (ROW)**					
No policy baseline (no policy, also without the 2020 target)	no policy	**EU11**				
Reference: including the 2020 targets and 40% GHG reduction by 2050	"moderate policy" scenario ModPol; no emission trading across macroregions (but trade within macroregions e.g. within EU)	**EU1**	EU2	EU3	**EU4**	EU5
Mitigation1: 80% GHG reduction by 2050 (with Cap&Trade within the EU)	"moderate policy" scenario ModPol; no emission trading across macroregions (but trade within macroregions e.g. within EU)	**EU6**	**EU7**	**EU8**	**EU9**	**EU10**

3.1 Reference scenario: 40 % GHG emissions reduction and less natural gas

The base case, scenario EU1, is defined by a moderate climate policy and the availability of all technology options following current trends. It particularly 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 (new) nuclear plants are options in decarbonizing the future energy mix. Energy efficiency and renewable energies will improve following current learning-curves without any significant breakthroughs.

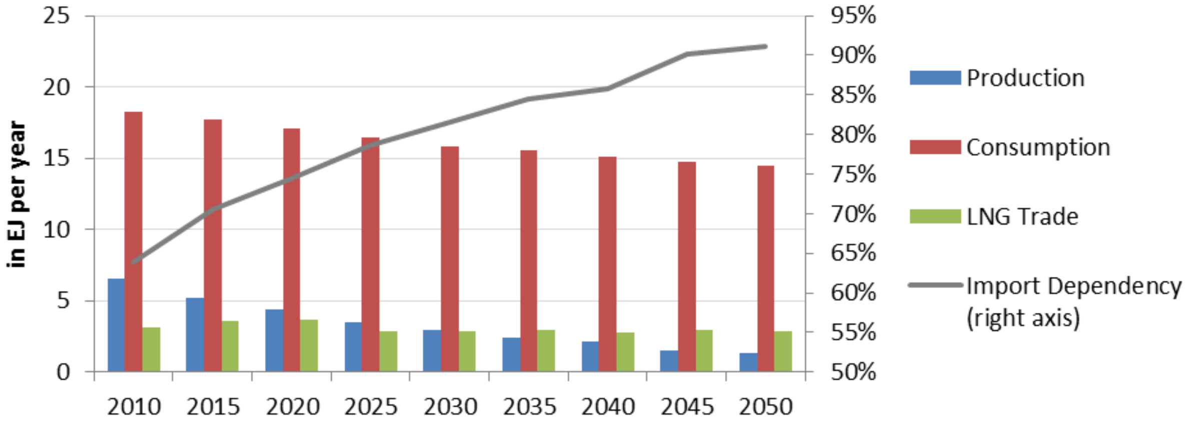

Figure 2: EU-27 GGM results for production, consumption, LNG trade and import dependency in scenario EU1 (in EJ/y and percentages)

In PRIMES, this scenario leads to 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 27 trend unambiguously points to a reduced importance of natural gas: 19 % less natural gas consumption in 2050 compared to 2010 comes with a reduction of the share of natural gas in the primary energy consumption from 24% to 21%.

We use the PRIMES EU1 results of each EU 27 country as data input for reference demand and production of natural gas in Europe for the following decades. (As indicated in Section 2 the outcomes can deviate somewhat from the PRIMES results.) Figure 2 shows how GGM projected natural gas consumption steadily decreases, departing from 18.3 EJ/y[4] in 2010 by 13% to 15.8 EJ/y in 2030. By the mid-2040s it reaches a level well below 15 EJ/y. Natural gas production within the EU decreases even stronger: from 6.6 EJ/y in 2010 to 2.9 EJ/y (-56%) in 2030 and to 1.3 EJ/y (-80%) in 2050. Except for the Netherlands and Romania all producing countries in the EU stop their natural gas extraction after 2040 at the latest. Domestic production levels decreasing at a faster rate than consumption

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[4] Following the EMF standard, all data on energy are given in exajoule (EJ), which is equal to 10^{18} joules. One unit of EJ corresponds to 26.3 bcm, assuming a calorific value of 38 MJ/m^3.

necessarily leads to an increasing import dependency. While in 2010 64% of EU natural gas consumption was covered by imports, this rate is goes up to 82% by 2030 and above 90% by 2050.[5]

As in the input data, the reduction in consumed natural gas is unevenly spread across the member states. The strongest decrease in natural gas consumption takes place in Germany (-27% between 2010 and 2050), the UK (-35%), the Netherlands (-41%) and France (-35%). Some countries increase their natural gas consumption in a shift away from coal, e.g. Greece (+126%), Spain (+30%) and Bulgaria (+26%). This heterogeneity in consumption paths is also reflected in the ranking of countries by natural gas consumption. While the UK has the highest natural gas consumption in 2010, both Germany and Italy consume more natural gas in 2030 than the UK. Furthermore, 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.

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 12.9 EJ/y until 2030 and by 13% to 13.2 EJ/y until 2050 compared to 2010 levels. Underlying these aggregate numbers large country heterogeneity can again 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). The production in the Netherlands decreases to a level just above self-sufficiency. Their role is projected to change 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 as well. 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.

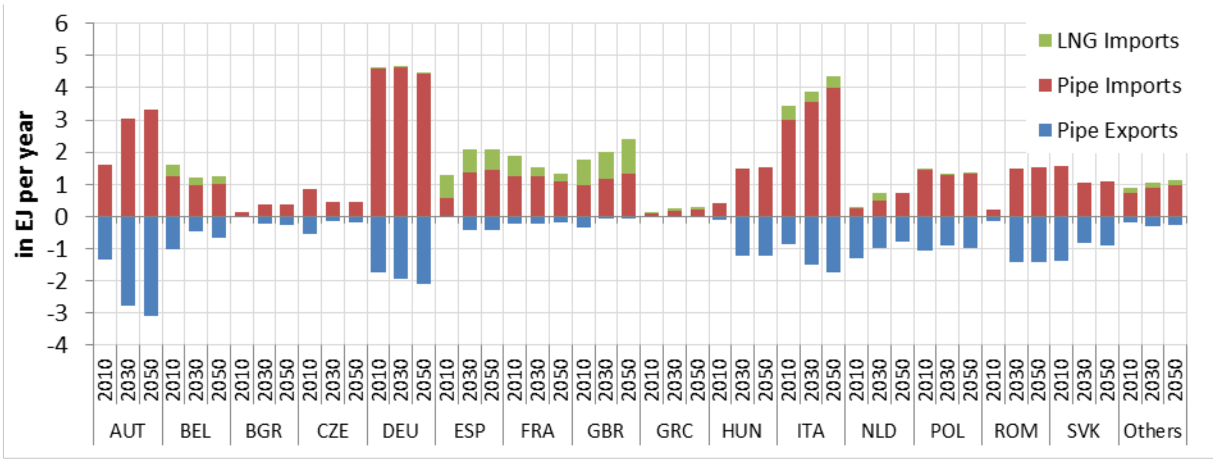

Figure 3: Imports and exports (pipelines and LNG) in 2010, 2030 and 2050 in scenario EU1 (in EJ/y)

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

Most imports are delivered by pipelines to the EU, both in 2010 and the next decades. LNG imports stay below a 30% share of total net imports (fluctuating around 3 EJ/y over time, see Figure 2) with the highest share in 2020 and declining thereafter. Most of the imported LNG comes from the Middle East and Africa (jointly more than 80% in 2010, more than 70% in 2050). However, African LNG exports to the EU decline after 2020 and Russia and South American supplies to Europe rise to almost 30% of EU LNG imports in 2050. Norwegian exports from the Far North are likely too expensive to be competitive and phased-out until 2020.

Overall, European natural gas imports—in form of LNG or transported through pipelines—are mainly satisfied by African, Russian and Norwegian exports and to a lesser extent from the Caspian region and the Middle East. Particularly the share of Africa increases significantly while Norwegian exports to Europe become lower over time. A notable divergence from the currently observed trade flows is the Russian export picture: in the model results throughout the entire model horizon Russia exports to Europe and Ukraine are considerably lower than observed in 2010. This is due to a “competition” for Russian gas with the domestic Russian market as well as the strong import demand in Asia-Pacific where the willingness-to-pay is higher and fewer alternative suppliers are available. This means that Russia can actually not fill all the large export pipelines to Europe that are 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. As Europe, in contrast to most other world regions, is well-supplied by a relatively large number of pipeline suppliers, its relative willingness-to-pay for LNG imports becomes smaller than in other regions. In particular the Asia-Pacific region with such booming natural gas markets as 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 and the Asia-Pacific region draws about 75% of the LNG exports from the other world regions (than ASP) in 2050.

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 too little interconnection with the Continental pipeline network. Spain’s LNG imports steadily decline over time while African pipeline gas becomes more important. A similar situation will be observed in Italy: additional pipeline gas imports from Africa and the Caspian substitute for LNG imports. Moreover, France’s LNG imports from Africa are phased-out over time due to unfavorable costs. Ireland, Poland, Germany and the Netherlands start importing LNG as of 2015.

The two main drivers for infrastructure expansions are increasing import needs and the market power assumptions for the particular traders.[6] The model results for consumption, production and trade are simultaneously determined with the decisions on infrastructure expansions. On the one hand, a change in the trade pattern determines the necessity of additional pipeline capacities and LNG

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[6] Even in the absence of additional import needs, a costly infrastructure expansion can be rational. 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.

infrastructure. On the other hand, the existing infrastructure as well as the costs and restrictions on further expansions determine to which extend trade between two regions is possible.

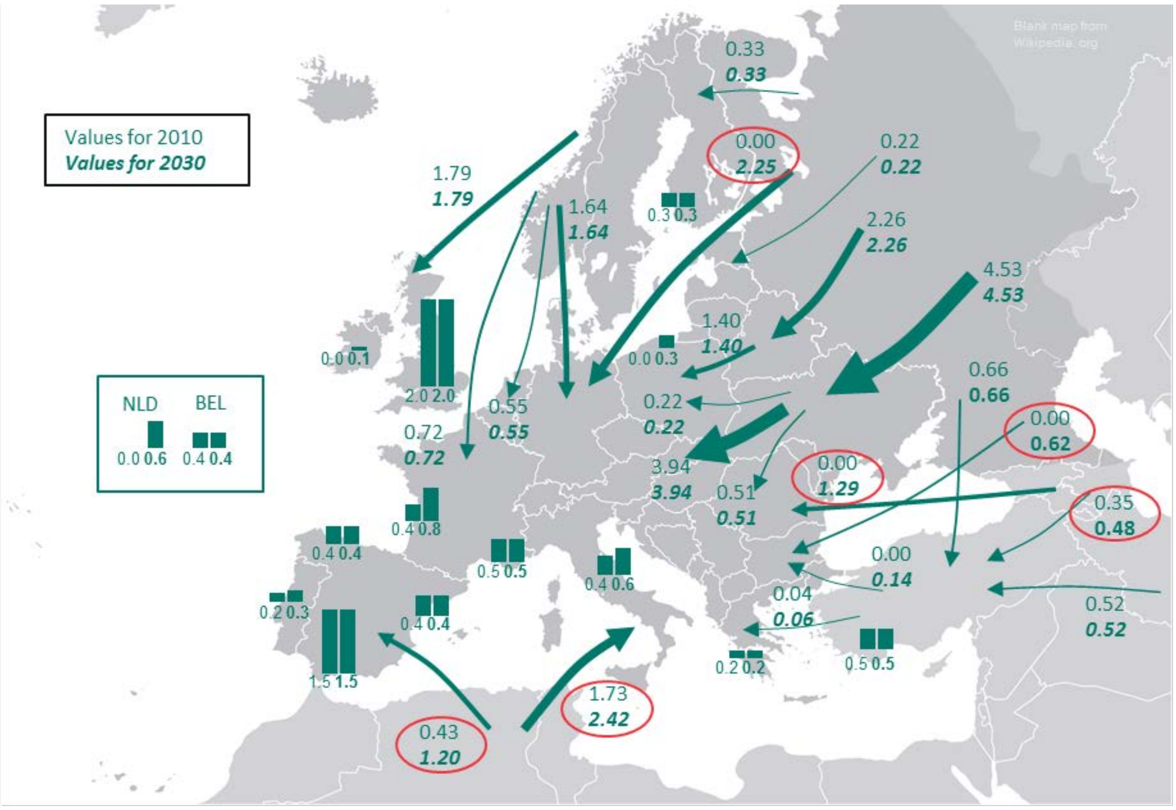

Figure 4: Pipeline and regasification capacities to Europe in scenario EU1 in 2010 and 2030 (in EJ/y)

Figure 4 depicts all major interconnecting pipelines into Europe as well as the regasification infrastructure comparing capacities in 2030 with those already existing in 2010. The size of a particular arrow in the illustration corresponds to the respective capacity of this interconnector in 2030. The largest cross-border pipelines are projected to run from Russia to the Ukraine (4.5 EJ/y via the already existing Brotherhood system) and to Germany (2.3 EJ/y via Nord Stream), between Africa and Italy (2.4 EJ/y via TransMed, Greenstream and GALSI) and Spain (1.2 EJ/y via MEG and Medgaz), and from Norway to the UK (1.8 EJ/y via Langeled) and to Germany (1.6 EJ/y via Europipe and Norpipe). The model results include a newly built pipeline between the Caspian region and Romania (1.3 EJ/y in White Stream). Since the construction of South Stream was started in late 2012,[7] it is included in the data set from 2015 on with a link between Russia and Bulgaria (0.6 EJ/y), and a subsequent pipeline between Bulgaria and Serbia (0.2 EJ/y). Further expansions towards Hungary are determined endogenously.

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 (to-

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[7] Construction on the offshore section of the South Stream pipeline started on Dec. 7, 2012. See http://www.south-stream.info (visited on Dec. 19. 2012).

gether 1 EJ/y until 2050).[8] In other countries like France, Italy and Portugal the model suggests that it is not economically sensible to build additional capacities. Already planned—and therefore included—expansions in these countries are not used.

Figure 5 presents all major pipeline expansions towards EU-27 countries over time. The presented values reflect expansion decisions; additional capacities become available after a five year time gap. We restrict investments on existing pipelines to 20% of the maximum of the exogenous capacity in 2010 or 2015 and also allow investment into known projects under development. After 2020, we assume unlimited potential expansion for all defined connections, and we observe some more expansions.

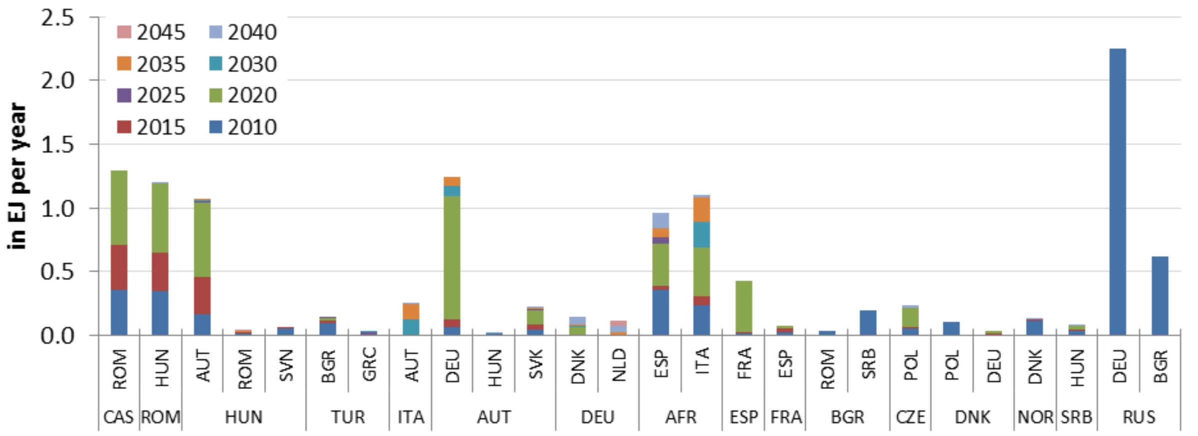

Figure 5: Pipeline expansions in scenario EU1 with destination within the EU-27 member states (lower part of horizontal axis is the pipeline's origin; in EJ/y)

Five major pipeline projects can be identified: First, the exogenously included Nord Stream pipeline from Russia to Germany (2.25 EJ/y) is built until 2015 and won't 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 from 2020 on. This means a major expansion between the Caspian region and Romania (by 1.29 EJ/y), from Romania to Hungary (by 1.19 EJ/y) and further to Austria (by 1.06 EJ/y). From there, additional pipeline capacity to Germany (plus 1.25 EJ/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 1.10 EJ/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 0.25 EJ/y) and also explains the significant expansion between Austria and Germany (see above). The fourth major expansion project towards Europe can be seen between Africa and Spain (Medgaz pipeline with 0.96EJ/y). This endogenous expansion is partly explained by African exports to France, which is reflected in additional capacity from Spain towards France (0.42 EJ/y). Finally, the first section of South Stream is included with exogenous expansions between Russia and Bul-

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[8] For Poland and the Netherlands these expansions have been already scheduled and are incorporated as inputs for 2015 in the model.

garia (0.62 EJ/y) and from Bulgaria towards Serbia (0.19 EJ/y). Since it is only sparsely used, endogenous expansion originating in Serbia is little (to Hungary).

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. Moreover, the new infrastructure capacities contribute to an increased diversification of imports as several of them open up new import paths or new transit routes.[9] Hence, the infrastructure investments lead to the improvement of supply security and also of market structure (through an increase of the number of suppliers in each market), despite these factors not being an explicit part of the optimization problems in the model.

Most of the described expansions take place before 2030. Exceptions are a further increase of pipeline capacity from Africa to Italy (by 0.41 EJ/y) and to Spain (by 0.19 EJ/y) as well as from Italy to Austria (by 0.25 EJ/y) and from Austria to Germany (by 0.15 EJ/y) (see Figure 5). Given our assumptions on pipeline length and expansion costs and taking into account the investment into additional LNG infrastructure, total investment costs for the EU-27 can be estimated at around € 25 bn. until 2050.[10] More than 65% of these costs fall due before 2020, more than 94% before 2025.

3.2 Variations from the base case - Other EMF (decarbonization) scenarios

In this section, we briefly discuss the GGM results for the EMF scenarios EU4 (40% GHG emissions reduction), EU6 to EU10 (80% GHG emissions reduction) and EU11 (no climate policy). The scenario input is again based on the PRIMES results of the respective scenario. While the aggregate EU-27 production level decreases in a similar way in all EMF scenarios, it is only marginally lower in the 80% scenarios than in the 40% scenarios. However, aggregate consumption differs significantly between the other EMF decarbonization cases (see Figure 6 and Figure 7). Two observations can be made: First, the consumption of natural gas in the EU declines in all scenarios which assume at least a moderate climate policy. Only the counterfactual scenario EU11, abstracting from any climate policy in the EU, is characterized by an increasing natural gas consumption until 2030 which is slightly declining thereafter to still reach a level above the 2010 level in 2050. Second, among the climate policy scenarios, two clusters can be identified—corresponding to the strictness of assumed GHG reduction targets. The natural gas consumption in the 40% scenarios EU1 and EU4 stays at a similar level which is significantly higher than that of all 80% reduction scenarios. In the second cluster, the scenarios EU7 and EU9 lie above the other ones.

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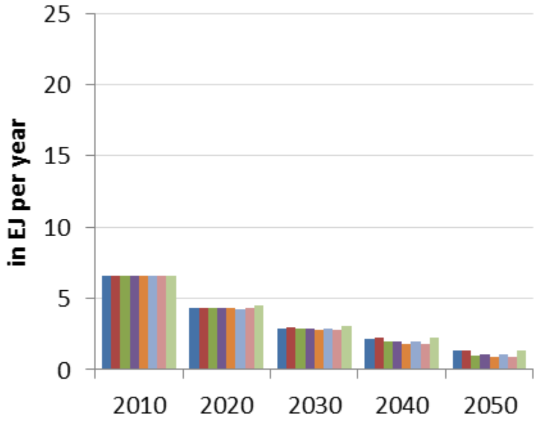
[9] This can be seen in the model output of trade flow origins where we observe a diversification in most European countries that is not reported here due to space constraints.

[10] This figure includes the total costs of investments in regasification facilities and of all pipeline expansions within the EU. Expansion costs of pipelines which start or end in the EU are accounted for with only 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.



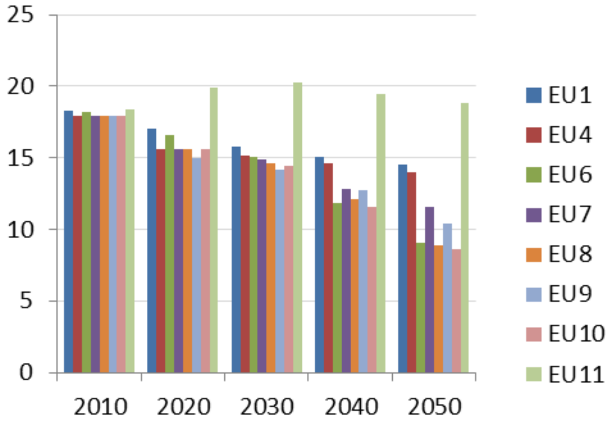


Figure 6: Production levels for EU- 27 by scenario (in EJ/y)

Figure 7: Consumption levels for EU- 27 by scenario (in EJ/y)

As can be inferred from the consumption and production patterns, similar clusters form concerning EU-27 net imports of natural gas. In the 40% and EU11 scenarios the net imports increase over time. In contrast, in all 80% scenarios the net imports increase slightly in the first periods, but start to decrease in 2030 at the latest. Hence, in all 80% scenarios the motivation for additional infrastructure at most fulfilled in the first periods. Transportation network expansions can consequently be expected to be of a small scale.

Figure 8 depicts the absolute deviations of cumulative infrastructure expansions until 2050 for all EMF scenarios relative to the base case EU1. As expected, expansions in all 80% scenarios are generally below those of the 40% scenarios.[11] 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. Among the 80% reduction scenarios, EU7 is characterized by a relatively higher pipeline expansion. This is in line with the relatively higher consumption levels. For the 40% scenarios, the infrastructure capacities are similar across scenarios, but the expansions in scenario EU4 are generally smaller than in the base case EU1. For the connection between Africa and Spain this difference is particularly pronounced. Moreover, regasification facilities are endogenously built only in Ireland, but with smaller capacity than in EU1 (i.e. about 0.1 EJ/y of new capacity until 2030).

Naturally, scenario EU11 results in considerably higher expansions for all major pipeline projects. Moreover, a new route via Turkey to Greece and from Greece to Italy (ITGI) is added to bring Caspian natural gas to Southern Europe. Additionally, in Germany a significant amount of regasification capacity is built (0.22 EJ/y). A similar and more detailed discussion of pipeline expansion in a context of increasing natural gas consumption can be found in the next section which analyzes the “Back-

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[11] There are two minor exceptions: in EU8 and EU10, small amounts of additional capacity are built between Germany and Denmark to satisfy a considerably higher Danish demand compared to other scenarios and between Greece and Italy to compensate for the phasing-out of Italian production.

Up" scenario. In contrast to EU11, the "Back-Up" scenario is not defined to be counterfactual but is by itself in line with a moderate climate policy.

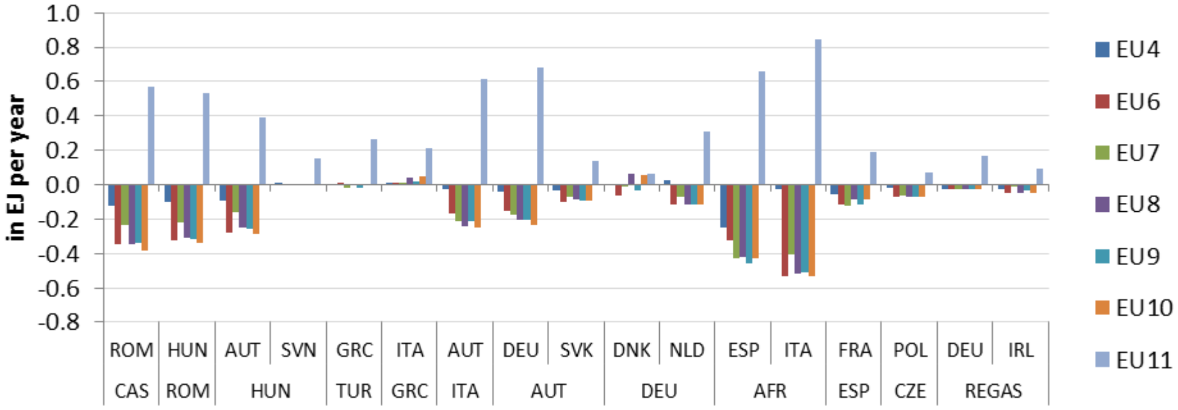

Figure 8: Cumulative expansions until 2050 with destination within the EU-27 relative to the base case EU1 (absolute deviations in EJ/y)

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

The EMF scenarios discussed in the previous section are all characterized by a decrease in EU natural gas consumption—independent of the underlying assumptions on both the political framework and the availability of technology options (cf. Figure 7). 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".[12] 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 go beyond the analysis of our PRIMES-based EMF scenarios and investigate projections from other model frameworks characterized by increasing natural gas consumption in the EU.

In this respect we have created two alternative scenarios in which natural gas plays a vital role—at least in the short-run—for the transition to a low carbon economy. The alternative climate scenarios are consistent with respective to the CO_2 emission reduction paths. The first scenario, "Back-Up" (discussed in Section 4.1) is based on the World Energy Outlook 2012 (WEO) recently published by the International Energy Agency (IEA, 2012) providing projections for the global energy system until 2035. Particularly we argue that the WEO's New Policy Scenario (NPS) is comparable to the 40% reduction EMF scenarios. In the NPS, the underlying moderate EU climate policy leads to an

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[12] For instance, see the speech of the 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

overall reduction in the use of fossil fuels with a shift from coal and oil to renewables and natural gas. Hence, 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 EU7 scenario, i.e. a scenario characterized by a 80% GHG reduction in the EU by 2050 (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). 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 analyzing with respect to infrastructure expansions.[13]

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

According to the IEA, the New Policies Scenario (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). Consequently 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 potentially be employed only on a limited scale.

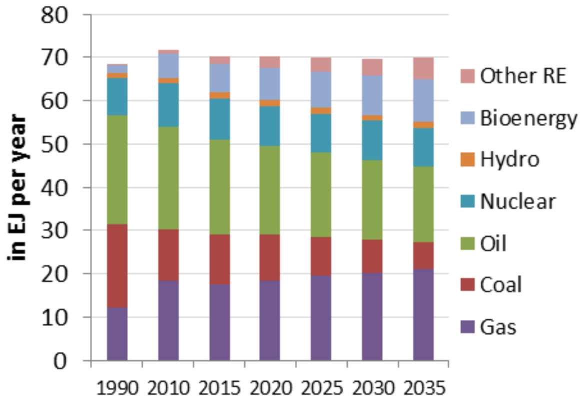

Figure 9: WEO TPED (in EJ/y) (Source: IEA, 2012, p. 572)

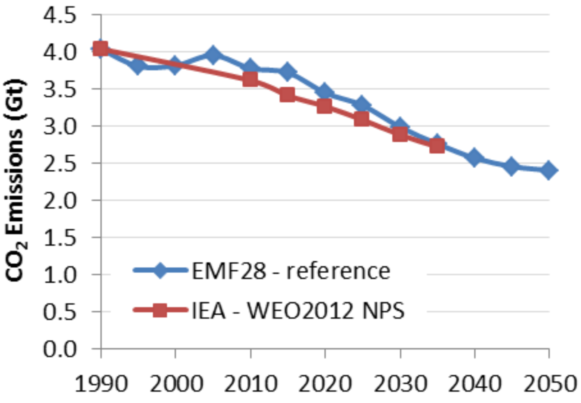

Figure 10: CO_2 emissions WEO vs EMF Reference (in Gt/y) (Source: IEA, 2012, p. 574; EMF storylines)

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 CO_2 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 ef-

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[13] 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.

fect (see Figure 9). 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 CO_2 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, the remaining one third to the substitution effect. As can be inferred from Figure 10 the NPS emissions reduction path is comparable to the assumed path within the EMF 40% reduction scenarios. Both projections reach a similar level of CO_2 emissions in 2035 which is about 30% lower than the level of 1990.

Our first alternative scenario, which is discussed in the following, is based on the NPS with a conservative extrapolation of the use of different energy technologies in the EU and in accordance with the 40% reduction target by 2050. The consumption of fossil fuels in total is further reduced; the consumption of natural gas is projected to slightly increase to a level about 20% higher than in 2010.[14] In accordance with the underlying assumptions of a moderate climate policy (-40% reduction) we discuss the alternative scenario relative to the base case EU1.

The general setting and aggregate differences are summarized by Figure 11. While EU production levels are only marginally larger than in the base case, by construction in the WEO-based “Back-Up” scenario the EU-27 consumption of natural gas lies well above EU1 levels. In 2030 about 20 EJ/y are consumed (27% more than in the base case EU1) increasing to 22 EJ/y in 2050 (52% more than in the base case EU1). Consequently, the discrepancy between falling production and steadily increasing consumption leads to an even higher import dependency than in the Base Case, reaching up to 94% in 2050, which is partly satisfied by a higher level of LNG imports (see below).

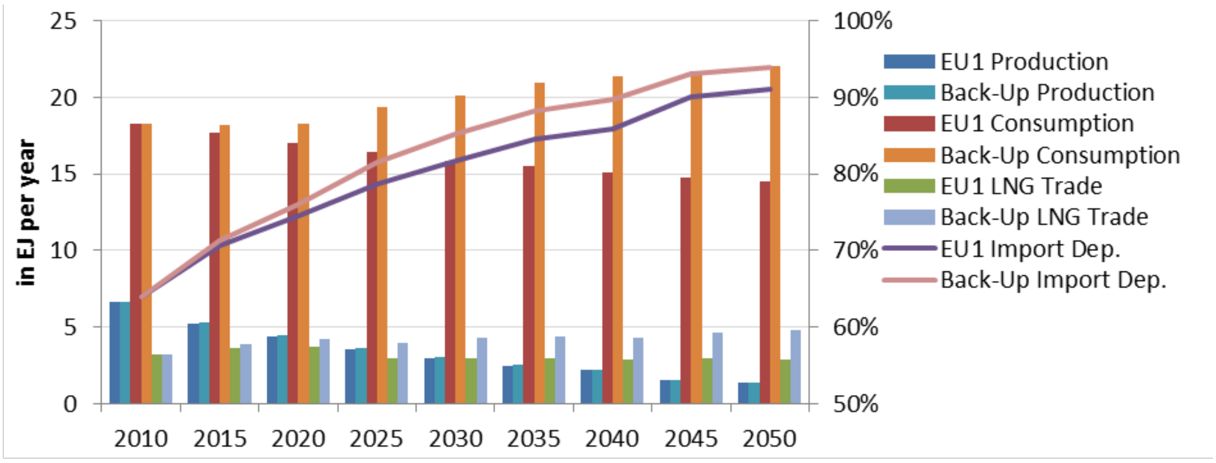

Figure 11: Volumes and import dependency of the EU-27 in Back-Up scenario (in EJ/y)

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[14] 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"). Except for the German commitment to phase out nuclear, no reduction in nuclear power generation in EU countries is assumed.

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-27 (EU-30) share in global consumption decreases from 15% (17%) in 2010 to 7% (8%) in 2050 in the base case EU1; while it decreases to 11% (12%) only 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 absolute terms) in Germany, Italy, the UK and Poland. The latter is due to significant substitution of natural gas for coal in power generation.

In 2030 total net imports into the EU (17 EJ/y) are 33% higher than in the base case rising to a 57% higher level (21 EJ/y) in 2050. In absolute terms additional net imports are mainly going to Germany, Italy, the UK and Poland (see Figure 12 for a 2030 comparison). All major EU1 flows are seen and intensified further in the “Back-Up” scenario. More trade takes place via the White Stream pipeline and through imports from Africa. The role of Austria, Hungary, Romania and Slovakia as transit countries is consequently more pronounced in the “Back-Up” scenario.

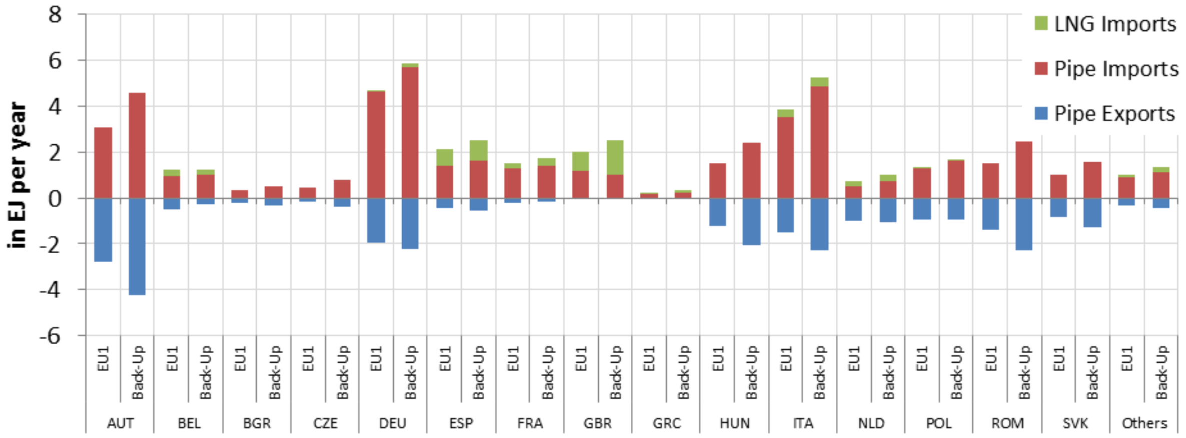

Figure 12: Imports and exports through pipelines and in form of LNG in 2030; “Back-Up” vs base case EU1 (in EJ/y)

Natural gas traded in form of LNG oscillates around a 25% share of total EU net imports. Accordingly, almost 5 EJ/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 base case lead to a small increase in the expansion of regasification facilities in the EU. Until 2050 a capacity of 1.9 EJ/y is built up compared to only 1.7 EJ/y in the base case (thereof around 1.5 EJ/y exogenously given in both scenarios). The expansion is higher in Ireland and Germany (about +0.1 EJ/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 13 contrasts cumulative pipeline expansions for selected connections until 2050 in the “Back-Up” scenario with the base case. 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 base case EU1, pipeline expansion from the Caspian region to Asia is diverted towards Europe. One additional import pipeline to Europe (EU-30) 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 base case EU1. They reach almost 43 bn € until 2050, with investments before 2025 being already significantly higher than total expenditures in the base case.

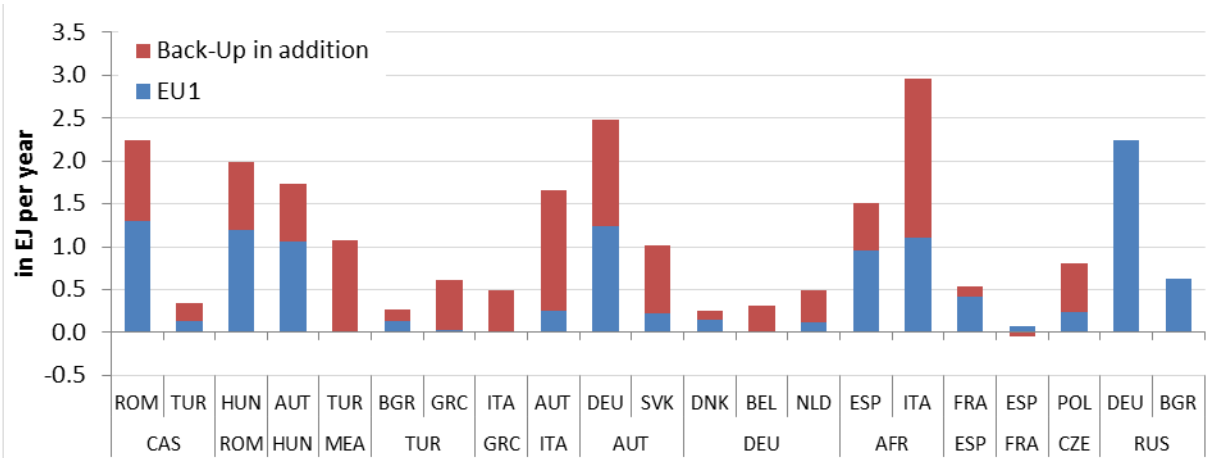

Figure 13: Cumulative pipeline capacity expansions worldwide (in EJ/y)

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” scenario which we define based on the PET model’s results for the EMF scenario EU7. This second alternative scenario is characterized by an 80% GHG emission reduction policy in the EU. 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, followed by a sharp divergence between both scenarios thereafter (see Figure 14). 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 5 EJ/y in 2020—a share of up to 32% of net imports.

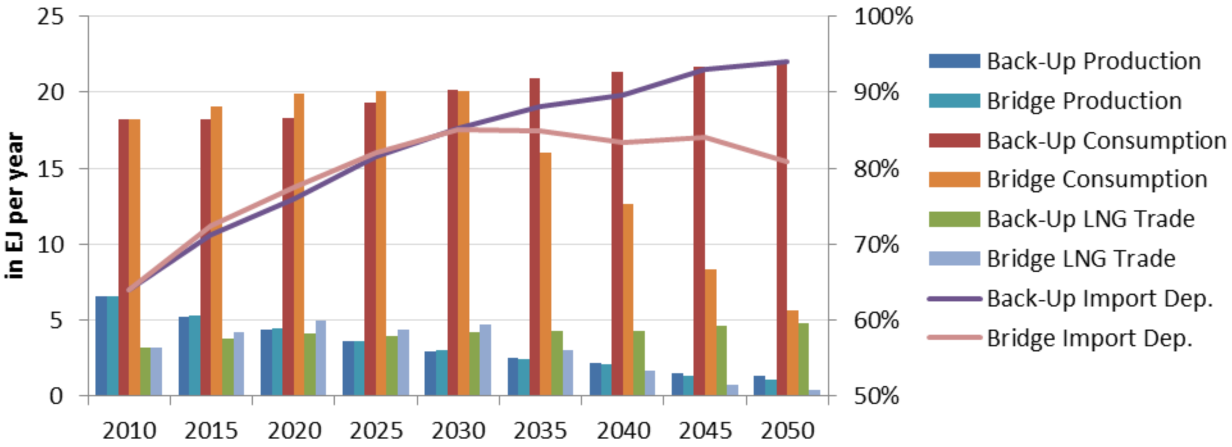

Figure 14: Comparison between the "Back-Up" and the "Bridge" scenario (in EJ/y and percentage)

Indeed, there is spare LNG capacity in the EMF decarbonization and the Back-Up scenarios which is fully used in the Bridge scenario until 2030 because it can flexibly serve the additional demand for the limited time period until 2030. 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 alternative short-term option to serve the high demand.

Let us look in detail at the different infrastructure expansion schemes caused by the short-term similarities and long-term differences between both alternative scenarios. Figure 15 shows the absolute difference between cumulative infrastructure expansions until 2050 in the "Back-Up" and the "Bridge" scenario relative to the base case EU1. The pipeline expansion levels in the "Bridge" scenario are close to the base case levels. This is in contrast to the other 80% scenarios (see Section 3), compared to which the Bridge expansions are generally higher (with a few exceptions). However, expansions of regasification facilities are highest in the "Bridge" scenario (2.14 EJ/y compared to 1.90 EJ/y in the "Back-Up" scenario).[15] 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. Figure 16 illustrates cumulative infrastructure expansions in both pipelines and LNG facilities until 2050 for the "Bridge", the "Back-Up" and the EU1 scenario. Until 2025 the two alternative scenarios follow a similar expansion path, slightly higher than the one of the base case. After 2025, only in the "Back-Up" scenario the cumulative expansions increase gradually up to a significantly higher level.

Total EU infrastructure investments in the "Bridge" scenario are about € 26 bn., close to the expenditure figures in the base case—hence 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 is done before 2025 compared to only 69% in the "Back-Up" scenario.

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[15] The infrastructure expansion primarily takes place in pipelines because supplies from relatively near sources are plentiful available. Variable and fixed costs of pipelines are relatively cheaper than LNG costs for short distances, while LNG becomes relatively cheaper for very long distances.

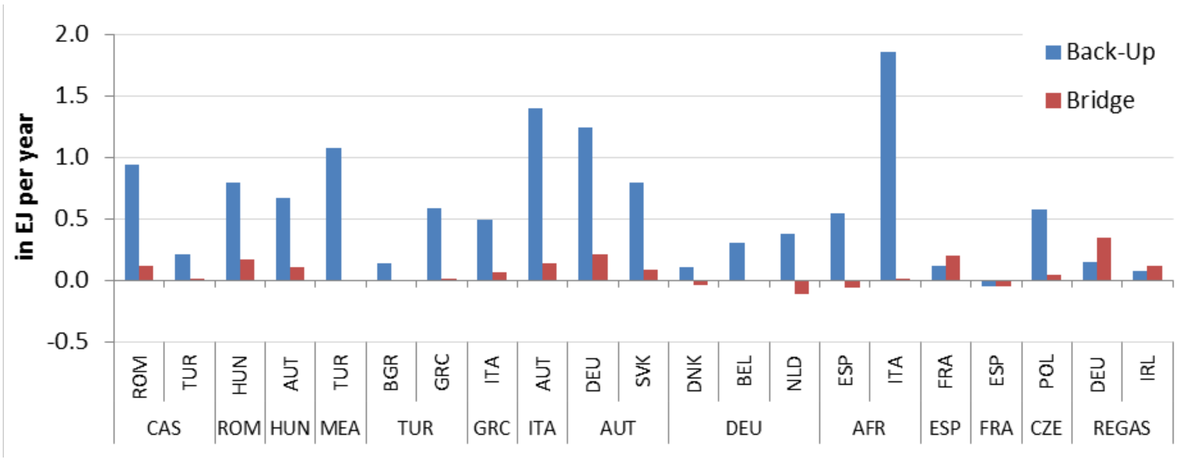

Figure 15: Deviations of "Back-Up" and "Bridge" scenario from the base case EU1 of selected cumulative expansion until 2050 (in EJ/y)

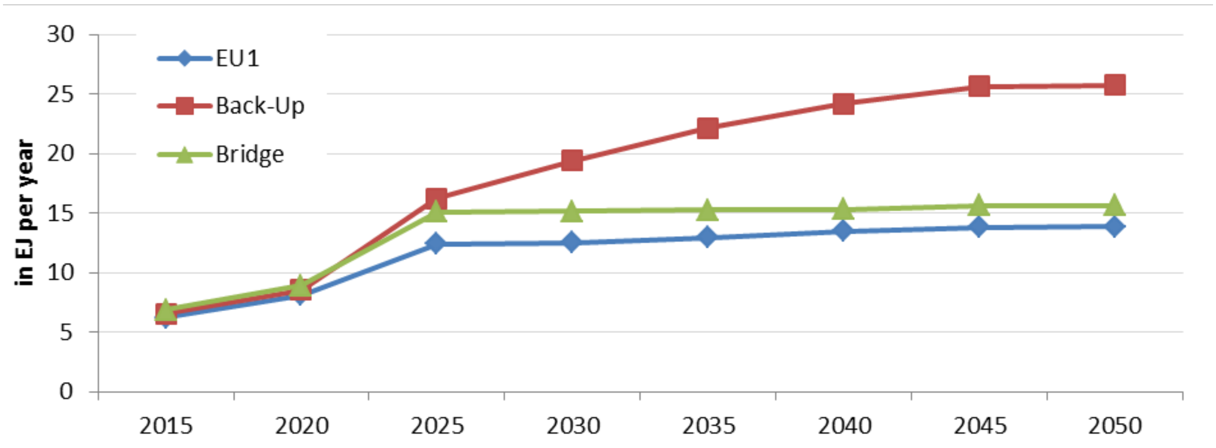

Figure 16: Cumulative infrastructure expansions with pipeline destination and re-gasifier location within EU-27 member states (in EJ/y)

5 Regional Focus: Perspectives of Central and Eastern Europe

In this section, we take a closer look at the results for Central and Eastern Europe (CEE) with a particular focus on infrastructure expansions and their role for supply security. We concentrate on the base case EU1 and the "Back-Up" scenario to highlight the results of the two extreme scenarios.

Central and Eastern Europe 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).[16] While natural

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[16] 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

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, cf. Stern, 2010) and 2011/2012 (strong winter and gas dispute). 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 17 shows all major pipeline expansions in this region—illustrated by arrows for the "Back-Up" scenario and compared to the base case EU1. 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 mashed 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 (currently under construction, hence exogenous model input).

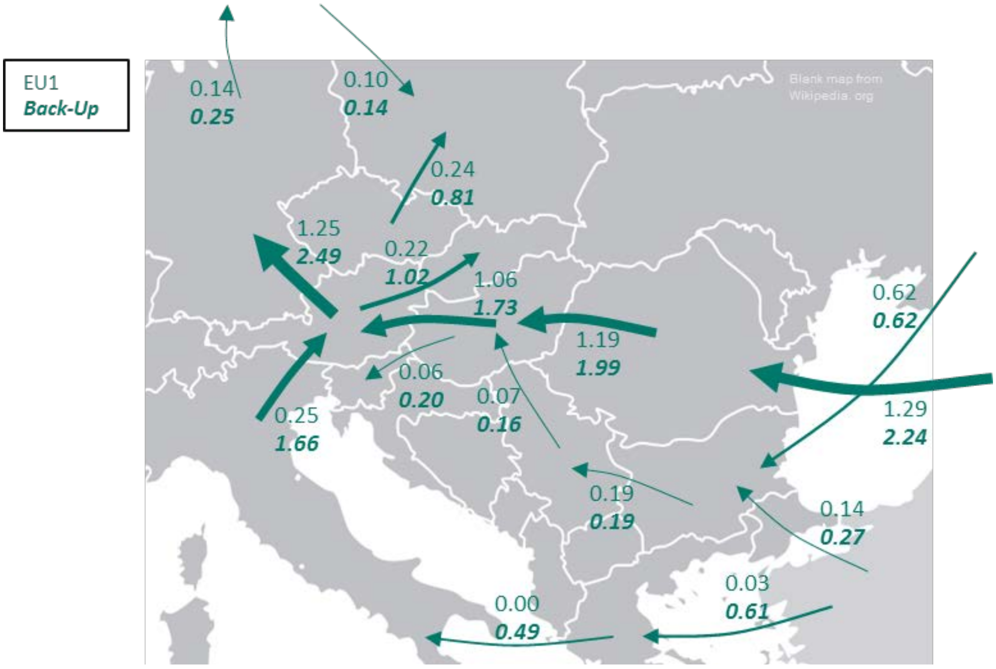

Figure 17: Major cumulative pipeline expansions in Central and South East Europe until 2050 in the EU1 and the "Back-Up" scenario (in EJ/y)

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 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 Re-

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reduction of natural gas consumption in most scenarios, shale gas hardly seems to have a perspective in Europe anyways.

gion 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 2.5 EJ/y.[17]

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.[18] 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.

6 Conclusions

A European low-carbon future relies necessarily on a significant change in the current energy system. Analyzing the different possible GHG mitigation pathways until 2050 is the main concern of the EMF 28 effort. In this paper we take a closer look at the natural gas 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 eight climate scenarios based on input from the PRIMES energy system model. These EMF scenarios have been defined along the two dimensions of technology availability and policy stringency. All these scenarios with an implemented climate policy are characterized by a decreasing natural gas consumption—the more stringent the climate policy the lower the level of consumption. Hence, in the 80% GHG reduction scenarios there is no need for large-scale pipeline expansions. The decline in European domestic production and the increasing reliance on African and Caspian exports to supply Europe, however, lead to some expansions from Africa to Spain and Italy and from the Caspian 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

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[17] Originating in Germany in turn, pipelines towards the Netherlands, Denmark and Belgium are expanded (in the “Back-Up” scenario) between 0.25 and 0.5 EJ/y each.

[18] Due to small size these latter expansions are not depicted in Figure 17 which includes only expansions that are larger than 0.1 EJ/y. in the Back-Up scenario.

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 the 40% GHG reduction scenarios, the pipeline expansions from Africa and the Caspian region to Europe are more pronounced than in the 80% scenarios. In an alternative moderate climate policy scenario the continuously increasing natural gas consumption is analyzed ("Back-Up" scenario). Expansions are significantly higher than in the EMF decarbonization scenarios, 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" stringent climate policy scenario show that long-term trade relations are needed to economically justify pipeline infrastructure construction. In this scenario hardly more infrastructure expansions take place than in the PRIMES-based EMF decarbonization scenarios. Instead, the existing idle LNG import capacities are used during the high demand period, supported by some additional expansions in regasification facilities.

The outcomes of all scenarios show an improvement of the import diversification of the European importers, in particular with 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.

Future work 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 a rich picture can be expected with strongly increasing demand in the emerging natural gas markets 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. (2013) present the results of using a stochastic model to analyze the EMF decarbonization scenarios.

The next five to ten years will show if the tendency of lowering natural gas consumption in Europe as indicated by the PRIMES-based EMF decarbonization scenarios will realize. Indeed, a stronger reliance on natural gas may be a probable energy future and our alternative scenarios indicate the economic feasibility of such a pathway.

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Appendix

Table 2: Abbreviations for countries and regions

EU-27	
Austria	AUT
Belgium	BEL
Bulgaria	BGR
Czech Republic	CZE
Denmark	DNK
Estonia	EST
Finland	FIN
France	FRA
Germany	DEU
Greece	GRC
Hungary	HUN
Ireland	IRL
Italy	ITA
Latvia	LVA
Lithuania	LTU
Luxembourg	LUX
Netherlands	NLD
Poland	POL
Portugal	PRT
Romania	ROM
Slovakia	SVK
Slovenia	SVN
Spain	ESP
Sweden	SWE
UK	GBR

South East Europe	
Albania	ALB
Belarus	BLR
Bosnia and Herzegovina	BIH
Croatia	HRV
Kosovo	KOS
Macedonia	MKD
Moldavia	MDA
Montenegro	MNE
Serbia	SRB
Ukraine	UKR

Other country nodes	
Norway	NOR
Russia	RUS
Switzerland	CHE
Turkey	TUR

Other regional nodes	
Africa	AFR
Asia-Pacific	ASP
Caspian Region	CAS
Middle East	MEA
North America	NAM
South America	SAM

Table 3: Model parameter values for the base year 2010

	Production				Consumption						Transportation		Storage
	ref	cap	lin	cpg	refcL	refcH	refpL	refpH	intL	intH	trad+	trad-	cap
Node	EJ/a		$/GJ		EJ/a		$/GJ		EJ/a		EJ/a		PJ
AUT	0.06	0.06	1.32	-0.66	0.21	0.45	4.55	5.69	7.28	9.09	3.58	2.21	1.49
BEL					0.37	0.80	4.82	5.95	7.93	9.80	3.86	2.82	0.15
BGR	0.00	0.00	1.32	-0.66	0.07	0.13	4.63	5.64	7.02	8.55	1.02	0.76	0.09
CZE	0.01	0.01	1.32	-0.66	0.19	0.45	4.47	5.74	8.58	11.00	2.09	2.23	0.68
DEU	0.40	0.42	1.45	-0.72	2.35	4.37	4.93	5.88	9.05	10.79	8.00	3.25	4.33
DNK	0.31	0.32	1.32	-0.66	0.12	0.25	4.55	5.69	6.90	8.62	0.02	0.18	0.21
ESP	0.00	0.00	1.32	-0.66	1.18	1.45	5.86	6.17	8.47	8.93	3.01	0.30	0.94
EST					0.01	0.03	4.59	5.67	6.79	8.38	0.10	0.10	
FIN					0.12	0.21	4.75	5.57	6.53	7.66	0.33		
FRA	0.03	0.03	1.32	-0.66	0.98	2.53	4.92	6.31	9.33	11.97	3.52	0.40	2.64
GBR	2.17	2.23	1.32	-0.66	2.70	4.41	4.53	5.28	7.42	8.66	5.21	1.15	0.91
GRC					0.13	0.14	5.14	5.33	7.25	7.52	0.37	0.00	0.02
HUN	0.08	0.08	1.32	-0.66	0.23	0.60	4.39	5.78	7.85	10.33	0.95	0.50	1.28
IRL	0.01	0.01	1.32	-0.66	0.18	0.23	5.03	5.41	7.14	7.68	0.39		0.05
ITA	0.29	0.29	1.32	-0.66	2.01	3.73	5.20	6.14	8.32	9.84	4.40	2.25	3.00
LTU					0.05	0.16	4.28	5.86	6.45	8.83	0.27	0.07	
LUX					0.04	0.06	4.87	5.50	7.81	8.82	0.10		
LVA					0.03	0.09	4.28	5.86	6.22	8.52	0.38	0.13	0.48
NLD	2.57	2.96	1.45	-0.72	1.21	2.06	4.22	5.04	6.90	8.24	0.92	4.56	1.09
POL	0.16	0.16	1.32	-0.66	0.39	0.69	4.97	5.86	9.44	11.11	1.66	1.17	0.36
PRT					0.19	0.18	5.30	5.24	7.45	7.36	0.43	0.13	0.04
ROM	0.38	0.39	1.32	-0.66	0.36	0.57	4.83	5.52	8.33	9.53	0.57	1.02	0.56
SVK	0.00	0.00	1.32	-0.66	0.12	0.31	4.39	5.78	8.41	11.07	4.35	3.61	0.59
SVN					0.03	0.04	4.71	5.59	8.23	9.77	0.13	0.10	
SWE					0.04	0.09	4.51	5.71	6.75	8.55	0.12		0.00
CHE					0.06	0.19	4.28	5.86	9.15	12.52	1.72	0.78	0.01
NOR	3.88	4.46	1.05	-0.66	0.18	0.29	4.83	5.52	7.33	8.39		4.96	
TUR	0.02	0.02	1.32	-0.66	1.14	1.51	4.99	5.43	7.21	7.85	2.60	0.04	0.33
ALB	0.00	0.00	1.32	-0.66	0.00	0.00	4.87	5.50	8.98	10.15	0.00	0.00	
BIH					0.01	0.01	4.87	5.50	8.17	9.24	0.03		
HRV	0.09	0.09	1.32	-0.66	0.08	0.13	4.83	5.52	8.31	9.51	0.32		0.11
KOS					0.00	0.00	4.87	5.50	8.09	9.14	0.00		
MDA					0.05	0.07	4.87	5.50	6.71	7.58	0.08		
MKD					0.00	0.00	4.87	5.50	6.91	7.80	0.03	0.00	
MNE					0.00	0.00	4.87	5.50	8.09	9.14	0.00		
SRB	0.01	0.01	1.32	-0.66	0.05	0.07	4.87	5.50	7.81	8.82	0.18	0.03	0.10
BLR	0.01	0.01	1.32	-0.66	0.60	0.90	3.03	3.66	4.11	4.97	2.26	2.60	0.36
UKR	0.70	0.72	0.79	-0.66	1.58	2.38	4.61	5.24	7.31	8.31	5.49	5.53	6.69
RUS	22.38	24.62	0.26	-0.66	16.68	14.79	1.97	1.97	2.75	2.75	2.43	9.10	12.91
AFR	7.94	8.74	0.26	-0.66	3.99	3.99	1.97	1.97	2.78	2.78		5.69	
ASP	18.74	19.68	0.92	-0.66	20.27	22.86	4.75	4.94	6.68	6.95	16.31	5.10	1.67
CAS	5.71	6.28	0.26	-0.66	3.80	3.80	1.97	1.97	3.23	3.23	0.53	2.98	2.00
MEA	17.51	19.26	0.26	-0.66	13.89	13.89	1.97	1.97	2.96	2.96		6.09	
NAM	31.39	32.96	1.05	-0.66	26.49	35.11	3.67	4.11	6.05	6.78	7.09	0.08	27.24
SAM	6.13	6.43	0.53	-0.66	5.61	5.61	3.42	3.42	5.40	5.40	0.62	1.18	

Explanation of abbreviations: **ref**=reference; **cap**=capacity; **lin**=linear term of production cost function; **cpg**=Golombek term of production cost function; **refcL**=reference consumption April-September; **refcH**=reference consumption October-March; **refpL**=reference price April-September; **refpH**=reference price October-March; **intL**=intercept of inverse demand curve April-September; **intH**=intercept of inverse demand curve October-March; **trad+**=import capacity via pipelines and regasification; **trad-**=export capacity via pipelines and liquefaction

Table 4: Reference consumption and production levels

	Consumption					Production				
Node	**2010**	**2020**	**2030**	**2040**	**2050**	**2010**	**2020**	**2030**	**2040**	**2050**
AUT	0.331	0.272	0.274	0.233	0.235	0.062	0.031	0.025	0.009	
BEL	0.586	0.581	0.743	0.682	0.629					
BGR	0.097	0.103	0.118	0.115	0.112	0.003	0.002	0.001	0.001	
CZE	0.325	0.302	0.286	0.288	0.277	0.007	0.007	0.006	0.006	
DEU	3.364	3.280	2.913	2.682	2.456	0.404	0.331	0.215	0.084	
DNK	0.185	0.163	0.140	0.125	0.137	0.308	0.230	0.133	0.091	
ESP	1.315	1.384	1.607	1.456	1.623	0.002				
EST	0.021	0.021	0.023	0.023	0.024					
FIN	0.164	0.139	0.168	0.175	0.164					
FRA	1.755	1.509	1.304	1.225	1.129	0.026				
GBR	3.556	2.869	2.420	2.549	2.539	2.169	0.826	0.447	0.075	
GRC	0.135	0.178	0.248	0.297	0.293					
HUN	0.414	0.370	0.321	0.288	0.267	0.082	0.066	0.058	0.047	
IRL	0.203	0.171	0.194	0.205	0.209	0.014	0.012	0.013	0.009	
ITA	2.870	2.827	2.476	2.624	2.557	0.287	0.246	0.203	0.109	
LTU	0.105	0.091	0.084	0.073	0.068					
LUX	0.051	0.053	0.058	0.063	0.069					
LVA	0.062	0.045	0.039	0.046	0.050					
NLD	1.636	1.429	1.148	1.005	1.032	2.572	2.304	1.530	1.439	1.102
POL	0.540	0.502	0.489	0.425	0.405	0.156	0.125	0.109	0.071	
PRT	0.188	0.149	0.115	0.113	0.124					
ROM	0.466	0.402	0.356	0.356	0.340	0.382	0.329	0.291	0.291	0.246
SVK	0.214	0.223	0.217	0.218	0.205	0.004	0.004	0.004	0.004	
SVN	0.035	0.037	0.031	0.029	0.026					
SWE	0.064	0.030	0.029	0.050	0.052					
CHE	0.124	0.115	0.106	0.103	0.101					
NOR	0.235	0.217	0.201	0.195	0.190	3.880	3.591	3.292	3.011	2.847
TUR	1.325	1.223	1.132	1.097	1.073	0.023	0.022	0.020	0.018	0.017
ALB	0.000	0.000	0.000	0.000	0.000	0.002	0.002	0.002	0.002	0.002
BIH	0.008	0.007	0.007	0.006	0.006					
HRV	0.105	0.097	0.090	0.087	0.085	0.088	0.081	0.074	0.068	0.064
KOS	0.000	0.000	0.000	0.000	0.000					
MKD	0.003	0.002	0.002	0.002	0.002					
MDA	0.061	0.061	0.061	0.061	0.061					
MNE	0.000	0.000	0.000	0.000	0.000					
SRB	0.059	0.054	0.050	0.049	0.048	0.011	0.010	0.009	0.008	0.008
BLR	0.749	0.749	0.749	0.749	0.749	0.006	0.006	0.006	0.006	0.006
UKR	1.981	1.827	1.692	1.640	1.603	0.705	0.653	0.598	0.547	0.517
RUS	15.738	17.659	18.952	21.176	22.033	22.380	27.075	32.161	35.030	35.808
AFR	3.988	5.197	6.164	7.440	7.976	7.943	12.968	16.169	19.169	19.857
ASP	21.567	36.300	46.285	60.272	64.701	18.740	29.491	35.724	40.436	41.229
CAS	3.799	4.652	5.362	6.198	6.459	5.706	8.713	10.473	12.088	12.553
MEA	13.890	18.224	23.407	28.632	30.559	17.507	24.645	29.787	35.384	36.764
NAM	30.803	33.309	35.246	36.673	36.963	31.392	33.127	35.691	37.356	37.670
SAM	5.613	8.271	9.284	10.733	11.225	6.127	9.190	10.198	11.756	12.253

Table 5: Gross pipeline capacity input values

From	To	2010	2015
Intra-EU pipelines			
AUT	DEU	0.316	
AUT	HUN	0.161	
AUT	ITA	1.424	
AUT	SVK	0.218	
AUT	SVN	0.096	
BEL	FRA	1.044	
BEL	DEU	0.356	
BEL	LUX	0.061	
BEL	NLD	0.390	
BEL	GBR	0.973	
BGR	GRC	0.135	
BGR	ROM	0.000	
CZE	DEU	2.032	
CZE	POL	0.000	
CZE	SVK	0.195	
DEU	AUT	0.134	0.034
DEU	BEL	0.568	
DEU	CZE	0.495	
DEU	DNK	0.019	
DEU	FRA	0.773	
DEU	LUX	0.034	
DEU	NLD	0.513	
DEU	POL	0.042	
DNK	DEU	0.039	
DNK	NLD	0.019	
DNK	POL	0.000	
DNK	SWE	0.123	
ESP	FRA	0.070	
ESP	PRT	0.226	
EST	FIN	0.000	
EST	LVA	0.099	
FRA	ESP	0.132	
GBR	BEL	0.762	
GBR	IRL	0.388	
GRC	ITA	0.000	
HUN	AUT	0.000	
HUN	ROM	0.065	
HUN	SVN	0.000	
ITA	AUT	1.433	
ITA	SVN	0.035	
LTU	LVA	0.069	

From	To	2010	2015
Intra-EU pipelines cont’d			
LVA	EST	0.099	
LVA	LTU	0.027	
NLD	BEL	1.631	
NLD	DEU	2.448	
NLD	GBR	0.480	
POL	DEU	1.168	
PRT	ESP	0.134	
ROM	BGR	1.015	
ROM	HUN	0.000	
SVK	AUT	2.013	
SVK	CZE	1.592	
SVN	AUT	0.000	
SVN	ITA	0.035	
Pipelines towards Europe			
AFR	ITA	1.729	
AFR	ESP	0.430	0.740
CAS	ROM	0.000	
CAS	TUR	0.352	
MEA	TUR	0.519	
RUS	BGR	0.000	0.623
RUS	FIN	0.328	
RUS	DEU	0.000	2.247
RUS	LVA	0.216	
RUS	ROM	0.000	
RUS	BLR	2.260	
RUS	UKR	4.528	
RUS	TUR	0.661	
Rest of the world pipelines			
CAS	RUS	2.426	
CAS	ASP	0.204	1.634
MEA	ASP	0.000	
RUS	ASP	0.000	0.413
RUS	CAS	0.526	

From	To	2010	2015
Other intra-European pipelines			
BGR	MKD	0.031	
BGR	SRB	0.000	0.192
DEU	CHE	0.669	
FRA	CHE	0.273	
GRC	ALB	0.000	
HUN	HRV	0.253	
HUN	SRB	0.177	
ITA	CHE	0.778	
SVN	HRV	0.065	
ALB	HRV	0.000	
ALB	MKD	0.000	
ALB	MNE	0.000	
BLR	UKR	0.960	
MKD	KOS	0.000	
SRB	BIH	0.031	
SRB	KOS	0.000	
UKR	MDA	0.077	
CHE	ITA	0.775	
NOR	BEL	0.551	
NOR	DNK	0.000	
NOR	FRA	0.715	
NOR	DEU	1.644	
NOR	GBR	1.788	
BLR	LTU	0.245	
BLR	POL	1.400	
SRB	HUN	0.000	
UKR	HUN	0.792	
UKR	POL	0.221	
UKR	ROM	0.506	
UKR	SVK	3.939	
BGR	TUR	0.597	
TUR	BGR	0.000	
TUR	GRC	0.039	

If not stated otherwise, input values for 2015 are equal to those for 2010. Endogenous pipeline expansions in the first two periods are in general restricted to 20% of the existing capacity. Some exceptions are made for potential pipelines, which are already in the planning phase, with restrictions according to their projected capacities (e.g., Nabucco, South Stream and White Stream).

Table 6: Shipping distances between liquefiers and regasifiers (grey shaded area) and capacities of those

	NOR	AFR		ASP	MEA	NAM		RUS		SAM		capacity		
		_North	_West			_Atlantic	_Pacific	_Pacific	_Atlantic	_Pacific	_Atlantic	2010	2015	2020+
TUR	4.1	1.6	5.1	7.0	3.8	6.2	11.1	9.0	4.4	7.4	5.2	0.47	0.47	0.47
ASP	11.1	8.1	9.3	1.5	5.1	10.6	4.8	2.1	11.4	10.0	10.4	16.110	18.078	19.215
NAM_Atlantic	3.7	3.7	5.2	10.3	8.4	999	8.2	11.0	4.0	4.5	1.8	6.694	6.945	6.945
NAM_Pacific	8.5	7.5	10.1	7.9	11.3	999	2.2	4.8	8.8	3.7	6.2	0.397	0.571	0.571
SAM_Atlantic	6.4	4.4	3.3	8.4	8.2	5.1	10.2	11.6	6.7	4.9	3.1	0.405	0.799	0.799
SAM_Pacific	8.2	7.2	6.7	9.6	10.6	3.8	6.9	9.6	8.5	0.8	5.9	0.221	0.290	0.290
BEL	1.4	1.6	4.2	8.4	6.3	4.8	9.8	11.7	1.7	6.1	3.9	0.347	0.347	0.347
FRA_West	1.8	1.2	4.0	7.9	6.0	4.6	9.8	11.5	2.1	6.1	3.8	0.386	0.386	0.771
FRA_East	3.2	0.5	4.0	7.7	4.6	5.3	10.1	10.0	3.5	6.4	4.1	0.533	0.533	0.533
DEU	1.3	2.0	4.6	8.7	6.7	5.2	10.1	12.5	1.6	6.4	4.3	0.000	0.000	0.000
GRC	4.2	1.2	4.8	6.8	3.7	6.1	10.9	9.2	4.5	7.2	4.9	0.193	0.193	0.193
IRL	1.7	1.4	4.1	8.3	6.1	4.5	9.5	11.5	2.1	5.7	3.6	0.000	0.000	0.000
ITA	3.4	0.7	4.2	7.6	4.5	5.5	10.3	9.8	3.7	6.6	4.3	0.436	0.617	0.617
NLD	1.3	1.7	4.3	8.5	6.4	4.9	9.9	11.9	1.6	6.2	4.0	0.000	0.463	0.617
POL	1.5	2.2	4.8	9.3	7.0	5.5	10.5	13.0	1.8	6.9	4.5	0.000	0.193	0.270
PRT	2.4	0.6	3.3	7.3	5.3	4.4	9.7	11.0	2.7	6.0	3.2	0.201	0.277	0.277
ESP_Atlantic	2.0	0.4	3.3	7.2	5.6	4.6	9.6	11.3	2.2	5.8	3.6	0.409	0.409	0.409
ESP_South	3.3	0.4	3.8	6.8	5.1	4.5	10.0	10.1	3.6	6.2	3.3	1.451	1.451	1.451
ESP_Med	2.9	0.3	3.8	7.8	4.7	5.0	10.0	10.1	3.2	6.2	4.0	0.455	0.455	0.455
GBR	1.5	1.4	4.1	8.3	6.1	4.7	9.5	11.5	1.8	5.8	3.8	1.971	1.971	1.971
HRV	4.4	1.6	5.1	6.5	4.4	6.3	11.2	10.2	4.7	7.4	5.1	0.000	0.069	0.069
2010	0.259	1.995	1.537	5.096	5.574	0.000	0.082	0.578	0.000	0.268	0.911			
capacity 2015	0.259	1.995	1.780	5.355	5.574	0.233	0.000	0.578	0.000	0.268	0.911			
2020+	0.259	1.995	2.595	8.226	5.574	0.864	0.000	0.578	0.000	0.268	0.911			