A Global Perspective on the Future of Natural Gas: Resources, Trade, and Climate Constraints

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Introduction

Natural gas has the potential to facilitate the transition to a low-carbon energy system and society. Its combustion leads to fewer CO_2 emissions per generated energy unit than coal and oil.[1] Moreover, natural gas can be used to improve the reliability of electricity systems that rely on intermittent renewable resources because gas-fired power plants can be ramped up quickly and provide flexible generation schedules. Nevertheless, the role of natural gas in a future climate-constrained world remains uncertain because, in the absence of widespread use of Carbon Capture and Storage (CCS), its combustion causes substantial CO_2 emissions. In fact, in 2010, worldwide natural gas consumption induced more than 6 gigatons (Gt) of CO_2 emissions, 20 percent of all energy-related CO_2 emissions (IEA 2013a).

Thus far, only the European Union (EU) has started to develop decarbonization scenarios for its economy and energy sectors that extend to 2050 (EC 2011a, 2011b, 2013). Although the European Commission describes natural gas as being "critical for the transformation of the energy system," it projects a (slow) decrease in natural gas consumption (EC 2011b, 11).

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[1]According to the Intergovernmental Panel on Climate Change (IPCC 2006), on average, about 56 kg of CO_2 are emitted per gigajoule (GJ) of generated energy from natural gas. The emission factors for crude oil and coal (anthracite) are 73.3 kg CO_2/GJ and 98.3 kg CO_2/GJ, respectively. Note that these factors neither reflect emissions of greenhouse gases (GHG) other than CO_2 nor include CO_2 that is emitted indirectly during the extraction and refining process.

This differs from the view of the OECD's International Energy Agency (IEA), which foresees an increasing role for natural gas globally, and particularly in Europe, as a replacement for coal-fired electricity generation (IEA 2013a).

This article, which is part of a symposium[2] on *Prospects for Natural Gas in a Low-Carbon Context*, identifies key drivers and uncertainties for natural gas markets in the coming decades. These include the availability of natural gas, the role of international trade, and, in particular, the impact of climate policies. To this end, we adopt a global perspective and provide an extensive overview of worldwide natural gas resource potential. We find that an increase in natural gas consumption can be fueled by natural gas reserves in the ground, but that market developments will depend more critically on the demand side, which will be influenced by climate policies.

Natural gas has long been an energy source in industrialized countries (see Neumann and Hirschhausen 2015). In the final decades of the twentieth century, long-distance natural gas trade increased rapidly, and by 2011, about one-third of global natural gas production (1,033 out of 3,364 billion cubic meters (bcm)) was traded internationally (BP 2013).[3] The largest shares of current natural gas production occur in the United States (20 percent), Russia (18 percent), and the Middle East (16 percent). In recent decades, production levels in Africa, Asia, and Latin America have increased significantly, while production in Europe has leveled out.

Three recent changes regarding supply, transportation, and demand are particularly important for the international natural gas market. Most remarkably, natural gas production increased sharply (by 33 percent) in the United States between 2005 and 2012, following years of a slow decline (IEA 2013b). Technological innovations have drastically decreased the production costs of certain natural gas deposits, leading to this unprecedented boom in U.S. natural gas extraction.

The second major change in natural gas markets is the rising share of liquefied natural gas (LNG) in global trade. In 2000, only twelve LNG exporting countries traded a total of 137 bcm with ten LNG importing countries (BP 2001). By 2012, 22 exporting countries shipped about 320 bcm to 25 importing countries (IEA 2013b). Current expansions and construction plans suggest that this trend will continue, leading to a projected 50 percent increase in global liquefaction capacity between 2010 and 2020 (GIIGNL 2011, 2012).

The third major development is that the future of natural gas markets depends critically on Asia. Natural gas consumption in the Asia-Pacific region has increased sharply in recent years, both in absolute values and in terms of its share of the world market. Thus, Asia is replacing Europe as the focus of research on natural gas markets, particularly when examining the long term.

The remainder of the article is organized as follows. In the next section we examine global conventional and unconventional natural gas reserves and resources and show that they will not

[2]The other articles in the symposium are Neumann and Hirschhausen (2015), which introduces the symposium and examines short-term and long-term trends in natural gas pricing and geopolitics, and Makholm (2015), which discusses the regulation of natural gas in the United States, Canada, and Europe.
[3]Bcm is a unit of volume that is often used in the natural gas literature. Using an average conversion factor to calculate the energy content, world natural gas production corresponds to about 3,000 Mtoe (million tonnes of oil equivalent), which is equivalent to about 125 EJ (exajoule). Natural gas prices are generally expressed in USD/MMBtu, i.e., in US Dollars per million British thermal units. One MMBtu corresponds to roughly 28 cubic meters.

constrain natural gas demand growth. Next, using model-based analyses, we identify the main drivers of future global and regional natural gas markets under climate constraints. Then we discuss the supply and demand uncertainties that underlie the future role of natural gas, including resource availability, investments in production and transportation capacities, and political issues related to climate policy. The final section summarizes and concludes.

Global Natural Gas Resources and Reserves

According to the widely used methodology that is based on McKelvey (1972), the distinction between reserves and resources is determined by two factors: the "degree of certainty" and the "feasibility of economic recovery." Reserves are those natural gas deposits that have been identified and are economically recoverable at current prices using available production technologies. Resources, on the other hand, are those deposits that are not (yet) economically or technically recoverable and that may not even have been discovered. By definition, reserve and resource figures are constantly changing due to exploration activities, technological progress, price changes, and ongoing extraction.

Natural gas reservoirs exist where natural gas is sealed in porous rocks with impermeable structures. Such reservoirs are said to contain nonassociated, or dry, gas. Associated gas refers to the gas cap above the oil in an oil reservoir and to natural gas that, due to circumstances such as high pressure, is dissolved in the oil. Associated gas can be recovered as a by-product of oil production.

Similarly, the distinction between conventional and unconventional natural gas is not based on the final product but rather on the characteristics of the deposit. However, the distinction between conventional and unconventional gas is not clear-cut and is even "more blurred than that for oil" (Rogner et al. 2012, 451). Basically, unconventional natural gas is found in "unusual types of reservoirs" (IEA 2005, 26) with low permeability (cf. Rogner et al. 2012). Special technologies like horizontal drilling and hydraulic fracturing ("fracking") are necessary to make the production of such natural gas economic.

Depending on the geological formation, unconventional natural gas exists in the form of tight gas, shale gas, and coal bed methane (CBM).[4] Unconventional gas can also occur in the form of gas hydrates and aquifer gas, but natural gas from these sources has not yet been produced commercially. Additionally, Rogner et al. (2012) classify natural gas occurring in deep reservoirs as pseudo-unconventional gas because of the technical complexities associated with its extraction.

Traditionally, unconventional gas deposits have been classified as resources rather than reserves. Nowadays, however, unconventional gas production accounts for a significant share—about 18%—of global production (IEA 2013c) and more than 65 percent of U.S. production (EIA 2013a). This means that the traditional distinction between reserves and resources needs to be adjusted to reflect today's natural gas sector. One way of doing this would be to classify more unconventional gas deposits as reserves, as in fact, some studies have done (e.g., BGR 2013).

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[4]Rogner et al. (2012) provide concise definitions of the different types of natural gas deposits.

Table 1 Estimates of global reserves of natural gas by region, in tcm

Region	BP (2013)	BGR (2013)	EIA (2014)	IEA (2013b)		Mean	Mean share	Range (Max-Min)
				Cedigaz	OGJ			
North America	10.8	10.8	11.7	11.0	10.1	10.9	6%	1.5
South America	7.6	7.6	7.6	7.5	7.6	7.6	4%	0.1
Europe	3.9	4.3	4.2	5.0	4.1	4.3	2%	1.1
Commonwealth of Independent States	54.5	61.6	61.3	64.7	61.6	60.7	31%	10.2
Middle East	80.5	80.5	79.3	79.7	79.6	79.9	41%	1.2
Africa	14.5	14.6	15.5	14.7	14.6	14.8	8%	1.0
Asia-Pacific	15.5	16.8	14.3	17.0	14.5	15.6	8%	2.7
World	187.3	196.2	193.8	199.6	192.2	193.8	100%	12.3
R/P ratio	55	58	57	59	57	57		4
CO_2 content in Gt	399	418	413	425	410	413		26

Notes: R/P ratio: Reserves over production level in 2012 according to BGR (2013); CO_2 contents are based on default emission factors from IPCC (2006).

Recent Estimates of Global Natural Gas Reserves

In addition to industry studies (e.g., BP on an annual basis), national geoscience institutions, in particular, the U.S. Geological Survey (cf. USGS 2000, 2008) and the German Federal Institute for Geosciences and Natural Resources (cf. BGR 2013), publish global natural gas reserve estimates on an irregular basis. In the recent Global Energy Assessment, Rogner et al. (2012) review reports and statistics of natural gas reserves and resources published in the previous 15 years.

While there is some variation across these studies, on average, global natural gas reserves are estimated at around 200 trillion cubic meters (tcm; see Table 1). This is about twice as much as cumulative historical production (BGR 2013) and is sufficient for 60 years of production at the current rate. Interestingly, natural gas reserves have increased significantly over time: current BP (2013) estimates are more than 2 and a half times the amount reported in 1980, despite significant extraction. According to Rogner et al. (2012), this increase of reserves is due mainly to the reclassification of resources rather than from substantial new discoveries.

Table 1 summarizes recent estimates of natural gas reserves by region.[5] Most reserves are conventional sources; less than 3 percent are shale gas or CBM (BGR 2013). Natural gas reserves exist throughout the world but are highly concentrated in a few regions. By far the largest reserves are located in the Middle East (around the Persian Gulf) and in former Soviet states (particularly in Russia, but also in Central Asia). Together, the Commonwealth of Independent States (CIS) and the Middle East account for more than 70 percent of global natural gas reserves, with more than 50 percent in three countries alone: Russia, Iran, and Qatar. Much smaller reserves, although sufficient to sustain significant future production, exist in the Asia-Pacific region (particularly in Australia, China, Indonesia, and Malaysia), Africa (namely, in Nigeria and Northern Africa), and North America (particularly in the U.S.). Still smaller

[5]Most of the variation in the estimates in Table 1 can be explained by a recent downward revision in the BP (2013) estimate of natural gas reserves in Russia.

Table 2 Estimates of natural gas resource potential worldwide, in tcm

Source	Conventional	Unconventional				Total resources	RP/P ratio	CO₂ (Gt) content
		Tight Gas	Shale Gas	CBM	Subtotal			
Aguilera et al. (2014)	322	425	283	906	1,614	1,939	571	4,127
BGR (2013)	501	63	209	52	324	825	243	1,759
IEA (2013a)	468	81	212	50	343	810	239	1,727
Rogner (1997)	386	208	453	256	917	1,306	384	2,777
Rogner et al. (2012)	321*	211	392	245	848	1,170	345	2,493

Notes: RP/P: resource potential over production level in 2012 according to BGR (2013); CO₂ content calculations are based on default emission factors given by the IPCC (2006). Historical extraction is subtracted from conventional resources estimates in Rogner (1997) (i.e., cumulative production between 1995 and 2012 according to BP, 2013) and in Aguilera et al. (2014) (i.e., cumulative production according to BGR, 2013). Rogner et al. (2012) provide estimates of global deposits of "deep gas" of 200 tcm that are not included in this table.
*USGS (2008)

reserves exist in South America (particularly in Venezuela) and Western Europe (especially in Norway and the Netherlands).

Recent Estimates of Global Natural Gas Resource Potential

Table 2 presents estimates of the global resource potential (reserves + resources), divided into conventional and unconventional deposits. There is much greater variation in the estimates of unconventional deposits than in the estimates of conventional deposits. This is due to the different accounting and extrapolation methods used in the studies, as well as high uncertainty because exploration and large-scale production has just begun.

The estimates in BGR (2013) and IEA (2013a) are similar, with a conventional resource potential that is slightly higher and an unconventional and total resource potential that is significantly lower than in the other studies. In both studies, shale gas plays a more important role than tight gas or CBM. Rogner (1997) and the update in Rogner et al. (2012) estimate a higher global resource potential. The highest estimated resource potential is in Aguilera et al. (2014), who provide significantly higher estimates of global tight gas and CBM availability, due mainly to the statistical extrapolation method used for yet-to-be discovered resources.

Unconventional deposits are more widely distributed than conventional deposits. According to BGR (2013), the Asia-Pacific region and North America each hold a quarter of the unconventional resources and the CIS, Africa, and South America each hold around 15 percent. Table 3 presents estimates for the ten countries with the largest shale gas deposits. It is interesting to note that China, potentially one of the largest future natural gas consumers, is likely to have abundant shale gas resources. However, the range of the estimates reflects the great uncertainty about shale gas resource potential.

Natural Gas Abundance and Its Climate Implications

The estimates presented in Table 2 suggest that at current production levels, the global resource potential would suffice for at least 200 years, and as much as 600 years based on the highest

Table 3 Countries with the largest shale gas resources (ranked according to BGR, 2013), in tcm

Country	BGR (2013)	EIA (2011b)	EIA (2013b)
China	25.08	36.10	31.57
Argentina	22.71	21.92	22.71
Algeria	20.02	6.54	20.02
U.S.	19.11	24.41	32.88*
Canada	16.23	10.99	16.23
Mexico	15.44	19.28	15.43
Australia	12.38	11.21	12.37
South Africa	11.05	13.73	11.04
Russia	9.50	not assessed	8.07
Brazil	6.94	6.40	6.94

*The value for shale gas resources in the United States varies significantly across sources. In its *Annual Energy Outlook*, the EIA (2013a) presents an estimate of about 18 tcm.

estimate. This suggests that natural gas availability is plentiful, and that we cannot rely on a substantial (scarcity-driven) price increase to significantly reduce natural gas use and its related greenhouse gas emissions.[6]

This abundance of natural gas has mixed implications for climate mitigation efforts. On the one hand, there is enough natural gas to reduce carbon emissions by switching from coal to gas. On the other hand, the extraction of all natural gas deposits conflicts with ambitious climate targets. Tables 1 and 2 include estimates of total CO_2 emissions if global natural gas reserves and resource potential were to be completely combusted (without applying CCS). The CO_2 content of the natural gas resources potential (1,700 to 4,200 $GtCO_2$) is higher than the estimated global carbon budget (about 1,000 Gt of future CO_2 emissions) required to keep the global mean temperature increase below 2°C.[7] Natural gas reserves alone would emit more than 400 $GtCO_2$.

Hence, any sufficient limitations on natural gas use will have to come from the consumption side, through political action mandating a global CO_2 emissions cap or CO_2 emissions taxes. In the next section we discuss economic models of natural gas markets and other numerical exercises that can be used to inform the evaluation of alternative global climate policies.

Modeling International Natural Gas Markets

International natural gas markets have been the subject of economic research for several decades. Early work was driven mostly by the industry's need to support operational and strategic decisions and thus focused on cost minimization models. Beginning in the 1980s, with the rise of international trade and market liberalization efforts (mainly in the U.S. and the U.K., and later in the EU), the focus shifted toward industrial organization and supply security. More

[6]See Livernois (2009) for a discussion of the Hotelling Rule and the empirically low importance of scarcity rents in determining the price of nonrenewable resources.
[7]The IPCC (2013, p. 27) calculates the global carbon budget, i.e. cumulative emissions that will keep the increase in global mean temperature below 2°C (with probability larger than 66%), to be approximately 3,670 $GtCO_2$. Subtracting historical emissions and accounting for "non-CO_2 forcings," this budget reduces to about 1,000 $GtCO_2$. Combusting all reserves of natural gas, coal, and oil would lead to CO_2 emissions in the range of 3,000 Gt (cf. Meinshausen et al. 2009, p.1160).

recently, climate change has become a major focus of energy economics research, including natural gas market analyses.

Historically, natural gas markets have been dominated by long-term contracts with rigid delivered prices and volumes. These characteristics warranted the use of cost-minimizing operational and investment models in order to find the cheapest way to meet all contractual obligations. However, the modeling of imperfectly competitive natural gas markets, which are characterized by multiple profit-maximizing strategic agents requires advanced approaches such as equilibrium models.[8] Thus, numerical natural gas market models, which address game-theoretic behavior, started being used in the 1980s (e.g., Mathiesen et al. 1987; Golombek 1995). Concerns in North America about the security of supplies and market structure analyses of the (North) Western European natural gas market drove many methodological advances in equilibrium modeling.

Early Modeling Efforts

In 1986, the Massachusetts Institute of Technology (MIT) Center for Energy Policy Research conducted the first-of-its-kind survey of market trends in Western Europe, North America, and Asia with a focus on international natural gas trade (MIT 1986). The three separate regional studies reflected the fragmentation of the markets at the time. The recently deregulated North American market was still searching for the optimal regulatory framework for its interconnected pipeline market; Western European markets were in a comfortable supply position; and in Asia, only a few countries consumed natural gas, mostly imported as LNG under long-term contracts.

At about the same time, Stanford University's Energy Modeling Forum (EMF) organized one of the first academic working groups on natural gas markets, EMF no. 9, which examined North American markets (1986–1989; cf. Huntington and Schuler 1990). The focus was on supply and demand perspectives, in particular the substitutability of natural gas and oil.

Since then, natural gas market models have gradually been developed further, featuring increased time resolution, broader geographical coverage, and more detailed representation of the actors in the market. For the European markets, such models include GASTALE (Boots et al. 2004; Egging and Gabriel 2006; Lise et al. 2008), GASMOD (Holz et al. 2008), the European and World Gas Model (Egging et al. 2008, 2010), Columbus (Hecking and Panke 2012), and the Global Gas Model (GGM; Egging 2010, 2013; Holz et al. 2013). Gabriel et al. (2005) developed a similar model for the North American market.

Equilibrium Models

Gabriel and Smeers (2006) provided an overview of equilibrium models of natural gas markets, which followed an earlier assessment of the capabilities of such models by Smeers (1997). In particular, equilibrium models allow for the representation of several types of players into one model, when some players behave strategically. Modeling imperfect competition has been especially relevant for the monopolistic European and Asian natural gas markets and for the fragmented LNG trade. Between 2004 and 2008, EMF no. 23 brought together several modelers who used equilibrium and optimization approaches to investigate future global trade flows.

[8]This model class is also called mixed complementarity problems (MCP). See Facchinei and Pang (2003).

One common conclusion of these models was that natural gas markets have a strong resilience to supply shocks (cf. Huntington 2009).

An MIT (2011) study on the prospects for natural gas use employed a computable general equilibrium model to investigate the future role of natural gas in different sectors of the U.S. economy. This study accounted for the U.S. shale gas boom and was one of the first to specifically investigate the impact of climate policy on the natural gas market. In an extension of this study, Jacoby et al. (2012) showed that increased domestic production, stemming partially from shale gas, could help the United States reduce climate change mitigation costs, in particular costs related to early deployment of CCS. Moreover, Paltsev et al. (2011) emphasize the role of natural gas as a "bridge" fuel in the U.S. power sector and foresee slightly increasing natural gas consumption under a strict mitigation scenario.

Global Outlooks

Two organizations that regularly publish "outlooks" on the global natural gas market are the IEA and the U.S. Department of Energy's Energy Information Administration (EIA). The IEA has traditionally focused on supply side issues and provided one of the first comprehensive assessments of the perspectives and challenges of shale gas production on a global scale (IEA 2011, 2012b). In its *Annual Energy Outlook* (e.g., EIA 2013a), the EIA provides forecasts for energy supply and consumption in the United States; the EIA also projects global developments in energy markets in its *International Energy Outlook* (e.g., EIA 2011a), which is similar to the IEA's *World Energy Outlook*. It is important to note that in its reports, the EIA usually assumes less ambitious climate policies than the IEA and thus far has not provided a stringent climate scenario (EIA 2011a).

Modeling Uncertainty

Because of its ambiguous role in decarbonizing the energy system, the future of the global natural gas market is highly uncertain. Various models explicitly address uncertainty in natural gas markets by including stochastic parameters, often stochastic demand. Haurie et al. (1987) were the first to represent (oil price) uncertainty in an oligopolistic European natural gas market setting. Later, Zhuang and Gabriel (2008) developed a stochastic model of the North American market, and Egging (2010, 2013) developed a large-scale stochastic equilibrium model of the global natural gas market. Computational tractability is a major challenge for solving large-scale stochastic dynamic equilibrium problems because traditional decomposition approaches cannot be applied in a straightforward manner (Egging 2013).

Regional Trends and Global Trade of Natural Gas in a Climate-Constrained World

In this section we use one of the natural gas market models presented in the previous section—the GGM—to investigate the future role of natural gas in a climate-constrained scenario relative to a base case (both of which are based on projections by the IEA).

IEA Forecasts and Climate Scenarios

The *World Energy Outlook* (IEA 2012a) identifies various potential pathways for a future fuel mix in the energy system with two main scenarios: the New Policies Scenario (NPS) and the 450ppm scenario. The NPS assumes a moderate implementation of current plans and initiatives for climate and energy policies. Climate policies are concentrated in Europe and the OECD countries, where yearly CO_2 emissions in 2035 are significantly below 2010 levels. However, global CO_2 emissions increase further and are projected to be more than 20 percent higher in 2035 relative to 2010. This is because annual global primary energy demand is projected to increase by more than a third between 2010 and 2035, with the share of natural gas projected to increase slightly (from 21 to 24 percent).

In contrast, under the 450ppm scenario, climate policies are assumed to be implemented effectively and cooperatively, aiming at a global temperature increase of no more than 2°C. However, annual total primary energy demand is still projected to increase by 16 percent between 2010 and 2035. Nevertheless, due to a shift to less CO_2-intensive energy sources (renewables, in particular) and the deployment of CCS, CO_2 emissions per unit of generated energy are projected to decrease significantly. But total worldwide energy-related CO_2 emissions will continue to increase until about 2020, followed by a rapid decline in later years. As under the NPS, the most developed countries bear the brunt of the climate policy burden, but the rest of the world contributes to mitigation, too. In 2035, emissions from OECD countries are projected to be 45 percent below the 1990 level, while emissions from non-OECD countries will be above the 1990 level, but 12 percent below the 2010 level.

Driven mainly by demand in the Asia-Pacific region, worldwide natural gas consumption under both IEA (2012a) scenarios increases substantially between 2010 and 2035—although at a slower rate under the 450ppm scenario (+20 percent) than under the NPS scenario (+50 percent). Regional consumption and production levels differ significantly, both over time in each scenario and between the two scenarios, because of the different distributions of climate policy efforts. While under the NPS scenario, natural gas consumption increases in all regions, the picture is more diverse for the 450ppm scenario: here, consumption in Europe, Russia, and North America is lower in 2035 relative to 2010, with the Asia-Pacific region driving the worldwide increase. Consumption in the Asia-Pacific region grows the fastest under both scenarios, and by 2025 the region is even projected to surpass North America as the largest natural gas-consuming region.

The Global Gas Model and Climate Scenarios

In order to analyze more carefully some market-specific aspects of the IEA forecasts, and in particular to take a more detailed look at the natural gas sector—its trade flows as well as its infrastructure needs—we apply the Global Gas Model (see Egging 2013). The GGM is an equilibrium model for global natural gas production, consumption, and international trade representing the entire value chain of the natural gas sector (Egging 2010). It includes profit-maximizing players, both upstream and downstream (i.e., natural gas producers, traders, storage system operators, and transmission system operators) and assumes they all have perfect foresight. The model features a high level of detail, including seasonality in consumption, market power exertion by trading agents, and endogenous expansions of storage and transport

capacity of the pipeline network, as well as LNG liquefaction and regasification terminals. Because it ignores institutional friction, such as long-term contracts and oil-price linking, the model's results represent the cost-efficient long-term equilibrium in the presence of market power.

We constructed two scenarios in line with the two IEA (2012a) scenarios and analyze them using the GGM. Our baseline scenario ("Base") is comparable to the NPS and the demand path of our second scenario ("Climate") follows the 450ppm scenario. For our model runs, natural gas consumption reference values are based on IEA (2012a) and combined with supply side information, including production capacities and cost considerations from additional sources.

We used a detailed data set that covers 74 countries, represented by 94 nodes.[9] This level of detail is considerably more disaggregated than the IEA (2012a) data set and allows us to analyze both intraregional and inter-regional trade flows. The base year is 2010 and the results are reported for every fifth year (2015, 2020, 2025, and so on) until 2040.

Global and Regional Results

The model results indicate that under the Climate scenario, despite lower global natural gas consumption, volumes of global inter-regional trade are slightly higher than in the Base scenario up to the year 2035. Under both scenarios, global natural gas trade more than doubles between 2010 and 2040. However, regional import and export balances differ substantially between the scenarios, with a marked shift to the Asia-Pacific region, particularly under the Climate scenario (see Figure 1). Under both scenarios, in every year, the EU and Asia-Pacific region together account for more than 96 percent of total global imports.

While natural gas consumption increases in all regions under the Base scenario, the picture is more diverse for the Climate scenario. Here, the consumption levels in Europe, Russia, and North America are lower in 2040 compared to 2010, with the Asia-Pacific region driving the worldwide increase. Consumption grows the fastest in the Asia-Pacific region in both scenarios, surpassing North America by 2025. Under both scenarios, natural gas production remains highest in North America over time but increases sharply in the Asia-Pacific region, especially in China and Australia (see Figure 2).

The EU and the Rest of Europe

Although in the Base scenario, consumption growth in the EU is relatively modest, the EU's net import position increases sharply due to declining domestic production, consistent with the trend in recent decades.

By 2040, among EU countries, only the Netherlands will still produce significant volumes of natural gas; Norway, which is in the Rest of Europe, will also continue to be a large producer. Not surprisingly, the EU's increased import dependency is more pronounced in the Base scenario (net imports of 565 bcm in 2040) than under the Climate scenario (net imports of 367 bcm). The traditional import patterns of Europe will largely persist. That is, pipeline transportation will predominate over LNG imports, and Russia will remain an important EU supplier (about 120 bcm in 2040), albeit with a declining market share. The increasing

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[9]The list of countries included in the data set, as well as their regional assignments and respective abbreviations, is presented in Appendix Table 1.
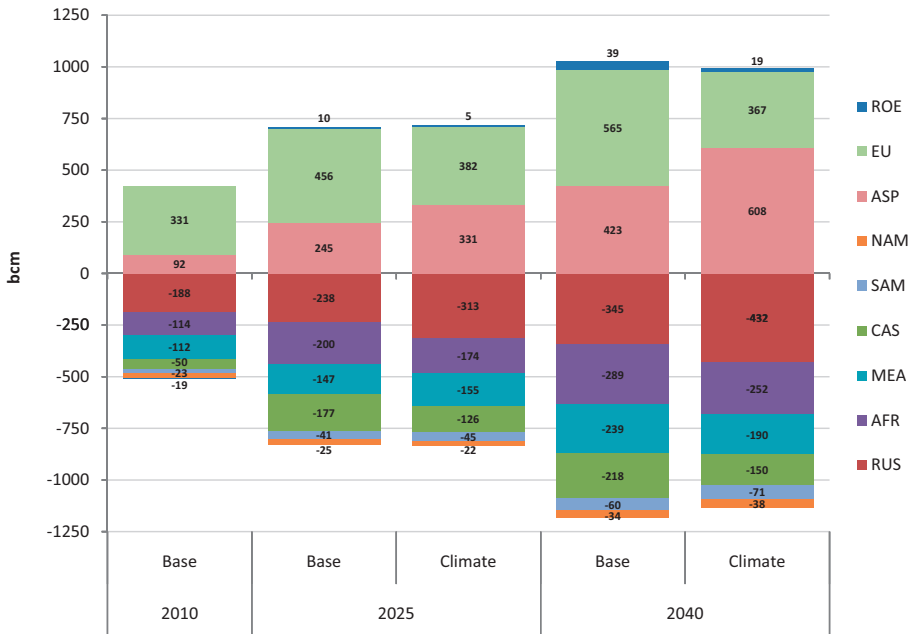
Figure 1 Regional natural gas supply balances under GGM scenarios, in tcm
Note: Positive values reflect net imports; negative values reflect net exports. Differences in the aggregates are due to transportation losses. The abbreviations of the regions are explained in Appendix Table 1.
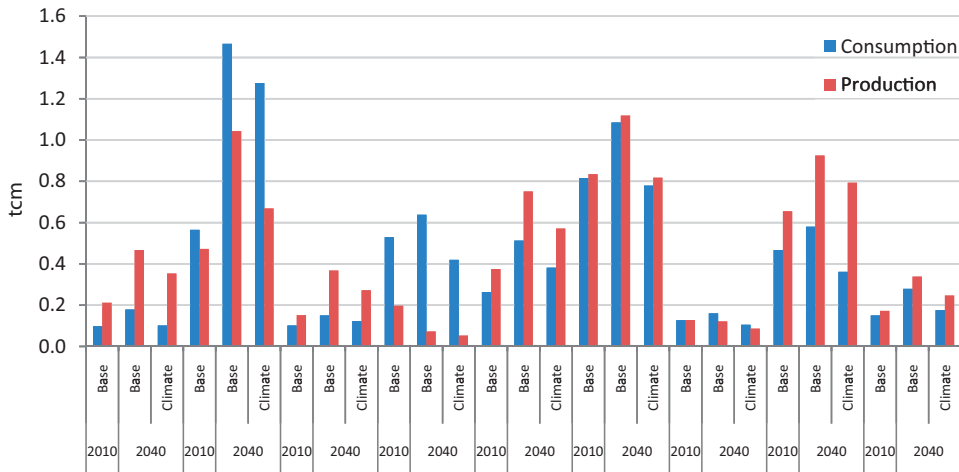*Source*: Authors' numerical analyses using the GGM.

Figure 2 World gas consumption and production by region and scenario in 2010 and 2040, in tcm
Source: Authors' numerical analyses using the GGM.

share of supplies to the EU from North Africa and the Caspian region would require construction of new transportation infrastructure from these regions.

The Asia-Pacific Region

Although the Asia-Pacific region is composed of heterogeneous countries, the model results indicate that all will face rapidly rising natural gas demand, regardless of climate change

mitigation efforts. Natural gas production will also grow (particularly in China and Australia), although at a lower rate than consumption. Under the Climate scenario, after 2030, the Asia-Pacific region becomes the world's largest import destination of natural gas, with an import dependency above 40 percent. Due to the dramatic increase in its market size, the region's share of world natural gas trade will grow from 22 percent in 2010 to 41 percent or 61 percent in 2040 under the Base and Climate scenarios, respectively. Under the Climate scenario, the Asia-Pacific region represents a third of world demand in 2040, almost doubling from 18 percent in 2010. There will also be considerable intraregional trade flows in the Asia-Pacific region as there are some major LNG exporters in the region, and they will focus on meeting the region's demand. Australia's natural gas production doubles (Climate scenario) or even triples (Base scenario) between 2010 and 2040, with most of it exported as LNG. Other traditional LNG suppliers such as Brunei, Malaysia, and Indonesia will also continue to play an important role in meeting the region's LNG demand.

China, in particular, will see further growth in its natural gas production over the next decades, based largely on unconventional gas in the form of CBM or shale gas. However, domestic production will not be sufficient to meet demand. China started importing LNG in 2006 and has been rapidly increasing its regasification capacity. It may surpass Japan as the largest Asian LNG importer as early as 2020. In addition to LNG imports (predominantly from Australia and the Middle East), China will seek pipeline imports from Russia and Central Asia. More than half of China's natural gas imports in 2040 are projected to come by pipeline from its northwestern neighbors.

Russia, Caspian Region, and Central Asia

All major exporting regions are projected to significantly increase their net exports under both scenarios. Russia, the Caspian region, the Middle East, and Africa together account for about 90 percent of global inter-regional exports in all years. Although Europe has traditionally been the main destination for natural gas from Russia and the rest of the former Soviet Union, the booming Asian market will be an important new market in the medium and long term (see also Paltsev 2014). Even though the former Soviet Union depends almost completely on Europe for its exports today, under the Base scenario, only about half of Russian and Caspian exports will go to Europe by 2040; the rest will be directed mostly to Asia. Due to lower European demand, this trend is even more pronounced under the Climate scenario, where Asian demand becomes relatively more important and Europe accounts for only 42 percent (27 percent) of Russian (Caspian) exports.

The Middle East

The Middle East has been the world's traditional hydrocarbon supplier and, as discussed earlier, has the largest conventional reserves of natural gas. In particular, Qatar is and will likely remain the region's largest natural gas exporter. It continues to export about 80% of its natural gas production and is the largest LNG exporter worldwide (almost 100 bcm in 2011). Iran will be able to increase its production if international sanctions are removed, but it is projected to export only small amounts due its sustained domestic demand. The Middle East will intensify its exports to Asia in the future (as climate policies are adopted in other regions), especially to India, but also to its traditional destinations—Japan and South Korea.

Africa

Africa currently produces natural gas in the North and the West, and there are prospects for development in the Southeast. Exports from the North go mainly to Southern Europe and are delivered by pipeline or LNG via the Mediterranean Sea. The major producer in West Africa is Nigeria, but recently some smaller producers such as Equatorial Guinea and Cote d'Ivoire have started to enter the world market. Mozambique and Tanzania in Southeast Africa are also planning to export LNG.

North America

The United States is currently the world's largest natural gas producer and will likely maintain this position until 2040 (see Figure 2). Unconventional sources will play an important role in the U.S. natural gas sector, driving further expansion of production capacity from roughly 600 bcm in 2010 to more than 800 bcm after 2030 under the Base scenario. The development of shale and other unconventional gas in North America will potentially allow for LNG exports. However, similar to the IEA (2012a, 2012b) forecasts, our Base scenario results indicate only modest North American LNG exports. Under the Climate scenario, North American net LNG exports increase to almost 50 bcm in 2025 before leveling out at around 20 bcm in later years. The strong increase in unconventional production in North America is absorbed mostly by the domestic market, contributing to a stabilization of greenhouse gas emissions from North America as the region shifts from coal to natural gas.

South America

South America becomes an increasingly important natural gas supplier globally, with net exports in 2040 of 60 bcm under the Base scenario and 71 bcm under the Climate scenario, all via LNG. Historically, the region was more or less self-sufficient in natural gas but became a net importer in recent years. However, with new conventional and unconventional reserves (e.g., deep-sea offshore Brazil, shale gas in Argentina) production capacity is projected to significantly increase in the next few decades. Natural gas exports to other regions are now mostly from Trinidad and Tobago but will increasingly come from Venezuela, Bolivia and, eventually, Brazil.

Infrastructure Development

The projected increase in global trade volumes and the shift toward the Asia-Pacific region will require the development of new infrastructure. Particularly in China and India, the increase in natural gas imports will need to be facilitated by pipeline and regasification expansions. Worldwide, there are many construction plans for natural gas transportation infrastructure. In fact, pipelines currently under construction amount to about 13 percent of the existing global capacity in 2010; liquefaction capacity will increase by 50 percent and regasification capacity by 25 percent if current expansion plans are actually implemented (GIIGNL, various issues).

In addition to these planned expansions, the GGM identifies infrastructure projects that are economically viable. Figure 3 shows projected cumulative import capacity expansions by origin and destination region until 2040. While in the Base scenario, capacities are expanded by approximately 1,000 bcm (24 percent of the aggregate 2010 capacities), expansions under the
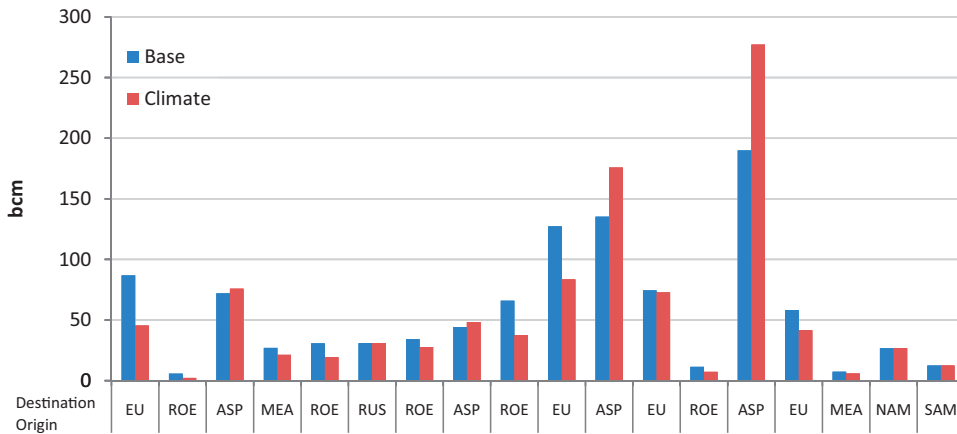
Figure 3   Worldwide inter-regional natural gas import capacity expansions (pipelines and regasification) until 2040 by origin and destination, in bcm
Source: Authors' numerical analyses using the GGM.

Climate scenario reach only 700 bcm (17 percent). In particular, there is significantly less expansion of pipelines toward the EU under the Climate scenario due to the lower natural gas consumption associated with an ambitious climate policy; Asia-Pacific is the only region where pipeline expansions are higher under the Climate scenario than under the Base scenario.

Interestingly, total expansions in the LNG chain are significantly higher in the Climate scenario, indicating the major shift of exports toward Asia, where it is easier to land LNG than pipeline gas. In contrast, the cumulative expansion of pipelines is significantly lower in the Climate scenario than in the Base scenario.

Price Projections

The equilibrium modeling approach computes price-quantity pairs for each year, season, and market. However, because of the need to make assumptions about production costs, it is important to be careful not to interpret the price results as "forecasts". Rather, price developments over time and the relative prices between regions provide useful insight about relative market developments under the different scenarios. Figure 4 shows projected natural gas prices in some major regions and countries between 2010 and 2040. There is a clear segmentation of regions, with producing and exporting regions facing low price levels (e.g., Russia, Middle East, U.S.) and net importing regions facing high price levels (e.g., EU, Japan, China).[10] Nominal prices in consuming regions could reach 20 U.S.-$/MMbtu by 2040, while in exporting regions prices will remain below 13 U.S.-$/MMbtu.

Figure 4 indicates no price convergence between the two groups of regions over time. Interestingly, however, Brazil, which is projected to shift from net importer to net exporter, moves from one group to the other and experiences stabilization and even a reduction in its

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[10]We have assumed an annual 2.75 percent increase in reference prices and costs in all regions. The endogenous model prices can deviate from the reference prices, which are an input to the demand functions of each market.
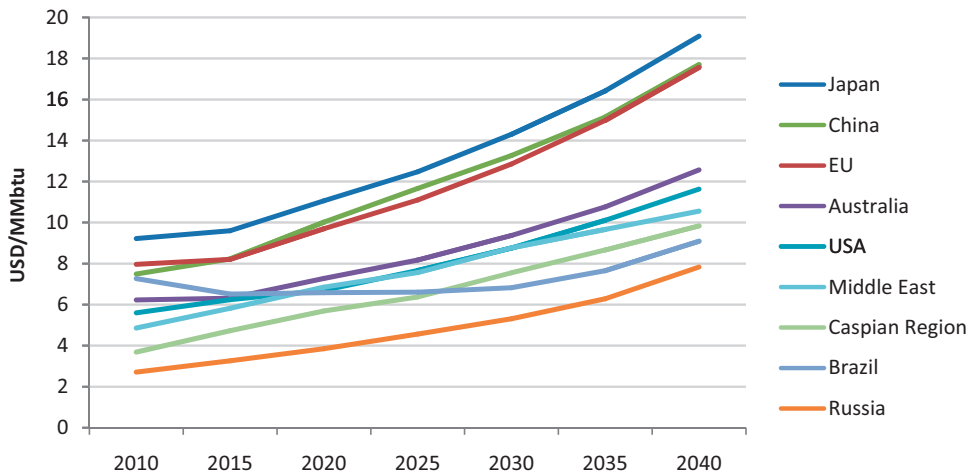
Figure 4 Regional natural gas price developments in the Base Scenario, in USD/MMbtu
Source: Authors' numerical analyses using the GGM.

natural gas price, since it will no longer have to rely on suppliers exerting market power to meet domestic demand. The relative difference in prices between the two groups is constant over time (e.g., Japanese prices are constantly about 1.6 times the U.S. prices); however, the absolute level of the price difference visibly increases (from 3.6 to 6.3 USD/MMbtu between Japan and the U.S.).

It is also important to note that these model results are for a long-term equilibrium, which does not take into account short-term constraints and shocks. For instance, in the years since the Fukushima disaster, the actual price difference between Japan and the United States has been considerably higher than projected by the model because of the rise in Japan's LNG demand (IEA 2013a).

The Uncertainties Ahead

Our discussion of future trends in global natural gas markets has focused on two climate policy scenarios. However, there are many uncertainties that may affect the future energy system in general and the role of natural gas in particular. These uncertainties can be broadly divided into those affecting the supply side and those affecting the demand side of natural gas, with the latter depending critically on policy decisions including climate change mitigation efforts.

Supply Side: Globally Plentiful but Locally Insecure

As discussed earlier, the physical availability of natural gas is not likely to constrain its future use. The resource base is broad and is adequate to sustain the current production level for the next several decades. However, the regional supply allocation does not match the regional demand distribution; thus transportation will continue to play a vital role in the constant necessity of bringing natural gas to end users (IEA *World Energy Outlooks* various editions; Rogner et al. 2012). Thus, it is essential to continue to make sufficient and timely investments in

natural gas production and transportation infrastructure in order to bring new production sites online. In some regions these investments could be constrained in the short-term by inefficiencies and lack of financial resources, for example, in Russia (Stern 2009), Central Asia, and Africa (IEA 2013c).

Constraints on Unconventional Natural Gas

The widespread distribution of unconventional sources may reduce the divergence between regional supply and demand in the future. As noted earlier, global unconventional natural gas deposits can be found in many major (future) demand regions, particularly in China. However, environmental concerns, technical complexity, and an uncertain recoverable potential may hamper large-scale production of unconventional gas in regions other than North America. The production of unconventional gas is water-intensive, and according to Hu and Xu (2013), water scarcity is a major obstacle to the development of China's shale gas deposits. In Europe, high expected production costs and environmental concerns have led to low expectations for unconventional natural gas production (IEA 2013c). In fact, France, Bulgaria, the Czech Republic, and the Netherlands have enacted (temporary) bans.

While the IEA speaks of a looming "golden age of gas," it also emphasizes that a number of "golden rules" need to be put in place before unconventional natural gas is produced on a large scale (IEA 2012a, 2012b). These rules are related to environmentally sound technology regulation and investor-friendly energy market regulation.

Moreover, the outlooks from the IEA (2013a) and the EIA (2013a) are based on uncertain estimates of resource availability and costs of unconventional gas production. For instance, in the United States, a continued boom in shale gas production is not guaranteed (cf. Richter 2015). There is also uncertainty concerning the export potential (economic, technical, and regulatory) of the United States and Canada, and the willingness to pay of European and Asian consumers for North American LNG when other (conventional) natural gas deposits, such as those from the Middle East, are more easily available.

In the very long term, natural gas reserves could be substantially extended if gas hydrates become economically recoverable. According to Rogner et al. (2012), the energy content of economically recoverable gas hydrate potential may be of the same order of magnitude as the estimated global conventional gas resource potential; the technical potential is 15 times higher. Although this type of natural gas is not yet commercially extractable, Japan and Canada are carrying out research that has led the IEA to suggest that the "next revolution-in-waiting" may be upon us in a few decades (IEA 2013a, 119).

Political Factors

Political tensions (e.g., in the Middle East, North Africa or between Russia and Europe) may also cause short-term supply bottlenecks by affecting the production and transportation of natural gas. However, several model-based studies (e.g., Lochner and Dieckhöner 2012, on Libya's production disruption in 2011, and Richter and Holz (2014) for disruption scenarios of Russian exports to Europe) have shown that regional markets like Europe, as well as global supplies, are flexible and resilient enough to compensate for (modest) short-term disruptions because of the large number of exporters available (Huntington 2009).

Nevertheless, longer-term (i.e., more than a few months) or larger-scale disruptions would require adaptation of the transportation infrastructure, particularly in pipeline-based markets such as Europe.

Demand Side: Uncertainty of Interfuel Competition

Uncertainty on the demand side of natural gas is determined primarily by political decisions. In particular, the future global energy system will be framed by international climate change mitigation efforts. However, it remains uncertain whether an international climate treaty will be reached, and if it is, what its targets will be. The relative costs of various technology options will determine the future energy mix, including the role of natural gas. Among the most influential factors is the price of CO_2 emissions, although relative costs are also affected by innovations and support schemes for renewables. Moreover, public acceptance will play a vital role in determining the future of technologies such as nuclear power generation, CCS, and the large-scale use of renewables. These technology types are the main low-carbon alternatives to natural gas that play an important role in the IEA (2012a) 450 ppm scenario projections. However, while increasing CO_2 prices may stimulate the use of these technologies, their overall potential and the necessary political and public acceptance are uncertain.

It is also unclear how natural gas would be affected given the 2°C target if both nuclear and CCS were used only on a small scale. On the one hand, natural gas consumption would be encouraged at the expense of coal and oil, the more carbon-intensive fuels. Moreover, additional renewable energy capacity in the global energy system would require flexible balancing capacity, which can be provided by natural gas-fired power generation. On the other hand, without the availability of CCS the potential for fossil fuel combustion would be reduced leading to a decrease in natural gas consumption.

Uncertainty of the Climate Impacts of Natural Gas

The uncertain climate impact of using natural gas derives from two major issues related to its main component: methane.[11] On the one hand, the global warming impact of methane depends on the trade-off between its higher greenhouse gas potential and its shorter lifetime in the atmosphere relative to CO_2. On the other hand, it is unclear how much methane is actually released along the natural gas supply chain, particularly from unconventional gas production. This is because in upstream production, more or less emission-intensive well-completion techniques can be used. The higher the proportion of natural gas being vented, the more emission-intensive the natural gas production becomes. Various techniques such as flaring, or capturing and then selling the natural gas, lead to substantially lower GHG emission factors (cf. O'Sullivan and Paltsev 2011).

Howarth et al. (2011, 2012) calculate that when leaked methane—in addition to direct emissions during combustion—is considered, GHG emissions per energy unit of shale gas may be higher than those from coal. If this is indeed the case, then unconventional natural

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[11]See WRI (2013) and AEA (2012) for comprehensive discussions of this issue.

gas would have no beneficial properties for climate change mitigation and would not contribute to the transition to a low carbon energy system. On the other hand, Cathles et al. (2011), O'Sullivan and Paltsev (2012), and others argue that the role of venting is overestimated. Similarly, Allen et al. (2013) find that methane emissions from selected U.S. unconventional production sites are lower than those found by earlier studies. This suggests that methane emissions could be significantly reduced with adequate regulation (i.e., by mandating the capture of leaking methane).

Summary and Conclusions

The future role of natural gas in a low carbon energy system is uncertain. Natural gas could serve as a bridging fuel during the transition phase; its role could increase together with an increase in (intermittent) renewable electric power generation; or its use could gradually decline under increasingly stringent climate policies as it is replaced by emission-free alternatives. Moreover, the prospects for natural gas are likely to vary by region.

Given the global abundance of natural gas, the future of natural gas depends on demand choices, the evolution of alternative fuels (like renewable energies), and, most importantly, political decisions that frame economic behavior. It is unclear whether a globally coordinated effort to mitigate climate change will occur, and, if it does, to what extent CO_2 emissions will be limited.

We have explored the implications of two climate scenarios for natural gas markets: a moderate global climate policy that is accompanied by a strong increase in global demand for natural gas, and a more ambitious global climate policy characterized by a moderate increase in global consumption, but decreasing demand in traditionally large consuming regions like Europe and North America.

We have found that regardless of the magnitude of climate policy efforts, the major trend in natural gas markets will be a growing demand in Asia, particularly in China. Even if China participates in climate mitigation efforts, its natural gas consumption is projected to further increase due to its growing energy demand. Asia will replace Europe as the dominant force in international natural gas trade; it will also surpass the current importance of the North American market, and will influence global trade in several ways. First, the share of internationally traded natural gas directed to Asian markets will rise. Second, the share of LNG in international trade will increase. In contrast to the European market, the long distances and lack of a land connection to some major exporters (e.g., Middle East, Australia) makes LNG the preferred transport option in most Asian markets. Finally, the growing Chinese market will strengthen Russia's role in supplying natural gas to the world market, particularly if strict climate policies are implemented.

As illustrated by the recent unexpected rise of unconventional natural gas production in North America, which was unforeseen less than a decade ago, the future development of global natural gas markets is hard to predict. Prominent uncertainties include the role of unconventional production, costs and reserves, the demand development that is linked to climate policies, and the political support for alternative fuels, be they renewables or coal. Regardless of these uncertainties, we expect the future of natural gas to be framed by strong demand in Asia and a further increase in LNG trade.

Appendix Table 1 Countries included in the GGM and assignment to model regions

European Union (EU)	**North America (NAM)**	**Asia-Pacific (ASP)**
Austria	Canada	Australia
Baltics	Mexico	Bangladesh
Belgium	United States	Brunei Darussalam
Bulgaria		China
Croatia	**South America (SAM)**	India
Czech Republic	Argentina	Indonesia
Denmark	Bolivia	Japan
Finland	Brazil	Korea
France	Chile	Malaysia
Germany	Colombia	Myanmar
Greece	Peru	Pakistan
Hungary	Trinidad & Tobago	Singapore
Ireland	Venezuela	Taiwan
Italy		Thailand
Netherlands	**Africa (AFR)**	Vietnam
Poland	Algeria	
Portugal	Angola	**Middle East (MEA)**
Romania	Egypt	Iran
Slovak Republic	Equatorial Guinea	Iraq
Spain	Libya	Kuwait
United Kingdom	Mozambique	Oman
	Nigeria	Qatar
Rest of Europe (ROE)	South Africa	United Arab Emirates
Belarus	Tunisia	Yemen
Norway		
Serbia	**Caspian Region (CAS)**	
Switzerland	Azerbaijan	
Turkey	Kazakhstan	
Ukraine	Turkmenistan	
	Uzbekistan	
	Russia (RUS)	

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