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Cartelization in gas markets

Studying the potential for a "Gas OPEC"

Abstract:
Natural gas is increasingly important as a fuel for electric power generation as well as other uses due to its environmental advantage over other fossil fuels. Using the World Gas Model, a large-scale energy equilibrium system based on a complementarity formulation, this paper analyzes possible future gas cartels and their effects on gas markets in a number of regions across the world. In addition, scenarios related to lower transport costs and decreased unconventional gas supply in the United States are considered.

Keywords: natural gas, market equilibrium, complementarity model, energy

JEL classification: Q41, D43

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1. Introduction

Natural gas markets are currently in the process of dramatic changes, such as globalization of these markets (EMF, 2007; Huntington, 2009), rising shares of LNG trade and spot contracts (WEO 2008, IEA), and, last but not least, a substantial increase in the prospects of unconventional gas supply (Potential Gas Committee, 2010). These changes will alter the playing field for natural gas producers worldwide, and one particular question is whether cartelization in the international gas markets may arise and if so, what kinds of impacts it may have.

In 2001, the Gas Exporting Countries Forum (GECF) was founded in Tehran, as an international body representing the interests of gas-producing nations. Ever since, there have been regular speculations about whether GECF would turn into a gas cartel like OPEC, i.e., a so-called gas-OPEC (Hallouche, 2006; Jaffe and Soligo, 2006; Wagbara, 2007). GECF consists of 11 member countries, including the three biggest in gas reserves: Russia, Iran and Qatar. It also has member countries in Africa and Latin America.[1] Together, in 2009, GECF accounted for 64% of remaining gas reserves, 34% of current gas production, and 41% and 54% of current pipeline and LNG export, respectively (BP, 2010).

The mission of GECF is to "identify and promote measures and processes necessary to ensure that Member Countries derive the most value from their gas resources", and to "promote the appropriate dialogue among gas producing and consuming countries to ensure (…) fair pricing for both producers and consumers" (www.gecforum.org). This mission can be interpreted in various ways, and recent statements from different member countries show disagreement about issues like coordinated supply cuts.[2] Currently, however, the two most important member countries Russia and Qatar seem reluctant to such suggestions.[3]

Russia, Iran and Qatar together hold about half of the world's remaining gas reserves, and their positions will obviously determine whether GECF will turn into an effective gas cartel or not in the years to come. More generally, the effectiveness of any gas cartel (GECF or not) will depend on the

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[1] The current members of GECF are (in descending order of reserves): Russia, Iran, Qatar, Nigeria, Venezuela, Algeria, Egypt, Libya, Bolivia, Trinidad and Tobago, and Equatorial Guinea. In addition, there are two observing members, Norway and Kazakhstan. (Source: www.gecforum.org, accessed June 2, 2010).

[2] For instance, prior to the GECF meeting in April 2010, Algeria called for coordinated cuts of gas production by GECF members, but this was not agreed upon at the meeting (WGI, 2010).

[3] Although Iran has somewhat bigger gas reserves and production than Qatar, its gas consumption is large and currently at the same level as its gas production, implying that Iran is not a net exporter of gas at the moment. This could change in the future if Iran manages to increase its production and export capacity.

decisions made by these countries. Both Russia and Iran are also big consumers of natural gas, and it is not in the interest of these countries to raise their *domestic* gas prices above their alternative costs of gas. Thus, what is relevant here is their exports of gas and how export cuts may influence on export profits. Furthermore, this could free up more gas supply for domestic consumers, possibly reducing gas prices within GECF countries.

The question analyzed in this paper is how a potential cartelization of international gas markets could affect these markets in the coming decades. We first consider a gas cartel consisting of the GECF member countries. Then we expand the cartel to also include the Caspian region and subsequently the rest of the Middle East, too. Our aim is to investigate whether such a cartel could significantly alter regional gas prices and production/consumption. Additionally, to what degree the cartel members may benefit from cartelization is examined. The answer to the latter question may be important for the likelihood of a future gas cartel.

Some gas consumers are concerned that a gas cartel will become as effective as OPEC has been in the crude oil market, resulting in higher gas prices due to curtailed production. Comaparing GECF to OPEC, there are both similarities and differences to be aware of. First, Middle Eastern countries are central in both organizations. However, whereas Saudi Arabia is the dominant country in OPEC, Russia is the most important country in GECF (see discussion of Russia and "gas-OPEC" in Finon, 2007). Second, both GECF and OPEC have a majority of remaining global reserves, and a large but not majority of global production. Third, the gas market has some important characteristics that differ from the oil market, which affects the impacts and likelihood of cartelization (see below). Finally, OPEC did not play a significant role in the oil market the first decade after it was founded, and now GECF is heading towards its 10-year anniversary.

One important difference between the oil and gas markets is that transport costs are much higher for gas than for oil. As a consequence, it has been more common to talk about regional gas markets than a global gas market. In addition, gas sales in Europe and Asia have been dominated by long-term contracts, with only a small share of spot sales. Similar market structure is true also in the United States where long-term contracts dominate over spot market sales. Volumes of LNG purchased in spot market are low but show relative increase in market share. In 1987 the share of international LNG trade was 1.5% while in 2002 it increased up to 8% (Britoand Hartley, 2007) The current trend, however, is towards a more globalized gas market with more spot sales, partly due to lower costs of LNG transport over the last decade. Nevertheless, the significant transport costs have some important implications for the cartelization issue. First, it presumably implies that the effects of cartelization will differ across regions, as regional prices will differ because of the transport costs. For instance, the U.S. market is located further away from most GECF countries than the European and Asian markets. Furthermore, the United States is no longer expected to import significant amounts of gas in the coming decades, which was the common thinking a few years ago (see below). Thus, we should expect less impact in the U.S. market than in the European and Asian markets.

Second, the gains from cartelization will not only depend on the total cut in supply from the cartel as a whole, but also how much each member country cuts back. For instance, it could be the case that it is optimal for the cartel as a whole that one member cuts back its production substantially whereas another member hardly at all, if they export gas to different regions. Clearly, this makes it more challenging to share the cartel benefits compared to in the oil market, where OPEC's total revenues are more or less unaffected by which member country cuts back on supply.[4] If transfers of profit are difficult to agree upon, divergence of interests among cartel members could put an additional restriction on the cartel's optimal behavior. Thus, several authors have argued that effective cartelization in the gas market may not be readily accomplished (Energy Business Review, 2005; Finon, 2007; Finon and Locatelli, 2008). Others have argued against this, positing that the natural gas "troika" composed of Russia, Iran, and Qatar could "produce more natural gas at a much cheaper cost for the U.S. market, effectively shutting down the Barnett Shale and other similar resource plays" (Fort Worth Business Press, 2008).

The likelihood of a gas cartel obviously depends on how the gas market develops over the next years and decades. Here it is important to emphasize two important drivers for the future gas market, unconventional gas and gas transportation, and to investigate how sensitive the impacts of cartelization may be to the development of these two factors.

Recently, the role of unconventional gas has greatly increased due to engineering advances such as hydraulic fracturing and horizontal drilling (NPC, 2007).[5] The projected role of shale gas in particular, especially in the United States but also elsewhere (Skagen, 2010), has lately been a major force in the increasing prominence of unconventional gas. In 2008, Cambridge Energy Research Associates indicated that this unconventional gas production could help delay by a decade the United States' need

[4] Of course, different costs of extraction can imply that it is more profitable for the cartel as a whole that the high-cost producers cut back (this applies to both gas and oil).

[5] Unconventional gas is defined as gas from tight sands, coalbed methane, and gas shales, and covers more low-permeability reservoirs that produce mostly natural gas (no associated hydrocarbon liquids) (NPC, 2007).

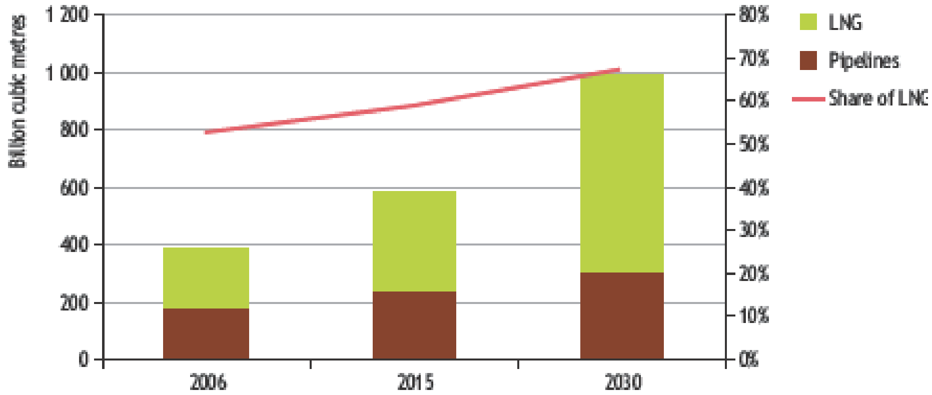
for substantial LNG imports (The Economist, October 4, 2008). Indeed, the Potential Gas Committee has concluded that the United States proved reserves of gas increased from 2006 to 2008 by a huge 35.4% from 43,387 to 58,739 billion cubic meters (Potential Gas Committee, 2010).Others such as the petroleum geologist Art Berman are more cautious about the ultimate supply due to the economics of producing shale gas (Cohen, 2009) or steeper decline rates for shale wells (Steffy, 2009). Additionally, there are also environmental risks with drilling for shale gas having to do with elevated levels of benzene in the water (National Public Radio, 2009ab) potentially due to the fracturing process for shale gas. These environmental considerations may inhibit future shale production. Indeed, the U.S. Congress has introduced two bills to "require the energy industry to disclose the chemicals it mixes with the water and sand it pumps underground in the fracturing process, information that has largely been protected as trade secrets." (Propublica, 2009)

These bills could have wide-ranging effects on the gas industry.

This rise in unconventional gas should be contrasted with a similar anticipated large increase in liquefied natural gas (LNG) trade worldwide. In order to reach demand regions often far from the supply location gas must be shipped by pipeline or increasingly as LNG. As indicated in Figure 1, LNG's share of inter-regional gas trade is anticipated to rise, with the International Energy Agency forecasting that more than 60% of internationally traded natural gas will be shipped as LNG by 2030 (WEO 2008, IEA). The increase in LNG trade observed over the last couple of decades is partly due to cost reductions in liquefaction and shipping during the 1990's and a few years into the new century (see for example, Jensen, 2004). Since then, LNG costs have risen along with the general cost increase in the energy sector. If transportation costs should start to decline again, relative to other supply costs, the international gas market may become more integrated than today.

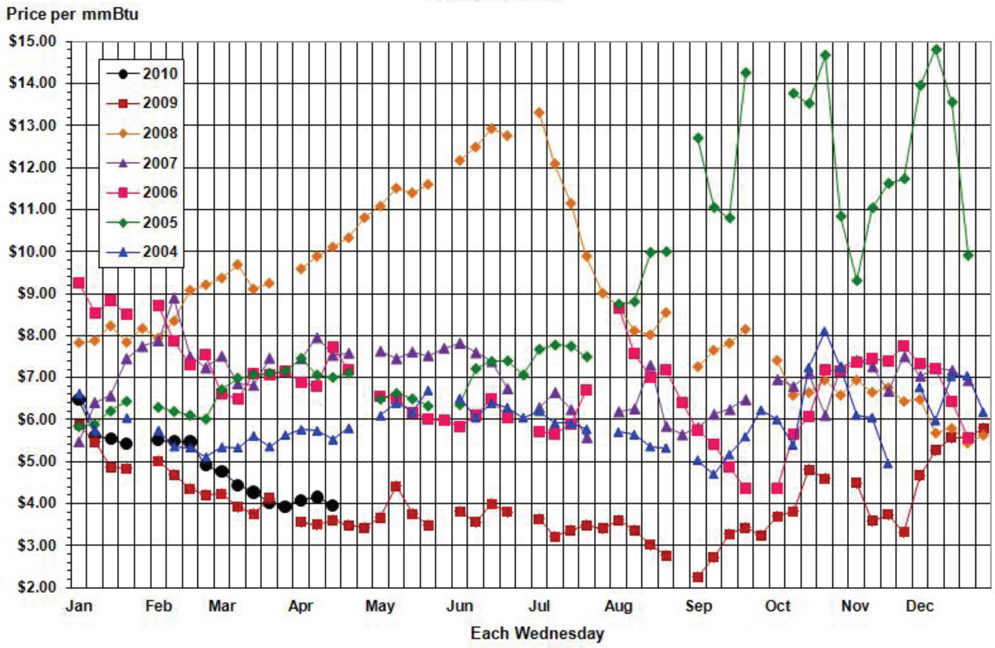
A natural question is how will these two trends—increased unconventional gas supply and increased LNG trade—affect the global gas marketplace? On the one hand, increased shale and other unconventional gas supply, all else being equal, will lower prices; this has already been observed with the U.S. Henry Hub spot market prices in 2009 and 2010 substantially lower than in previous years (Figure 2 and Figure 3). With reduced need for gas import into the United States, the potential gains from coordinated supply cuts from a gas cartel will probably diminish relative to the U.S. market. On the other hand, the rise of LNG activity, especially if this occurs in spot markets as opposed to contracts, could put more market power in the hands of key players such as Russia, Iran, and Qatar which collectively possess more than 55% of the global proved reserves (EIA, 2008) or even additional market power if a gas cartel based on the Gas Exporting Countries Forum (GECF) is formed. A more integrated gas market, due to lower LNG and pipeline cost, could also reduce the market power of suppliers, allowing for more competition. The relevance of market power was observed with the temporary shutoff of gas from Russia to Ukraine over contract disputes, which ultimately affected further downstream customers in Europe in 2006 (New York Times, January 3, January 13, 2006) and again in 2009 (The Economist, January 10, January 17ab, 2009) . These two trends are potentially opposing and analysis should be done to determine the net effects on the global gas market.

Figure 1. LNG as World Inter-Regional Natural Gas Trade* by Type in the Reference Scenario (WEO 2008, IEA)



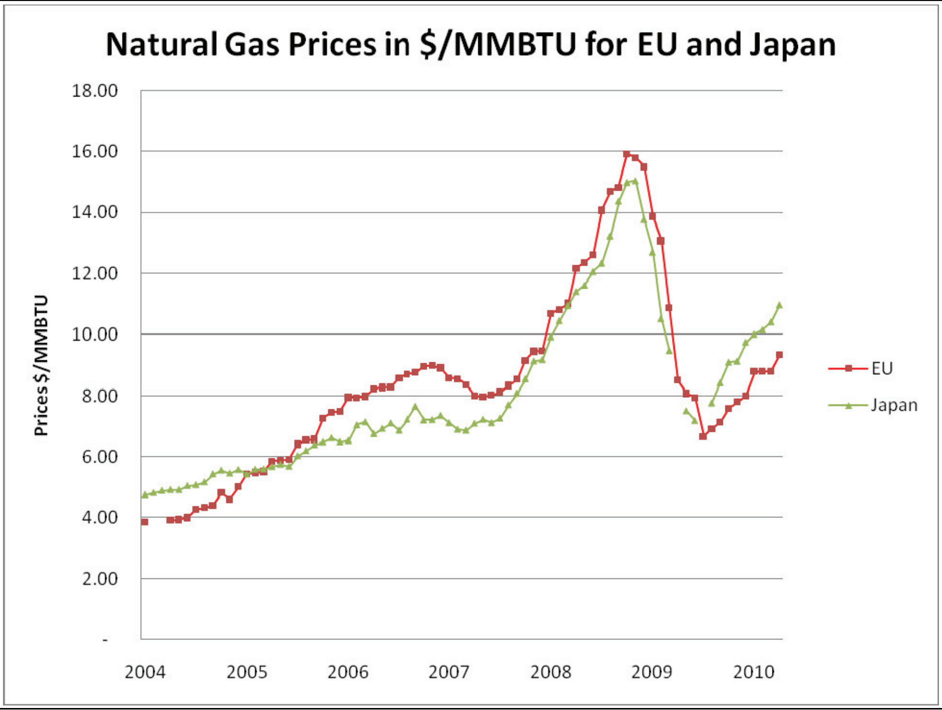
*Trade from major WEO regions, not including international trade within each region.

Figure 2. Natural Gas Spot Prices at Henry Hub ($/ million BTU)



Source: http://www.neo.ne.gov/statshtml/124.htm

Figure 3. Natural Gas Spot. Source: WGI, World Gas Intelligence



To our knowledge, there exist few previous in-depth studies that numerically analyze possible impacts of cartelization in international gas markets. One notable exception is Egging et al. (2009), which investigated the impacts of collusive behavior by the GECF members, using an earlier version of the model used in this paper. The model that presented and applied here has several adjustments relative to this earlier version, most importantly the current model allows for a representation of a cartel in accordance with economic theory. In the cartel studies extensions of the gas cartel beyond the GECF members are considered, which turn out to be crucial for both the impacts and the profitability of the cartel as well as the importance of unconventional gas and transportation costs. Lastly, the model has been improved to better represent cartel types of collusion (cf. Section 2 below).

The rest of this paper is organized as follows. In Section 2, the World Gas Model is presented and compared to relevant existing models; the formulation appears in the Appendix. Section 3 describes the various scenarios considered with Section 4 providing the actual numerical results and discussion. Lastly, Section 5 offers some conclusions and directions for future work.

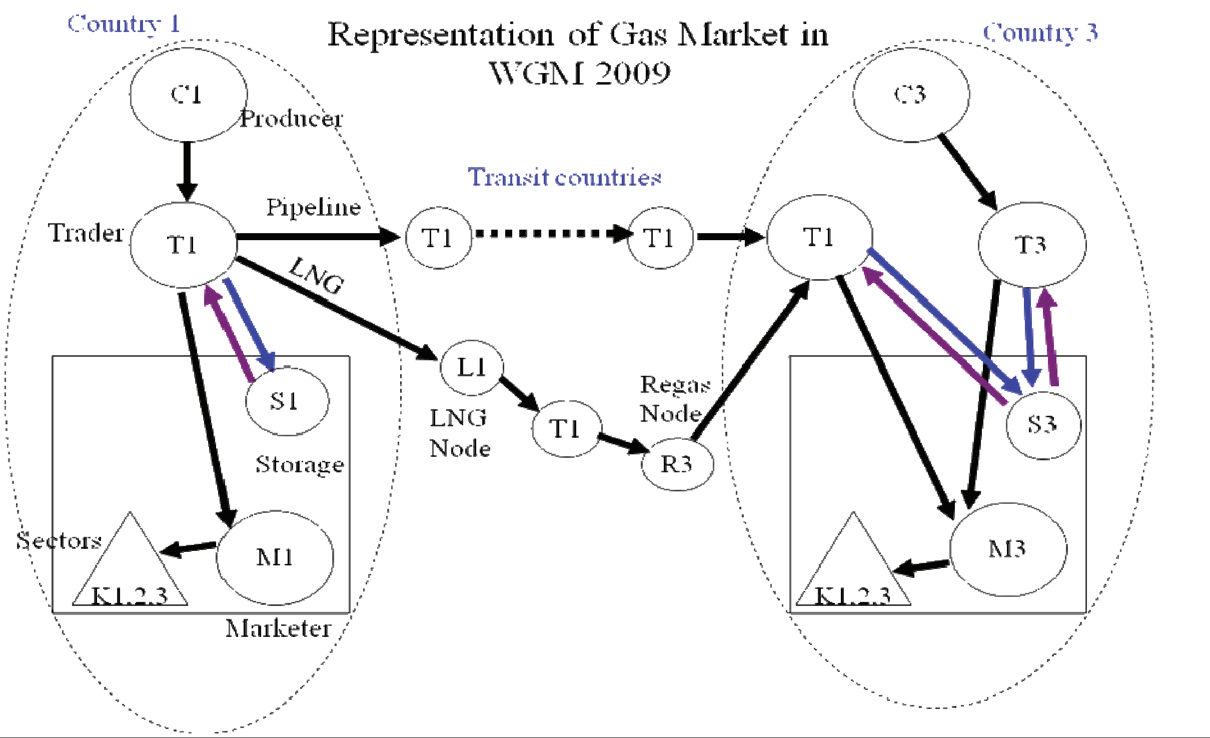
2. The World Gas Model

The World Gas Model (WGM) is a large-scale market equilibrium system developed by the University of Maryland[6] in collaboration with Deutsches Institut für Wirtschaftsforschung (German Economic Institute for Economic Research) and Technische Universität-Dresden, (Egging et al., 2008ab, 2009, 2010), based on the earlier works by Gabriel et al. (2005ab) and Egging and Gabriel (2006). Its purpose is to simulate the global gas marketplace using principles from game theory, optimization, and engineering and to gauge the effects of market power discussed above. As shown in the Appendix, WGM is an instance of a mixed complementarity problem (MCP) (Facchinei and Pang, 2003) generalizing optimization and game theory problems. MCPs or the related variational inequality problem have become quite prevalent in modeling large, complex systems such as the global gas market and offer much more flexibility and realism as compared to traditional single-objective optimization models.

Unlike most other large-scale economic models for natural gas, the WGM allows some of the players to be strategic (i.e., to withhold supplies to force up prices for larger profits). This feature is important given recent events natural gas markets such as the Russian withholding of gas to Ukraine based on price disputes. The WGM includes the following market players: producers, traders (dedicated trading arms of production companies), pipeline operators, and consumers. Each of these players except consumers is modeled as optimizing their profits subject to engineering and/or consistency constraints. The traders are imbued with market power and the other players are price-takers. Gathering the Karush-Kuhn-Tucker (KKT) optimality conditions (Facchinei and Pang, 2003) for all the optimization problems along with market-clearing conditions gives rise to the overall mixed complementarity problem (see Figure 4 for a depiction of the key model components and the Appendix for details on the actual formulation).

[6] National Science Foundation (DMS, Award #0106880), Principal Investigator ,S.A. Gabriel, "Computational Methods for Equilibrium Problems with Micro-Level Data," 09/01/2001-08/31/2005 and National Science Foundation (DMS, Award #0408943), Principal Investigator, S.A. Gabriel, "Methods and Models for Stochastic Energy Market Equilibria, "08/01/2004-07/31/2008.

Figure 4. Depiction of Modeling Components for the World Gas Model



2.1. Some Differences with Previous Versions of the World Gas Model

In the WGM the market power lies with the traders, both representing the pipeline and the LNG deliveries. This differs from the previous versions of the model wherein only the traders exerted market power in (Egging et al. 2008ab); and WGM-2008 in Egging et al (2009, 2010) where the regasifier could also exert market power. The formulation implemented in Egging et al. (2009, 2010) was unable to adequately represent cartel types of collusion and was modified in the current formulation to allow traders to coordinate both pipeline and LNG flows originating from the same country.

Usually storage facility operators provide a service. They inject, store and extract gas for a third party, and the storage operators do generally not own the (non-cushion) gas stored in the facility. In the WGM, the storage operators are modeled as regulated players. This is different from previous model versions wherein storage operators provided seasonal swing services by executing seasonal arbitrage.. Also in former model versions price-undercutting behavior was observed in the high and peak demand seasons by storage operators. The price undercutting was due to storage operators buying at perfectly competitive prices in the low demand season, and selling at wholesale prices to the marketer in the high and peak demand seasons. In the current form of the model, the traders coordinate the injection and extraction volumes, and the undercutting of prices in the high and peak demand seasons will not occur. Another adjustment relevant for the storage market is that the injection and extraction seasons are not specified. Previously the injection and extraction seasons where defined according to seasonal demand patterns in the northern hemisphere, which prevented countries in the southern to make use of their storage facilities. In the current model, injection and extraction can take place in any demand season, dependent on the local circumstances.

Lastly, the transportation system 0perator (TSO) and pipeline operator are integrated, to have a consistent modeling approach for both infrastructure services markets (e.g., the storage and pipeline markets). Agents which manage and expand the infrastructure, providing services to the traders at a regulated service fee.

2.2. The Current Version of the World Gas Model (WGM-2009)

The current model version is composed of 41 nodes representing individual or aggregated countries and covers some 98% of the worldwide consumption and production for 2005. The model operates with five year periods from 2005-2030 as well as two seasons (peak and off-peak). On the LNG side, both spot markets and a database of contracts are used to add realism. Typical decisions variables that the model solves for are operating levels (e.g., production, storage injection) as well as capacity investments (e.g., for pipelines, liquefaction). Overall, there are some 45,000 variables that make up the WGM complementarity system and it can be solved on a standard personal computer (e.g., 2GB of RAM and 1.2 GHz clockspeed) in about 50 minutes. See Figure 4 for details.

For the United States, the forecasts presented in the Annual Energy Outlook (April 2009 ARRA version, AEO, 2009) were used (www.eia.doe.gov). For Europe, the PRIMES model (European Commission, 2008) was used, which provided consumption and production projections for the EU27. For the rest of the world, the World Energy Outlook (International Energy Agency, 2008) was used. The WGM was then extensively calibrated to match these multiple sources for all countries/aggregated countries and years considered (2005, 2010, 2015, 2020, 2025, 2030).[7] For the Base Case, the Alaska pipeline is assumed to be an option (if feasible) to come online in 2020. Consequently, the Alaska LNG export terminal will be phased out in 2015. The resulting WGM output then constitutes the Base Case.

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[7] See the Appendix for details on the countries and regions included as well as other relevant geographic or nodal information.

To understand the capabilities of the WGM, it is instructive to compare it with other large-scale natural gas models.The Natural Gas Transmission and Distribution Module is (NGTDM) is one of the modules of the National Energy Modeling System (NEMS) that is developed and used by the U.S. Department of Energy.[8] NEMS is a multi-sector model for the United States that includes other fuels than gas. The NGTDM is the part that represents the natural gas market. The FRISBEE model (Aune et al., 2009; Rosendahl and Sagen, 2009), the Rice World Gas Trade Model (RWGTM) (Rice University , 2004, 2005), and the WGM provide much less detail for the North American market. The principal advantage of these three models is global coverage, which allows the models to better capture the interaction between natural gas markets in different world regions. The WGM also addresses the potential for the development of international market power, but it does not allow for the development of supply and demand conditions in a detailed bottom-up approach that takes into account changing economic conditions. GASMOD (Holz et al., 2008, Holz, 2009) and GASTALE (Lise and Hobbs, 2009) also address market power aspects explicitly via the complementarity format, but their coverage is strictly European when it comes to demand. Gridnet (www.rbac.com) and ICF's Gas Market Model (ICF GMM) offer U.S. coverage but are designed to support short- to medium-term business decisions. Neither is well suited for long-term scenario analysis. See Table 1 for a comparison of these models.

Table 1. Summary of Natural Gas Models

MODEL	Type[a]	Region(s)	Market power	Number of nodes	Time Scale	Density	Seasons	Sectors	Capacity expansions
NEMS	LP	USA+CAN	No	15[b]	2030	Yearly	2	5[c]	Endogenous
WGM	MCP	World	Yes	41	2030	Five years	2	3	Endogenous
FRISBEE	PE	World	No	13	2030	Yearly	1	3	Endogenous
RWGTM	CGE	World	No	460	2050	Five years	1	1	Endogenous
GASMOD[d]	MCP	Europe+LNG	Yes	6	2025	Ten years	1	1	Endogenous
GASTALE	MCP	Europe+LNG	Yes	19	2030	Five years	3	3	Endogenous
GRIDNET	LP	USA	No	18000	operational	Monthly	12	N/A	Exogenous
ICF GMM	NLP	USA	No	114	several years	Monthly	12	4	Exogenous

[a] LP: Linear Programming; MCP: Mixed Complementarity Problem; PE: Partial Equilibrium; CGE: Computable General Equilibrium

[b] United States 12, Canada 2 and Mexico 1

[c] Includes Electric Power Generation, which is not considered as an end-use sector in NEMS.

[d] The Dynamic Version of GASMOD

[8] www.eia.doe.gov/oiaf/aeo/overview/nat_gas.html

3. Description of Scenarios

This section describes the scenarios (cases studies) analyzed as well as hypotheses about how the various case assumptions could impact the model outcomes. First, three scenarios are defined in which various groups of countries collaborate in a cartel. Second, additional scenarios are included to examine the effects of a gas cartel under alternative assumptions about respectively, transport costs and unconventional gas.

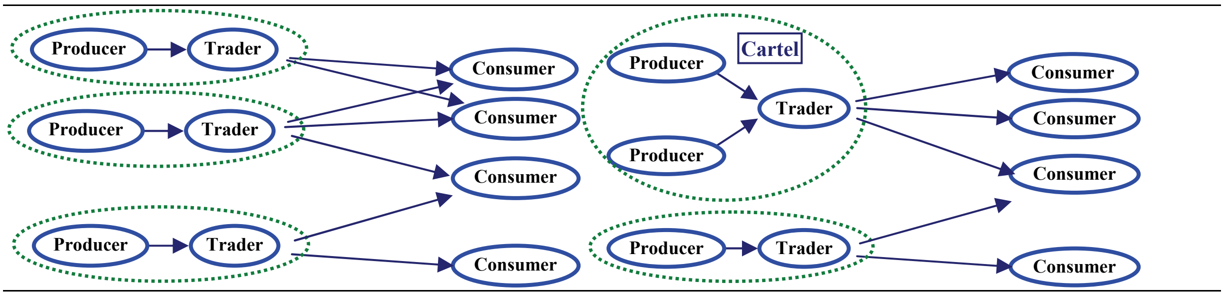
The outcomes of the scenarios are compared with the results of the Base Case (described above), for the period up to 2030. The Base Case projections in terms of produced and consumed volumes, trade flows, prices and profits, for a high and low demand season are not meant as a forecast but rather as a reference for comparison. The following table summarizes the Base Case assumptions.

Table 2. Summary of Base Case Assumptions

Summary Case Assumptions						
Case	Consumption North America	Production North America	Consumption Rest of the World	Production Rest of the World	Alaska Pipeline	AK LNG Export Terminal
Base	AEO 2009 April ARRA Update		EC Trends IEA WEO 2008		Option 2020	Phase Out 2015

In the Cartel Cases the member countries collaborate and enforce market power by operating through a single trader to jointly optimize cartel profits. Figure 5 (left-hand side) shows how in the Base Case all producing countries have their own trader that maximizes profits. On the right-hand side of this figure a cartel situation is depicted, where cartel countries sell through one trader that maximizes aggregate profits. In reality cartel members would negotiate the amounts to be produced by all members and it might be necessary to redistribute part of the profits to maintain all members in the group. In the model, the trader decides on the optimal quantities to sell and on the amounts that each member country produces, based on profit maximization. In an *ex post* fashion, the WGM can compute the share of cartel profits for each member but this is not done endogenously.

Figure 5. Producer-Trader Combinations (left, standard; right, cartel)



For a cartel to be successful, importing countries should not have (affordable) alternative supply sources. Therefore, the developments of cost effective resource bases of importing countries are important, as are the resources bases of non-cartel member exporting countries. Notably in Australia large gas deposits have been found in recent years. Especially in a world market with artificially high prices due to cartelization, Australian gas would become more attractive and could provide for an alternative supply source to importing countries worldwide. To analyze the impact of developments in transport costs (induced by possible technological progress or economies of scale in gas transport) and the U.S. shale gas reserves two more sets of scenarios have been defined that provide a comparison with the Base and Cartel Cases. In the Low Transport Cost sensitivity cases the investment costs in new pipelines and liquefaction and re-gasification capacity are 10% less expensive than in the Base Case, and operational costs and regulated fees stay at present levels instead of increasing with an inflationary trend of 1.5% per year. The other set of scenarios address lower availability of unconventional gas in the United States forming a sort of "worst case" relative to the dramatic unconventional gas increases of late. In both these sets of scenarios the influence of a gas cartel is investigated

The countries in the Gas Exporting Countries Forum as of mid 2009[9] are the starting point for the Cartel Cases (see Figure 16). The Caspian region[10] is thought to become a major gas exporter in the coming decades (IEA WEO, 2008) but countries in this region have not yet taken part in the GECF. Therefore in a second cartel scenario the Caspian region is also defined to be part of the cartel. Many major gas exporting countries also have a well-developed oil-export business, and several GECF members are also members of OPEC. A notable exception is Saudi Arabia, the leading country in OPEC and a country with significant gas reserves, but not a member of the GECF. Although Saudi Arabia is not an exporter of gas, and they have a policy of using more natural gas to replace oil domestically and allow more oil exports, their significant reserves could allow them to export gas. Other Middle Eastern countries which are currently not members of GECF could also decide to take part in a cartel. This is addressed in the third Cartel Case with the largest membership base: Besides GECF countries, the Caspian region and the rest of the Middle East is included.[11]

For the Cartel Cases, it is anticipated that the cartel members will produce lower amounts of natural gas to drive up market prices. It is likely that high cost producers within the cartel give up more market share than low cost producers. Non-participating producing countries will reap the benefits from higher market prices by increasing their output and export levels. Nevertheless, countries highly

[9] Member countries are taken as of mid 2009. The representation of this cartel in the WGM includes the following model nodes: North Africa, West Africa, Indonesia, Northern South America, Qatar and Russia. Note that there have been some shifts in the membership between mid 2009 and the publication date of this paper. The current members (as of mid 2010) were stated in an earlier footnote.

[10] WGM countries: Kazakhstan, Azerbaijan, Turkmenistan, Uzbekistan, Armenia, Georgia. Model region: Caspian

[11] WGM countries: Kuwait, Oman, Saudi Arabia, UAE, Yemen. Model region: Yemen (= Middle East – non-GECF)

dependent on gas imports to meet domestic consumption may see severely lower supplies and consequently much higher prices.

Since lower transportation costs make longer distance shipments more attractive it is anticipated that the associated scenario will result in a comparative advantage for suppliers further away from the importing markets. Since the analysis of cartelization is done for the case with the fewest cartel members, LNG exports by the non-GECF part of the Middle East and Australia will likely increase, as should long-distance pipeline exports from the Caspian region. For Norway, the increased demand from Europe would induce more pipeline exports and lower LNG exports, whereas the increased consumption from overseas LNG importers would induce higher LNG exports and lower pipeline imports, making the aggregate effect unpredictable.

Lower U.S. domestic unconventional production rates will result in higher market prices, higher production in Alaska, and higher imports from Canadian pipeline gas and LNG from overseas, all things being equal. This could potentially make North America more vulnerable to gas cartelization.

Between 2008 and 2009 EIA significantly increased the production projections for unconventional gas, especially for shale gas. In one sensitivity case described in the table below, we analyze how this upward revision of domestically produced gas in the U.S .would affect the impacts of a global gas cartel. Since the Base Case is calibrated to the – higher - AEO 2009 outlook for unconventional gas in the United States, to analyze this question it is necessary to reverse the analysis. In this sensitivity case the unconventional gas availability in the model is adjusted downward to match the values of the AEO 2008. These adjustments for the years 2010 through 2030 are between 7% and 23%.

Table 3. Summary of Scenarios Considered

CASE NAME	ABBREVIATION	DESCRIPTION
Base Case	Base	Reference case
GECF	GECF	Cartel along the lines of GECF membership
GECF+Caspian	Casp	Cartel along the lines of GECF membership plus the Caspian Region
GECF+Caspian +Middle East	Saud	Cartel along the lines of GECF membership plus the Caspian Region and all of the Middle East
Base Low Transport Costs	SS10	Base Case with Lower LNG and transport costs
GECF Low Transport Costs	SS10GECF	GECF Case with Lower LNG and transport costs
Base Low Unconventional Case	Unconv	Base Case with Lower availability of unconventional gas in USA
GECF Low Unconventional Case	UnconvGECF	GECF Case with Lower availability of unconventional gas in USA

4. Numerical Results

4.1. Base Case: Results

The Base Case is the reference for comparison of which the model outcomes have been calibrated to closely match the state of the natural gas market in 2005 as well as the projections for the coming decades provided by the Annual Energy Outlook (EIA, 2009), Natural Gas Information (IEA, 2008), European Energy and Transport: Trends to 2030 (EC, 2006, 2008) and the World Energy Outlook (IEA, 2008). Since none of these sources had the desired level of detail, multiple sources were required Due to different modeling starting points, and some variations in the three projections, the Base Case results differ slightly from each of these sources, however, the results have a similar trend in terms of production and consumption growth. A notable point affecting the results is the upwards revision of unconventional gas availability in the United States in the Annual Energy Outlook of 2009, resulting in much higher North American gas production in the longer term not accounted for in other projections. Naturally the higher North American gas production and lower imports affect LNG trade, regional trade balances, production and consumption globally.

As noted above, for the United States, the WGM was calibrated to the Annual Energy Outlook (AEO) 2009 figures (April 2009 ARRA version). Note that the WGM output is net production as opposed to gross production in the AEO 2009-ARRA data.[12] Table 4 indicates that on the whole, the percentage difference between the AEO and WGM figures is fairly low. The downward deviation in production is due to inconsistency in projections of calibration references for other parts of the World (IEA, 2008) with AEO 2009, while the upward deviation is due to the Alaska pipeline coming on stream earlier in our model than in the AEO.

Table 4. World Gas Model Base Case, U.S. Production and Consumption in Billion Cubic Meters. Difference Between World Gas Model Base Case and AEO 2009 in parentheses

Base Case	2010	2015	2020	2025	2030
Production	513.7 (-3.70%)	508.1 (-0.31%)	544.6 (4.21%)	588.2 (0.59%)	619.4 (0.81%)
Consumption	575.8 (1.50%)	556.8 (1.94%)	572.1 (2.37%)	607.2 (1.11%)	614.0 (1.20%)

[12] In the supply chain that brings gas from the production wells to the end-users, there are several steps that induce losses. The main difference between net and gross production is due to processing losses such as lease and plant fuel. From the consumption figures, also pipeline fuel must be subtracted, since these losses are accounted for in pipeline transportation. The WGM explicitly accounts for losses in liquefaction, LNG shipment, regasification, pipeline and storage losses, but AEO reports aggregate losses only. There are also usage categories, such as own use in the energy sector for enhanced oil recovery, that are not represented in the WGM. Production capacities and volumes in the WGM are net production volumes, i.e., volumes destined to a number of consumption sectors.

WEO (IEA, 2008) reports projections for two future years: 2015 and 2030. In WEO, values are not available for all countries, but for continental regions and some major gas consuming and producing countries only. Global production and consumption in 2015 are forecasted to be 3,512 bcm, and 4,434 bcm in 2030.Similarly as the AEO projections for the United States, the WEO presents gross values. To account for different maturity levels of domestic markets assumptions for how to divide regional projections to individual countries were made. In the WEO, the growth percentages for global production in the period 2005-2015, and 2005-2030 are about 21.8% and 53.8%; for consumption these values are 23.2% and 55.6% respectively. [13] In the WGM, the growth percentages in these periods are 19.0% respectively, 53.3% for production; and 18.9% resp 53.5% for consumption.

With respect to price projections a choice needed to be made. In AEO 2009 the gas prices vary somewhat over time, but stay relatively stable. In WEO prices quadruple in roughly 4½ decades with a yearly average increase of 3.1%. We have assumed a yearly increase in costs and consumer's willingness to pay of 1.5% to let prices increase gradually over the next decades.

In terms of price outcomes, Figure 6 shows that in 2030, the Base Case has dramatic price differences by region with Europe the highest at $10.13 per million BTU (MMBtu) due presumably to its diminishing domestic production, and the supply regions (Africa, Caspian, Mideast, Russia) the lowest in the range of $2.50-$3.50. The N. America, S. America, and Asia-Pacific make up the middle range of prices between $7-$8.

In terms of world trade flows of natural gas, from Figure 7 the trend is clear. Europe is the largest importer of gas (pipeline and LNG) and the Asia/Pacific region is the next highest with both North and South America negligible. On the other hand, Africa, the Caspian, the Mid-East, and Russia are major exporters of gas.

[13] Own calculations based on WEO data.

Figure 6. **World Gas Model Base Case, Average Wholesale Prices by Regions, $/thousand cubic feet**

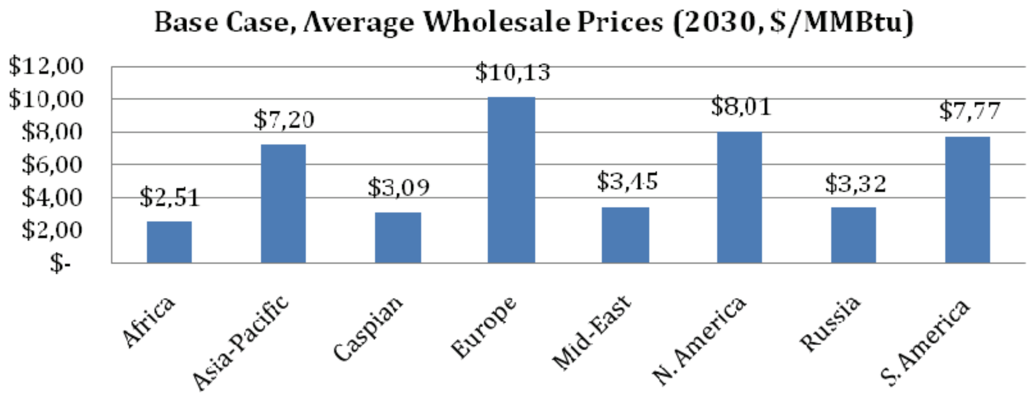


Figure 7. **World Gas Model Base Case, Exports (+) and Imports (+) by Region, bcm for 2030**

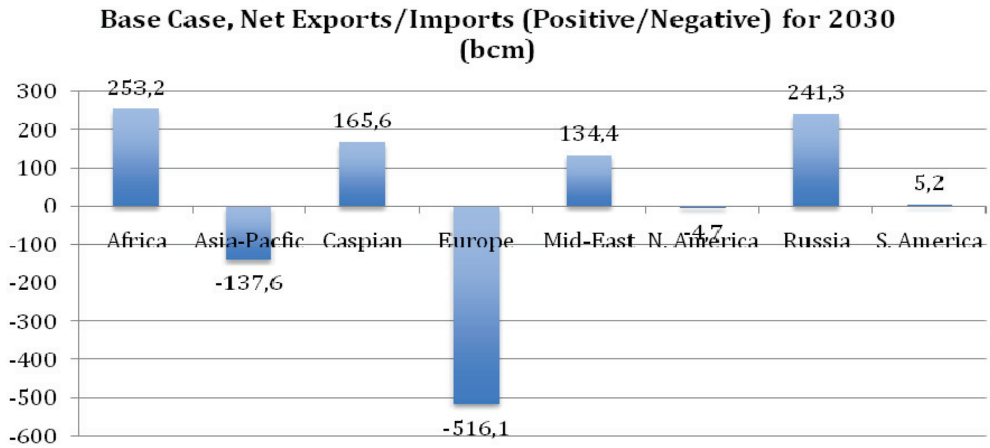


Figure 8. **World Gas Model Cartel Cases, Average Wholesale Prices by Regions, $/million BTU, 2020**

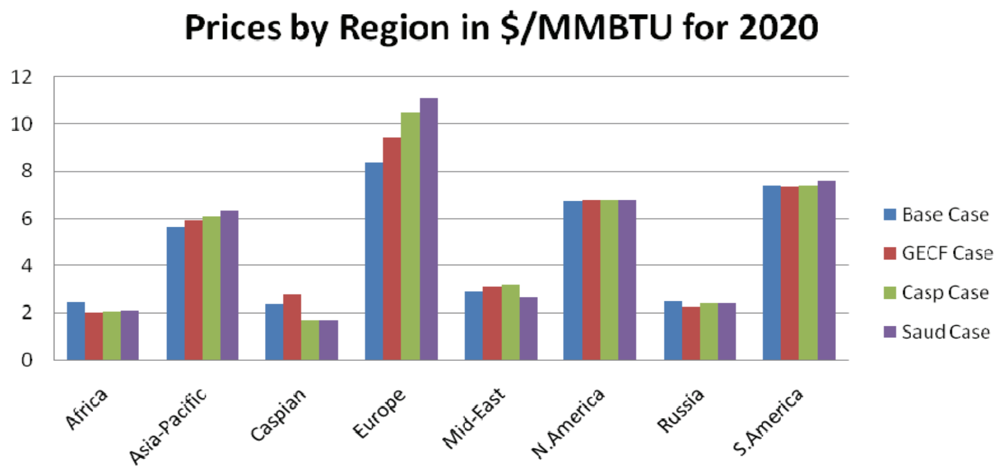


Figure 9. World Gas Model Cartel Cases, Average Wholesale Prices by Regions, $/million BTU, 2030

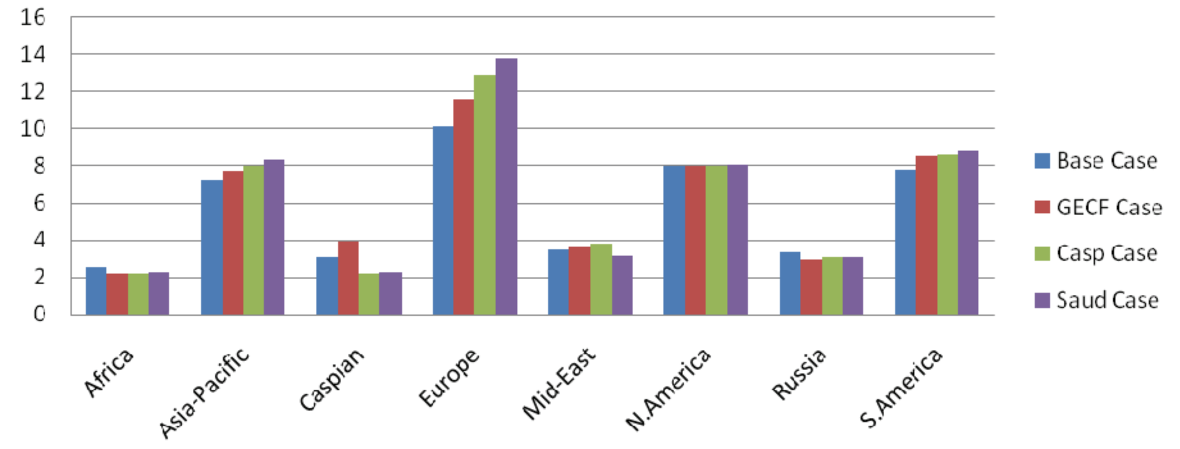


Figure 10. World Gas Model Cartel Cases, Consumption by Regions, billions of cubic meters/year, 2020

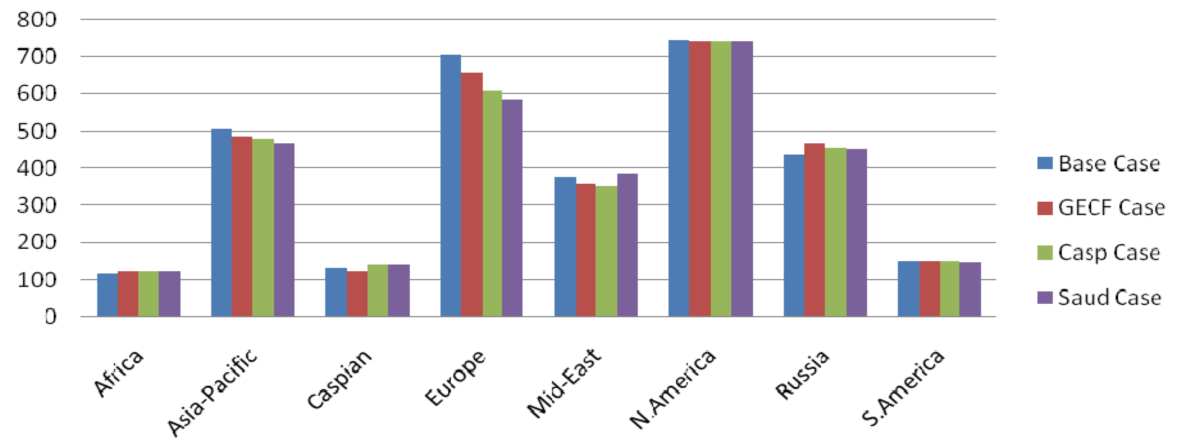
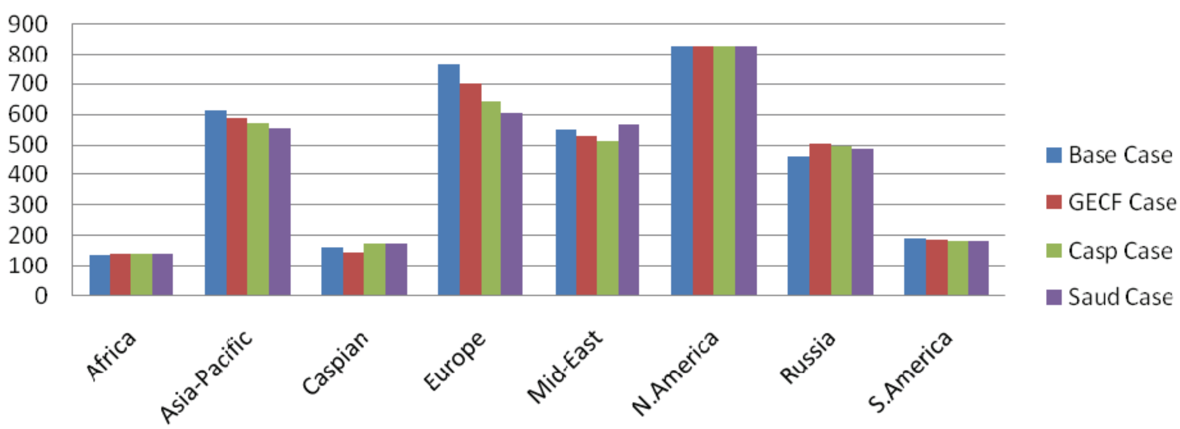


Figure 11. World Gas Model Cartel Cases, Consumption by Regions, billions of cubic meters/year, 2030



4.2. Cartel Cases: Results

In this section, the hypothesis that a cartel, if created could significantly raise prices and curtail production is examined. Each of the possible cartels considered is compared against the Base Case as well as against each other to gauge the magnitude of potential cartel-induced effects. The first cartel considered is the current configuration of the Gas Exporting Countries Forum (GECF) described above.

Figure 8 and Figure 9 show that that the price effects of the cartel vary greatly by region for 2020 and 2030. Europe sees the biggest price increase between the Base and GECF Case with about \$1/MMBTU in 2020 and about \$1.50/MMBTU in 2030. This makes sense since this region has depleting resources of its own and a strong dependence on cartel members (e.g., Russia), so it would face the brunt of such a cartel's effect. After Europe, the Asia-Pacific region and the Caspian have the next largest price increase at around \$0.30-\$0.40 in 2020 and \$0.50-\$0.80 in 2030. Asia (in particular Japan and South Korea) is heavily dependent on LNG imports. This also implies that they have more flexibility in choosing their suppliers, and so they are able to mitigate to some extent the effects of a cartel. Hence, the effect of cartel formation has less effect on the Asian nations. Countries that have their gas supply through permanent pipelines face more dramatic effect since they do not have as much options as those which import LNG. An additional reason for only moderate price increases on average in the Asian region is that some of the Asian countries are GECF members, and GECF member countries will typically see lower domestic prices as the marginal costs of domestic supply in GECF countries fall as exports are curtailed. The Caspian region, which in particular includes Kazakhstan, Turkmenistan, and Uzbekistan, face increased prices in case of cartel formation. An explanation is that this region starts exporting more gas, especially to Europe, and thus less is available for domestic markets without higher prices.

The Mid-East and North America see relatively small price increases in 2020 and 2030. For North America this is due presumably to their low level of initial gas trade combined with long distance to most GECF countries, which insulate this continent from the effects of the cartel. The Mid-East region in the model includes Iran and Qatar, which are members of the cartel, and Kuwait, Oman, Saudi Arabia, United Arab Emirates and Yemen, which are not. Thus, some of the Mid-East countries will see lower prices and some will see higher prices when the cartel is formed, which explains the small overall price effect in this region. Domestic gas prices in Russia and Africa decrease as a result of cartel formation. The explanation is that both Russia and the biggest gas producers in Africa (Algeria, Egypt, Libya, and Nigeria) are GECF members, and so more gas is available for domestic consumption when exports are curtailed. In particular, Africa cuts back a significant share of their export (see below), which moreover constitutes a large share of their initial production, in the GECF case, and thus prices fall by almost 20% in 2020. South America sees a small price decrease in 2020 but a price increase of $0.74 in 2030. Again, this is due to some countries being GECF members (Bolivia and Venezuela), and others not (e.g., Trinidad and Tobago). In 2020, the price decreases in GECF countries dominate the price increases in non-members, whereas in 2030 the opposite is the case.

Figure 10 and Figure 11 show that again Europe experiences the biggest effects of the GECF cartel with an almost 50 BCM (6.6% of Base Case levels) drop in consumption due to higher prices in 2020, and an approximate 60 BCM decrease (8.1%) in 2030. Less consumption in the range of 3-5% are felt also by Asia-Pacific, the Mid-East and the Caspian in 2020, with this range changing to 4-9% in 2030. The biggest reduction is in the Caspian region, which is located in between the three most important GECF members (Russia, Qatar and Iran). The Caspian region faces a 5.29% reduction in 2020 and 8.6% in 2030. North America witnesses almost no change in consumption due to its semi-isolation from the cartel. South America also has a negligible drop in consumption in 2020 (0.3%) but which is increased to almost 4% in 2030 due to the price increase mentioned above. Russian consumers are the big winners under the GECF Cartel case by increasing their consumption substantially (6% in 2020 and almost 10% in 2030).

GECF cartel countries reduce their production by 2.55% in total compared to the Base Case level. The regions that have substantial cutbacks in production are Africa, Russia, and South America, which all include cartel members (see Figure 17 and Figure 18). The curtailments in production for these supply regions range from about 4% (South America, 2030) all the way up to about 23% (Africa, 2030). To compensate for the decrease in production from the GECF cartel, there are three regions that substantially increase their own production in 2020 and 2030: The Caspian, Europe, and the Mid-East. Again, a similar pattern holds for North America, namely that there is not much change between the Base and GECF Cartel case in terms of production.

As a consequence of reduced exports from GECF members, inter-regional gas trade is reduced by 13% in 2020 (16% in 2030), see Figure 13. In particular, imports to Europe decrease by 15% (65 BCM) compared to the Base Case, whereas imports to North America and Asia-Pacific are hardly reduced at all. For North America, this is in line with previous explanations above. The Asia-Pacific region has two GECF members in the WGM (Indonesia and Malaysia, whhich have recently withdrawn, however). Thus, non-members in this region will see reduced imports even though the region as a whole has an almost unchanged trade balance. In 2030 the impacts of the GECF cartel on trade are very similar to the 2020 picture, except for Asia-Pacific which then imports 23% less than in the Base Case, which is due to reduced importance of Indonesia and Malaysia.

The GECF as a group benefits from cartelization in 2020, as the member countries' joint profits increase by 5%. However, there are substantial differences between countries, cf. Figure 14. First, note that Russia's profits go down when GECF acts as a cartel. Thus, without transfers of revenues between member countries, this outcome seems unlikely. North Africa also gets lower profits in the GECF cartel case, whereas other member countries benefit. Consider for instance the profits in Qatar/Iran which almost double. The explanation is that both Russia and North Africa cut back substantially on their exports (more than one third), whereas supply cuts in other member countries are more moderate. This decreased profitability would thus be a disincentive for Cartel members such as Russia to join GECF.

In 2030 the GECF as a group no longer benefits from cartelization. In fact, joint profits are reduced by 3%. African regions are particularly worse off in 2030 without transfers of revenues; see Figure 15. The decrease in joint profits is at least partly due to higher investments in transport capacity in non-member countries in the preceding years, which makes it more difficult for GECF to gain any cartel profits in the long run. For instance, the Caspian region invests 20% more in pipeline capacity up to 2030 in the GECF Cartel Case than in the Base Case, whereas Mid-East producers outside GECF expand their LNG liquefaction capacity much more rapidly.[14] On the other hand, in the short run there are significant profits to gain from cartelization: Profits in 2010 are 15% higher for GECF as a group compared to the Base Case. Thus, discounted profits over the time horizon considered are higher for the GECF members in the GECF Cartel Case than in the Base Case,[15]and this discounted stream of profits is what the WGM uses. Nevertheless, despite significant initial profits, the overall gains from cartelization seem small and probably too small to overcome the hidden costs of cartelization that are not included in our study (e.g., political costs, agreeing on issues like revenue transfers, etc.).

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[14] Russian investments in pipeline capacity and African investments in liquefaction capacity are substantially reduced in the GECF Cartel Case.

[15] Note that, with Cournot competition, a merging between two or more Cournot players does not necessarily lead to higher joint profits for these players, and the merging leads to increased supply from other producers. The opposite, i.e., a split-up of a Cournot player into two Cournot players, is for example analyzed in the context of the Russian gas market in (Tsygankova, 2010).

Not surprisingly, non-GECF producers such as the Caspian region, Norway and in particular the Mid-East gain from the cartelization of GECF. Profits in the Mid-East region are in fact tripled, although from a rather low level.

Table 5. Total profit in cartel member countries. Billion $

Year	CASE	GECF	GECF+Caspian	GECF+Caspian+Middle East
2010	BASE CASE	$33.619	$39.752	$47.883
	DIFFERENCE IN CARTEL CASE	$5.050 (+15%)	$11.798 (+30%)	$20.269 (+42%)
2020	BASE CASE	$56.579	$70.394	$88.346
	DIFFERENCE IN CARTEL CASE	$2.793 (+5%)	$12.320 (+18%)	$37.603 (+43%)
2030	BASE CASE	$88.675	$110.457	$130.882
	DIFFERENCE IN CARTEL CASE	-$2.559 (-3%)	$13.403 (+12%)	$42.127 (+32%)

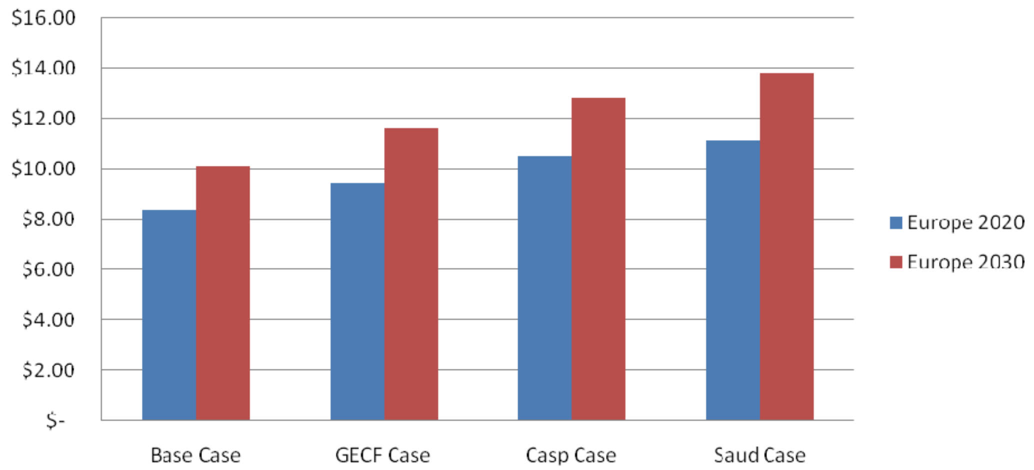
Two other variations on the GECF Cartel are next considered: adding the Caspian region to the cartel (particularly Kazakhstan, Turkmenistan, Uzbekistan, Azerbaijan), and adding the Caspian region as well as the whole Mid-East (not just Iran and Qatar). *Ex ante*, as more cartel members are added, one should see more dramatic results (i.e., higher prices for consumers, less production by cartel members). Figure 12 shows the evolution of prices in Europe over time for 2020 and 2030 under each of these cartel scenarios. The price effects are substantial and indeed increasing as more cartel members are brought in. In 2020, the Base Case price is $8.39 (per million BTU), and this rises to $9.45 with the GECF Cartel, $10.50 when the Caspian region is brought in, and finally $11.11 when the whole Mid-East region is also part of the cartel. This amounts to $2.72 of a price premium to the cartel or $63.8 billion in lost consumer surplus for Europe due to the formation of this most extreme cartel. A similar pattern exists for 2030 for Europe with an even more extreme premium of $3.69 or $91.4 billion in lost consumer surplus. This is alarming news for Europe and signals that this region may want to be sure about its supply diversity options to protect its economy.[16]

Consistent with higher prices, consumption of gas is reduced even more when more countries join the cartel. European consumption of gas is reduced by up to 17% in 2020 and 21% in 2030 when the cartel consists of both the Caspian and the Mid-East region. In the Asia-Pacific region, the relative

[16] Norway, currently being an observer to GECF, is an important supplier for the European region, accounting for 20% of total European gas consumption. If Norway should choose to participate in a gas cartel, e.g., adding Norway to the standard GECF cartel, gas prices in Europe would increase substantially although less than if the entire Caspian and Mid-East regions were included. In 2020, the price premium under the GECF-Norway case amounts to $1.95 ($2.24 in 2030), attesting to the strategic importance of this country as gas supplier to Europe.

consumption reduction is about half as big as in Europe. Consumers in North and South America on the other hand are still shielded from the effects of the cartel.

Figure 12. World Gas Model Cartel Cases, Comparison of Prices for Europe (2020 and 2030), $/MMBTU



When the Caspian region joins the cartel, Figure 13 indicates that gas supply from this region is dramatically reduced in 2020 (and 2030, more than one third in 2020 compared to the GECF Cartel Case). Some of the initial members now increase their supply somewhat (Russia and Africa), whereas others decrease output even more (Qatar/Iran). This reflects that expanding the cartel has two opposing effects on optimal output from incumbent members. On the one hand, reduced output from the new member improves the profitability of increasing production from other Cournot players, including the cartel. On the other hand, extending the cartel implies that higher prices due to reduced supply benefit more countries *within* the cartel.

Figure 13. World Gas Model Cartel Cases, Net Exports by Regions, billions of cubic meters/year, 2020

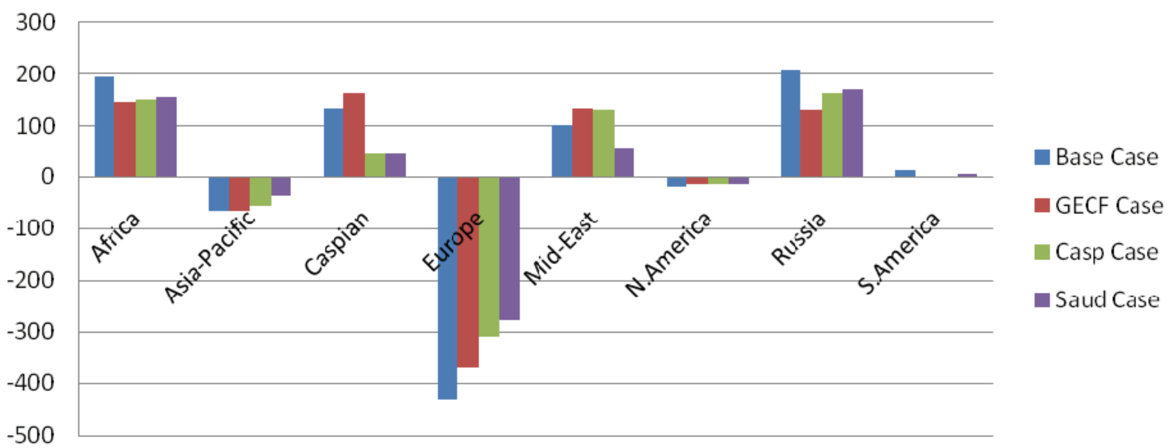


Figure 14. World Gas Model Cartel Cases, Profits by Regions, billion$/year, 2020

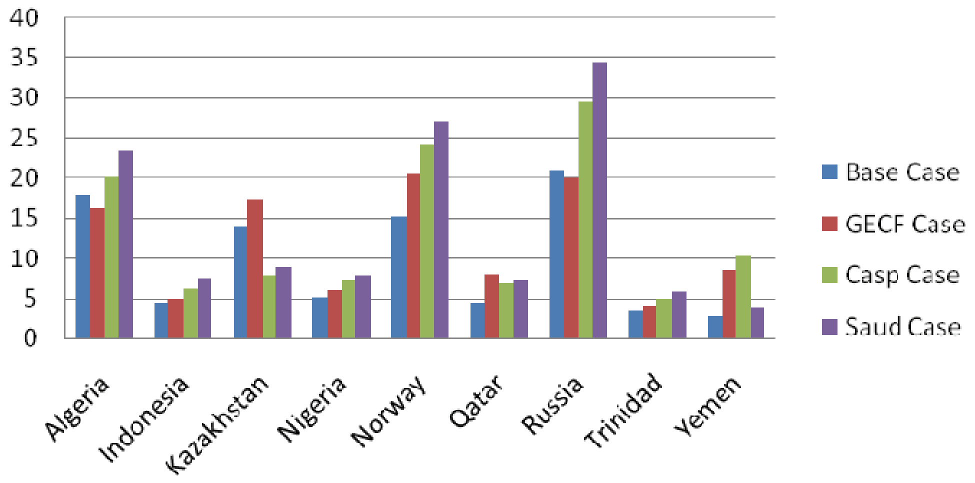


Figure 15. World Gas Model Cartel Cases, Profits by Regions, billion$/year, 2030

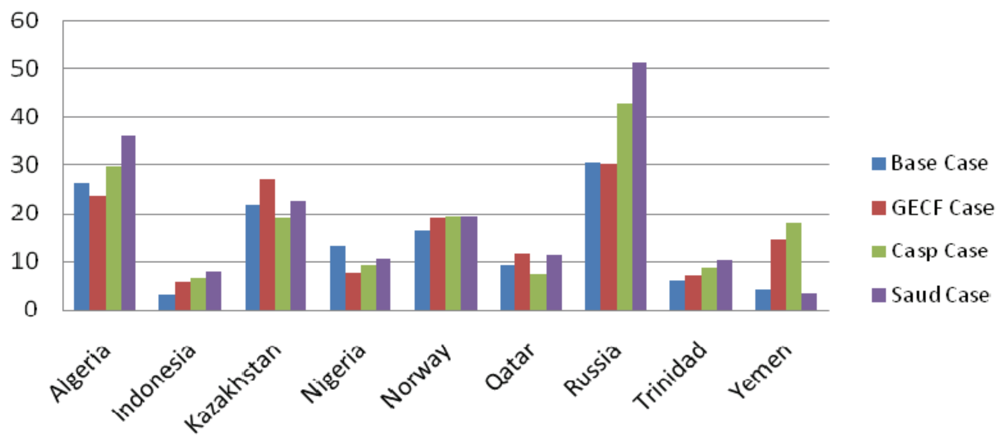


Figure 16. GECF member countries for cartel cases

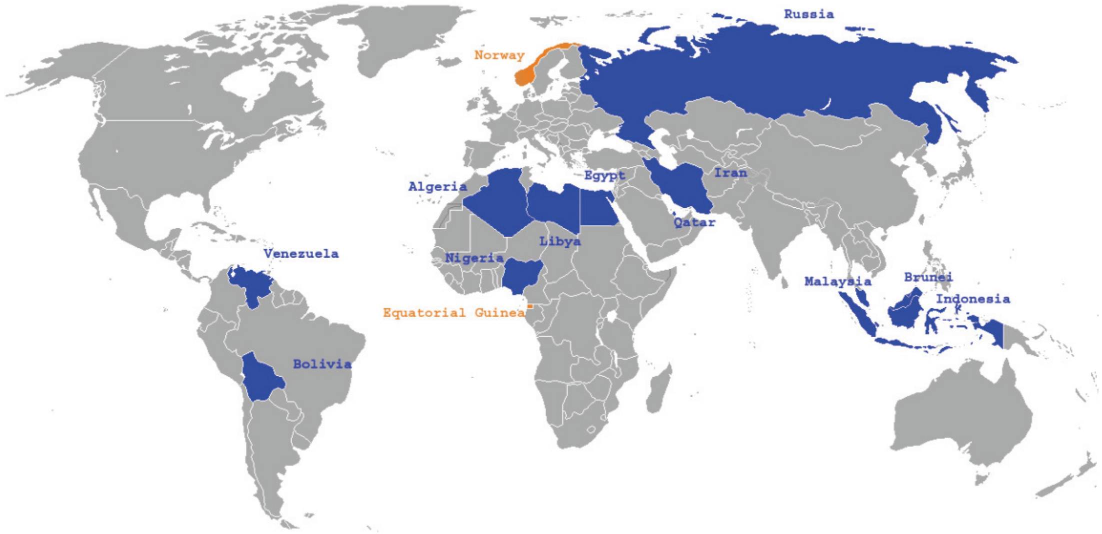


Figure 17. Production by region in billions of cubic meters for 2020, Cartel Cases

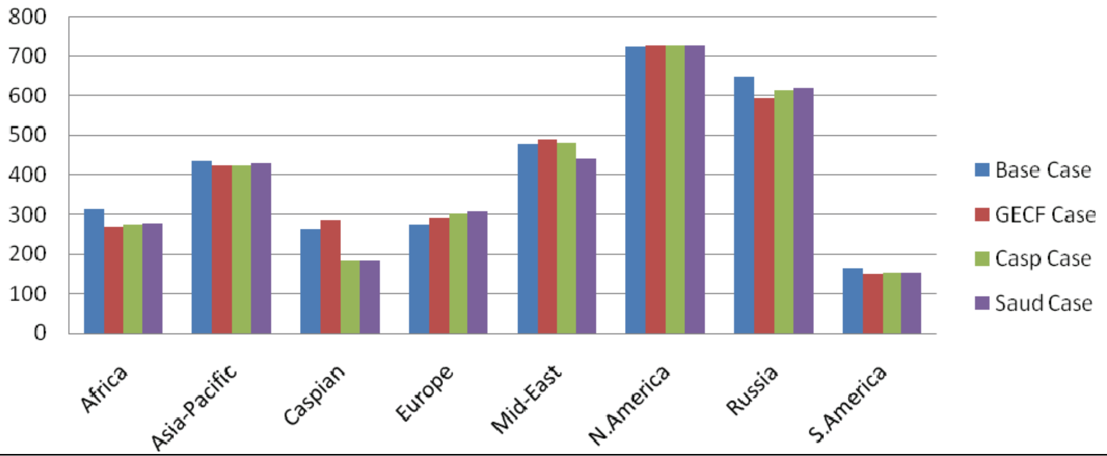
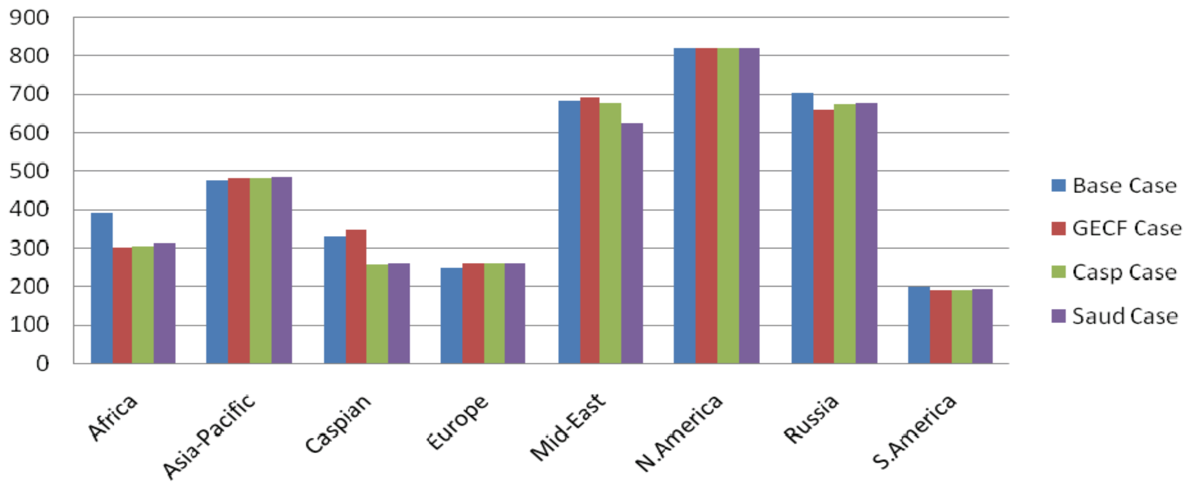


Figure 18. Production by region in billions of cubic meters for 2030, Cartel Cases



When all Middle Eastern countries are part of the cartel, total Mid-East production is reduced by almost 10% compared to the Caspian Cartel Case. In this case the other cartel members slightly increase their output. Global gas production reaches 5% below Base Case production in both 2020 and 2030.

The impacts on trade follow the consumption and production effects discussed above (see Figure 13 for 2020). Imports to Europe are reduced by 36% (33%) in 2020 (2030) when both Caspian and all Mid-East countries are members of the cartel (compared to no cartel). Even more dramatic, Caspian exports in 2020 are reduced by more than 70% when this region joins the cartel (i.e., vs. GECF Cartel Case), and slightly less in 2030 (60% reduction). Further, exports from the Middle East are reduced by 45% (60%) in 2020 (2030) when this entire region is part of the cartel (i.e., compared to the Base Case).

The relative gains from cartelization, i.e., the joint profits of all cartel members divided by the joint profits of these countries in the Base Case, are increased when the cartel is expanded. The countries in the GECF+Caspian cartel have jointly 18% (12%) higher profits in 2020 (2030) than in the Base Case, whereas the countries in the GECF+Caspian+Mid-East cartel have jointly 35% (34%) higher profits in 2020 (2030) than in the Base Case. These numbers are significantly bigger than the cartelization gains with only the GECF members. Thus, the results may suggest that if not only current GECF members but also other Middle Eastern countries as well as Caspian countries are ready to form a gas cartel, the benefits from cartelization could be substantial, and possibly large enough to overcome the hurdles discussed before.

When considering the profits of individual cartel members, Figure 14 shows that all members except the Caspian region ("Kazakhstan") benefit from cartelization in one or both of the two extended cartel cases in 2020. In 2030, (relative to the Base Case). however, other members also stand to lose. On the other hand, Russia now gains significantly from being part of the cartel, as opposed to in the GECF Cartel Case when for example, the Caspian region is not part of the cartel. The explanation is presumably a combination of less reduction in Russian output when more countries join the cartel, and higher export prices as new member countries (especially neighboring countries in the Caspian region) decrease instead of increase their output (see Figure 8 and Figure 17 for 2020). Figure 14 and Figure 15 also show that both the Caspian region and the non-GECF Middle Eastern countries ("Yemen") are much better off as free-riders outside a cartel than as cartel members. This is not surprising – gas exporting countries outside the cartel will benefit from higher prices without having to reduce export volumes. These aspects obviously influence the likelihood of establishing an effective gas cartel.

4.3. Other Sensitivity Cases: Results

In this subsection the importance of unconventional gas in the United States, and gas transport costs, respectively, are explored. That is, would the effects from cartelization have been bigger without the recent increase in shale gas and other unconventional gas reserves in the United States? And, how will the profits of cartelization change if costs of gas transport are reduced? Only the GECF Cartel Case is considered in these sensitivity analyses, and then compared to the revised cartel cases with revised base cases.

The increased estimates of unconventional gas reserves in the United States have implied that projected imports of gas to the United States are substantially lower than a few years back, and the results above have shown that gas cartelization has negligible impacts on the North American gas market. Thus, it is reasonable to presume that without this increase in gas reserves, a gas cartel would be more able to make additional profits in this market.

As expected, the model simulations suggest that with less unconventional gas reserves in the United States, gas prices in North America go up and consumption goes down, both in the revised Base Case and in the revised Cartel Case (see Figure 19, Figure 22). Prices and consumption in other regions of the world are hardly affected at all. Furthermore, the effects of cartelization on prices and consumption in North America are still small, but not as negligible as before.

Figure 19. World Gas Model Sensitivity Cases, Average Wholesale Prices by Regions, $/million BTU, 2020

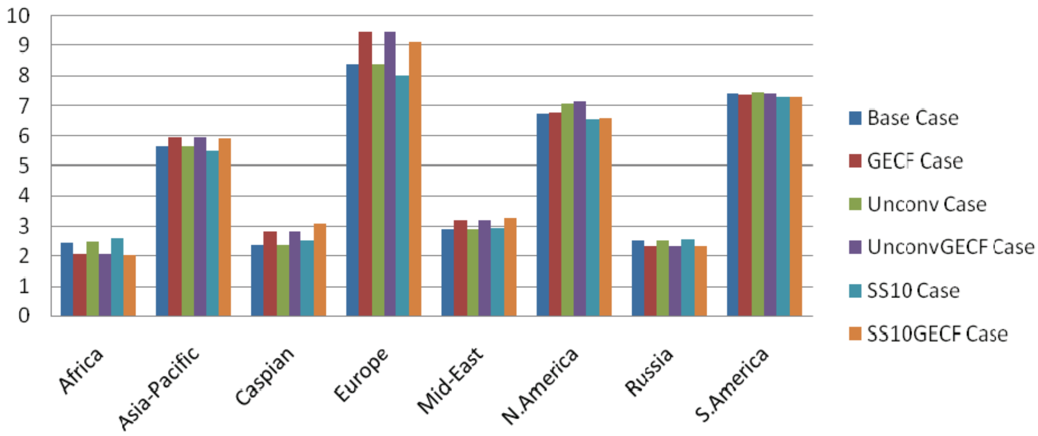


Figure 20. World Gas Model Sensitivity Cases, Average Wholesale Prices by Regions, $/million BTU, 2030

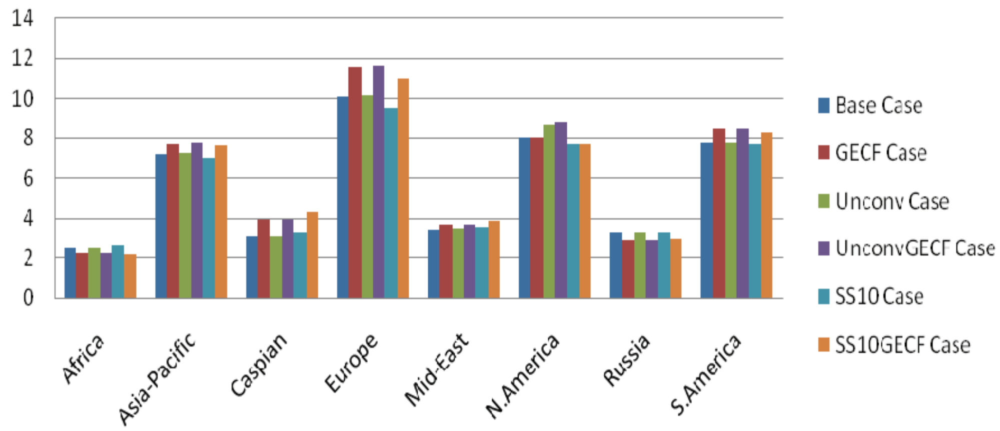


Figure 21. World Gas Model Sensitivity Cases, Consumption by Regions, billions of cubic meters/year, 2020

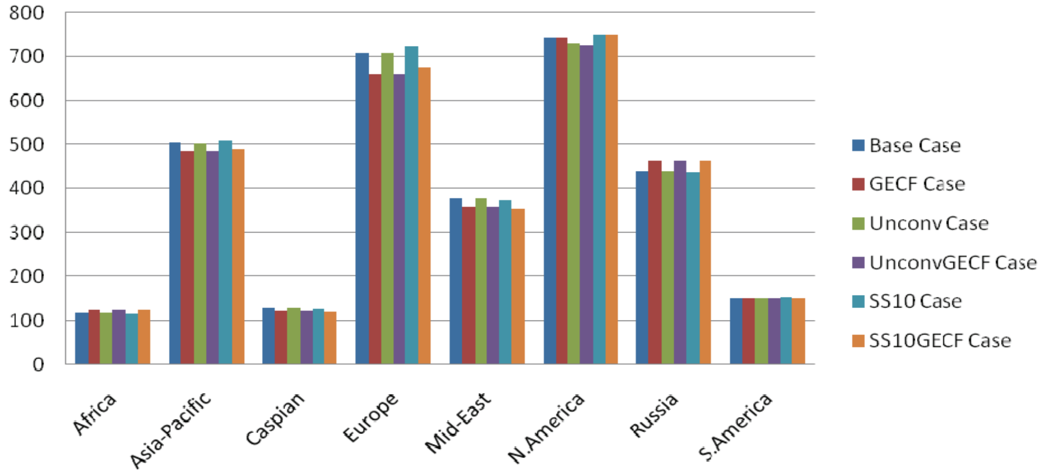
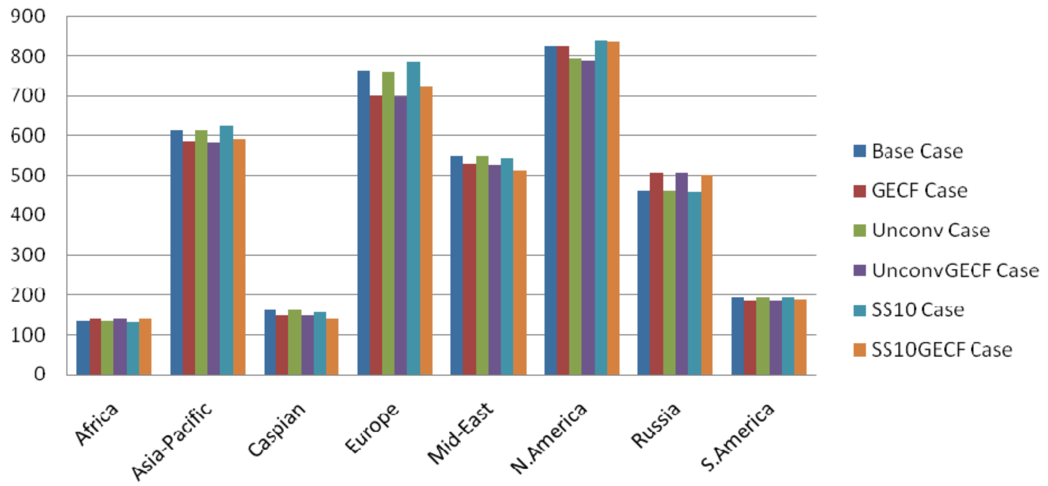


Figure 22. World Gas Model Sensitivity Cases, Consumption by Regions, billions of cubic meters/year, 2030



Gas production in North America obviously falls both with and without a gas cartel when unconventional reserves are reduced, but the impacts of cartelization are about the same as it was without this reduction in reserves. Production in other regions is more or less the same as before, whereas imports into the United States are slightly increased. Further, the effects of cartelization on U.S. imports are somewhat bigger than without reduction in U.S. gas reserves, which is consistent with the slightly bigger price effect.

Although the U.S. market would have been slightly more affected by cartelization if unconventional gas reserves were lower, the gains from cartelization are not changed. Thus, we may conclude that the recent uptick in U.S. gas reserves has not affected the likelihood of cartelization in international gas markets.

Lower transport costs make it easier (i.e., cheaper) for gas producers to export their gas to markets farther away, and thus exploit their market power in more markets overall. This is important as the biggest gas reserve countries (and GECF members) are located quite close to each other, and far from regions such as the Americas. On the other hand, lower transport costs can make it more difficult to exploit market power in closer areas, as gas consumers can more easily import gas from alternative gas suppliers. Reduced costs of transport in the gas market generally lead to lower prices and increased consumption in importing regions.[17] On the other hand, prices in export regions will tend to go up as more gas is exported and marginal costs of domestic production increase. This pattern is seen for example in Table 12, Table 13,
Table 14, Table 15 although the figures are small The price and consumption effects of cartelization, however, are more or less the same as before, although slightly bigger for some regions (e.g., 14% instead of 13% price increase in Europe in 2020).

Production of gas is higher in most regions in the revised Base Case, i.e., with lower transport costs. The exception is Europe, where domestic producers are outperformed by cheaper imports. Again, the impacts of cartelization are not very different from the previous results, although regions like Africa and Europe see somewhat bigger reductions and expansions, respectively, in their production. Not surprisingly, overall trade is higher with lower transport costs, and we also find that the cartelization brings about a slightly larger cutback in trade than in the original GECF Cartel Case.

Consistent with slightly bigger impacts on prices and quantities, the GECF as a group profits somewhat more from cartelization when transport costs are reduced. Their joint profits now increase by 8% in 2020 vs. 5% in the original GECF Cartel Case. In 2030 the change in profits is more or less the same as before, however. Thus, we might conclude that a more integrated gas market following reductions in gas transportation costs will increase the profits and thus the likelihood of gas cartelization, although not substantially. Furthermore, a combination of lower transport costs and more members of GECF could definitely increase the effectiveness of coordinated supply cuts, with GECF becoming closer to a “gas-OPEC”.

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[17] As shown in Rosendahl and Sagen (2009), prices can in fact increase in some import regions if the exporting region finds it profitable to increase exports to more distant markets.

5. Conclusions & Future Work

Natural gas is increasingly a fuel of choice in power generation as well as other sectors and securing reliable supplies are important for many countries especially in regions rely heavily on imports e.g., Europe. In this paper, using the World Gas Model, the effects of a gas cartel along the lines of the Gas Exporting Countries Forum (GECF) have been analyzed. Besides the basic GECF member countries, additional ones have also been added to see the supplemental influence on regional prices, consumption, and production.

In the most extreme scenario where GECF, the Caspian, and the Middle Eastern countries all form a cartel, the effects are dramatic. For example, in 2030, as compared to a Base Case, Europe sees an increase of $3.69 per million BTU or $91.4 billion in lost consumer surplus due to the effects of this supra-GECF cartel. Consequently European consumption of gas drops by about 21% which would be a dramatic change. By contrast, North America sees almost no change in prices, consumption, nor production being isolated to some extent.

By contrast, when the unconventional gas resource base in the United States is diminished, North America faces some changes in gas prices and consumption but the rest of the world is hardly affected. Lastly, lower transportation costs don't dramatically change prices in most regions except for Europe which sees lower values with or without the presence of the GECF cartel.

Future work on gas markets could include better characterizations of the shale gas basins in the United States and elsewhere and their effects on increasing global supply and reducing prices. A natural question is whether or not the large U.S. shale gas resource if exported to other parts of the world would be enough to offset effects of a potential cartel.

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Appendix A

This Appendix presents the optimization problems and market-clearing conditions that constitute the World Gas Model. The modeled market agents include producers (P), traders (T), liquefiers (L), LNG shipment, regasifiers (R), transmission system operator, storage operators (S), marketers (M) and several consumption sectors (K1, K2, K3).

Producers sell gas to their trading arms. Traders ship gas to consumer markets, domestically via distribution networks, or internationally via high pressure pipeline networks or LNG terminals, ships and regasifiers in other countries. Traders make use of storage services to balance their flows among seasons.

Nomenclature

This subsection lists the symbols used.

Sets

$a \in A$	Gas transportation arcs, e.g., {NNED_GER, LNOR_FRA, RGER_GER}[18]
$d \in D$	Demand seasons, e.g., {low, high}
$p \in P$	Producers, e.g., {P_NOR, P_RUW, P_RUE }
$m \in M$	Years, e.g., {2005, 2010, 2015, 2020}
$n \in N$	Model nodes[19], e.g., {N_NOR, N_RUW}
$s \in S$	Storage facilities, e.g., {S_NED, S_GER}
$t \in T$	Traders, e.g., {T_NOR, T_RUS}
$a^{+}(n)$	Inward arcs
$a^{-}(n)$	Outward arcs

For subsets of nodes where a player *x* is present, we use *N(x).* To refer to individual nodes in this set, we write *n(x)*. Similarly, to denote the subset of agents *X* present at node *n*, we use: *X(n)*, (e.g. *T(n)* are the traders with access to node *n)*; and to refer to individual set elements of this set, we write *x(n)*. The set elements are used as subscripts and super scripts in the other symbols.

[18] The first letter indicates the type of arc, combinations of three letters denote the region of country name. NNED_GER represents a pipeline from the Netherlands to Germany; LNOR_FRA an LNG shipping arc from the Norwegian liquefaction node to the regasification node of France and RGER_GER the arc from the German regasification node to the German country node. NNIG_LNG would denote the arc from the country node Nigeria to the Nigerian liquefaction node.

[19] Model nodes represent geographical regions in the world. They can be defined flexibly in the model data set. Due to the limited relevance and impact of countries that only produce and consume small amounts, several countries have been grouped with neighboring ones and are represented in the model data set on an aggregate level. For some countries the opposite is true: their consumption or production is so high, and the geographical distances so large, that a division of the countries in several regions is warranted.

Input parameters

b_{am}^{A} Arc capacity expansion costs (k$/mcm/d)

b_{sm}^{SI} Storage injection capacity expansion costs (k$/mcm)

b_{sm}^{SX} Storage extraction capacity expansion costs (k$/mcm)

b_{sm}^{SW} Storage working gas capacity expansion costs (k$/mcm)

$c_{pm}^{P}(.)$ Production costs (k$/mcm)

$\overline{CAP}_{am}^{A}$ Arc capacity (mcm/d)[20]

$\overline{CAP}_{sm}^{SI}$ Storage injection capacity (mcm/d)[20]

$\overline{CAP}_{sm}^{SX}$ Storage extraction capacity (mcm/d)[20]

CON_{tadm}^{T} Contractual supply obligation (mcm/d)[20]

δ_{tn}^{C} Level of market power exerted by trader in a market, $\delta_{tn}^{C} \in [0,1]$;

0 is perfectly competitive, 1 is fully Cournot.

$days_d$ Number of days in season, e.g., $days_{low}$=183

$\overline{\Delta}_{am}^{A}$ Upper bound of arc capacity expansion (mcm/d)

$\overline{\Delta}_{sm}^{SI}$ Upper bound of storage injection capacity expansion (mcm/d)

$\overline{\Delta}_{sm}^{SX}$ Upper bound of storage extraction capacity expansion (mcm/d)

$\overline{\Delta}_{sm}^{SW}$ Upper bound of storage working gas capacity expansion (mcm)

γ_m Discount rate in year, $\gamma_m \in (0,1]$

INT_{ndm}^{W} Intercept of inverse demand curve (mcm/d)

$loss_a$ Loss rate of gas in transport arc, $l_a \in [0,1)$

$loss_s$ Loss rate of gas storage injection, $l_s \in [0,1)$

$\overline{PR}_{pm}^{P}$ Daily production capacity (mcm/d)

$\overline{PH}_{p}^{P}$ Total producible reserves in time horizon (mcm)

SLP_{ndm}^{W} Slope of inverse demand curve (mcm/d/k$)

$\tau_{adm}^{A,reg}$ Regulated fee for arc usage (k$/mcm)

[20] Subscript *m* is to account for the year for expansions approved or under construction.

$\tau_{sdm}^{SI,reg}$ Regulated fee for storage injection (k$/mcm)

$\overline{WG}_{sm}^{S}$ Storage working gas capacity (mcm/d) [20]

Variables (all variables are taken to be nonnegative)

Δ_{am}^{A} Arc capacity expansion (mcm/d)

Δ_{snm}^{SI} Storage injection capacity expansion (mcm/d)

Δ_{snm}^{SX} Storage extraction capacity expansion (mcm/d)

Δ_{snm}^{SW} Storage working gas capacity expansion (mcm/d)

$FLOW_{tadm}^{T}$ Arc flow by trader (mcm/d)

INJ_{tndm}^{T} Quantity injected to storage by trader (mcm/d)

$PURCH_{tndm}^{T}$ Quantity bought from producer by trader (mcm/d)

$SALES_{adm}^{A}$ Pipeline capacity assigned to trader (mcm/d)

$SALES_{pdm}^{P}$ Quantity sold by producer to traders (mcm/d)

$SALES_{sdm}^{SI}$ Storage injection capacity assigned for use to traders (mcm/d)

$SALES_{sdm}^{SX}$ Storage extraction capacity assigned for use to traders (mcm/d)

$SALES_{tndm}^{T}$ Quantity sold to end-user markets by trader (mcm/d)

XTR_{tndm}^{T} Quantity extracted from storage by trader (mcm/d)

When presenting restrictions in the formulations below, Greek symbols in parentheses represent the dual variables used in the KKT derivation.

Dual variables

$\alpha, \beta \geq 0$ dual variables to capacity restrictions

φ *free* dual variables to mass balance constraints

$\rho \geq 0$ dual variables to capacity expansion limitations

π *free* duals to market-clearing conditions for sold and bought quantities

τ *free* duals market-clearing conditions for capacity assignment and usage.

In what follows, we describe the representation of the producer and other players.

Producer Problem

A producer *p* is modeled as maximizing his discounted profits, which are the result of revenues from sales $SALES^{P}_{pdm}$ minus production costs. Cash flows in year *m* are discounted with a factor γ_m. Since sales-rates are per day and may differ by season, the sales-rates and production costs are multiplied by the number of days in the season: $days_d$.

$$\max_{SALES^{P}_{pdm}} \sum_{m\in M} \gamma_m \sum_{d\in D} days_d \left[\pi^{P}_{n(p)dm} SALES^{P}_{pdm} - c^{P}_{pm}(SALES^{P}_{pdm}) \right] \quad \textbf{(A.1)}$$

The sales-rate is restricted by a production capacity $\overline{PR}^{P}_{pm}$ (that can vary by year):

$$s.t. \quad SALES^{P}_{pdm} \le \overline{PR}^{P}_{pm} \quad \forall d,m \quad \left(\alpha^{PR}_{pdm}\right) \quad \textbf{(A.2)}$$

Due to reserve limitations or governmental restrictions the aggregate production over all years in a time period is restricted by a production ceiling $\overline{PH}_p$.

$$\sum_{m\in M} \sum_{d\in D} days_d SALES^{P}_{pdm} \le \overline{PH}_p \quad \forall m \quad \left(\alpha^{PH}_{p}\right) \quad \textbf{(A.3)}$$

Lastly, the sales-rate must be nonnegative:

$$SALES^{P}_{pdm} \ge 0 \quad \forall d,m \quad \textbf{(A.4)}$$

The KKT conditions for the producer and all other agents can be found at the end of this Appendix. The market player described in the following sub-section is the trader.

Trader Problem

The trader maximizes profits resulting from selling gas to marketers ($SALES^{T}_{tndm}$), net of the gas purchasing costs and the costs: a regulated fee $\tau^{A,reg}_{adm}$ plus a congestion fee τ^{A}_{adm}, to transport the gas ($FLOW^{T}_{tadm}$) over high pressure pipelines *a*. The parameter $\delta^{C}_{tn} \in [0,1]$ indicates the level of market power exerted by a trader at a consumption node, with 0 representing perfect competitive behavior and 1 representing perfect Nash-Cournot oligopolistic behavior. Values between 0 and 1 indicate that we assume that some market power is exerted by the trader, but diluted relative to Cournot competition. The expression $\left(\delta^{C}_{tn}\Pi^{W}_{ndm}(\cdot) + (1-\delta^{C}_{tn})\pi^{W}_{ndm}\right)$ can be viewed as a weighted average of market prices resulting from the inverse demand function $\Pi^{W}_{ndm}(\cdot)$ and a perfectly competitive market-clearing wholesale price π^{W}_{ndm}. The trader also decides how much gas to inject in and extract from storage. The costs for injection are a regulated fee and a congestion rate; costs for extraction are a congestion rate only. Thus, trader *t* is modeled as solving the following optimization problem.

$$\max_{\substack{SALES^T_{tndm}\\PURCH^T_{tndm}\\FLOW^T_{tadm}\\INJ^T_{tndm}\\XTR^T_{tndm}}} \sum_{m\in M}\gamma_m \sum_{d\in D} days_d \left\{ \begin{array}{l} \sum_{n\in N(t)} \left[\begin{array}{l} \left(\delta^C_{tn}\Pi^W_{ndm}(\cdot)+(1-\delta^C_{tn})\pi^W_{ndm}\right)SALES^T_{tndm} \\ -\pi^P_{ndm}PURCH^T_{tndm} \\ -\sum_{s\in S(t)}\left(\begin{array}{l}\left(\tau^{SI,reg}_{sndm}+\tau^{SI}_{sndm}\right)INJ^T_{tndm} \\ + \quad \tau^{SX}_{sndm}XTR^T_{tndm}\end{array}\right)\end{array}\right] \\ -\left(\sum_{a\in A(t)}\left(\tau^{A,reg}_{adm}+\tau^{A}_{adm}\right)FLOW^T_{tadm}\right)\end{array}\right\} \quad \textbf{(A.5)}$$

Traders need to preserve mass balance at every node *n* in every season *d* of every year *m*:[21]

$$s.t. \quad \begin{array}{l} PURCH^T_{tndm}+\sum_{a\in a^+(n)}\left(1-loss_a\right)FLOW^T_{tadm}+XTR^T_{tndm}= \\ SALES^T_{tndm}+\sum_{a\in a^-(n)}FLOW^T_{tadm}+INJ^T_{tndm} \quad \forall n,d,m \ \left(\varphi^T_{tndm}\right)\end{array} \quad \textbf{(A.6)}$$

In each yearly storage cycle the total extracted volumes must equal the loss-corrected injection volumes.

$$\left(1-loss_s\right)\sum_{d\in D} days_d INJ^T_{tsdm}=\sum_{d\in D} days_d XTR^T_{tsdm} \quad \forall n,s\in S\left(N(t)\right),d,m \quad \left(\varphi^S_{tsdm}\right) \quad \textbf{(A.7)}$$

Some traders have contractual obligations, that can be modeled as follows:[22]

$$FLOW^T_{tadm}\geq CON^T_{tadm} \quad \forall a,d,m \quad \left(\varepsilon^T_{tadm}\right) \quad \textbf{(A.8)}$$

All other constraints are nonnegativity of variables:

$$SALES^T_{tndm}\geq 0 \quad \forall n,d,m \quad \textbf{(A.9)}$$

$$PURCH^T_{tndm}\geq 0 \quad \forall n,d,m \quad \textbf{(A.10)}$$

$$FLOW^T_{tadm}\geq 0 \quad \forall a,d,m \quad \textbf{(A.11)}$$

$$INJ^T_{tndm}\geq 0 \quad \forall n,d,m \quad \textbf{(A.12)}$$

$$XTR^T_{tndm}\geq 0 \quad \forall n,d,m \quad \textbf{(A.13)}$$

The inverse demand curve $\Pi^W_{ndm}(\cdot)$ is presented later.

The next section describes the transmission system operator, who is responsible for assigning available capacities to the traders needing transport capacity for exporting gas; and for expansions of the international transportation capacities. The international high pressure pipelines as well as the various

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[21] Pipeline losses are accounted for in this mass-balance equation; in contrast the storage loss-rate is accounted for in the storage-cycle constraint, equation (A.7).

steps of the LNG supply chain are represented as arcs with appropriate costs, losses and capacities. The underlying assumption is that all transportation infrastructure agents are regulated players.

Transmission system operator problem

The transmission system operator (TSO) provides an economic mechanism to efficiently allocate international transport capacity to traders. The TSO maximizes the discounted profit resulting from selling arc capacity to traders $SALES^{A}_{adm}$ minus investment costs for capacity expansions Δ^{A}_{am} . Loosely speaking, regulators base the maximum infrastructure usage charges (*regulated fees*) on the long-term marginal costs, i.e. the operating and maintenance costs plus a margin to earn a return on investment. In the model we make the simplified assumption that the regulated fees collected from the traders are to equal the costs; therefore the profit margin is equal to the congestion fee τ^{A}_{adm} . Note that these congestion fees are not paid in actuality, but merely facilitate the efficient allocation of a scarce capacity in the model.

$$\max_{\substack{SALES^{A}_{adm} \\ \Delta^{A}_{am}}} \sum_{m\in M} \gamma_m \left\{ \sum_{d\in D} days_d \sum_{a} \tau^{A}_{adm} SALES^{A}_{adm} - \sum_{a} b^{A}_{am} \Delta^{A}_{am} \right\} \qquad \textbf{(A.14)}$$

The assigned capacity is restricted by the available capacity. Available arc capacity at arc *a* is the sum of the initial arc capacity $\overline{CAP}^{A}_{am}$ and capacity expansions in the previous years $\sum_{m'<m} \Delta^{A}_{am'}$.

$$SALES^{A}_{adm} \le \overline{CAP}^{A}_{am} + \sum_{m'<m} \Delta^{A}_{am'} \quad \forall a,d,m \quad \left(\alpha^{A}_{adm}\right) \qquad \textbf{(A.15)}$$

There may be budgetary or other limits to the yearly capacity expansions:

$$\Delta^{A}_{am} \le \overline{\Delta}^{A}_{am} \quad \forall a,m \qquad \left(\rho^{A}_{am}\right) \qquad \textbf{(A.16)}$$

Lastly, all variables are nonnegative:

$$SALES^{A}_{adm} \ge 0 \qquad \textbf{(A.17)}$$

$$\Delta^{A}_{am} \ge 0 \qquad \textbf{(A.18)}$$

The following presents the storage operator problem.

Storage Operator Problem

The storage operator provides an economic mechanism to efficiently allocate storage capacity to traders. The storage operator maximizes the discounted profit resulting from selling injection capacity $SALES^{SI}_{sdm}$ and extraction capacity $SALES^{SX}_{sdm}$ to traders. In equilibrium the capacity sales-rates $SALES^{SI}_{sdm}$ and $SALES^{SX}_{sdm}$ must be equal to the aggregate injection and extraction rates. Similarly as for the TSO, we take as a starting point that the regulator sets a maximum capacity usage fee based on

the long-term marginal costs. Our simplified assumption is that the regulated fees collected from the traders equal the operating costs and therefore in the model the profit margin is equal to the congestion fees for injection τ^{SI}_{sdm} and extraction τ^{SX}_{sdm}. Note that these congestion fees are not paid in actuality, cf. the pipeline congestion fees. Besides the regulated tariffs for injection and extraction, costs may be accrued to expand capacities for injection, extraction and total working gas:
$b^{SI}_{sm}\Delta^{SI}_{sm} + b^{SX}_{sm}\Delta^{SX}_{sm} + b^{SW}_{sm}\Delta^{SW}_{sm}$.

$$\max_{\substack{SALES^{SI}_{sdm},\\ SALES^{SX}_{sdm},\\ \Delta^{SI}_{sm},\Delta^{SX}_{sm},\Delta^{SW}_{sm}}} \quad \sum_{m\in M}\gamma_m \sum_{d\in D} days_d \begin{Bmatrix} \tau^{SI}_{sdm}SALES^{SI}_{sdm} + \tau^{SX}_{sdm}SALES^{SX}_{sdm} \\ -b^{SI}_{sm}\Delta^{SI}_{sm} - b^{SX}_{sm}\Delta^{SX}_{sm} - b^{SW}_{sm}\Delta^{SW}_{sm} \end{Bmatrix} \qquad \textbf{(A.19)}$$

The aggregate injection rate in any season is restricted by the injection capacity (A.20). Injection capacities can be expanded; therefore the aggregate previous yearly expansions $\sum_{m'<m}\Delta^{SI}_{sm'}$ must be added to the initial capacity $\overline{INJ}^{S}_{s}$ to determine the total capacity. Equation (A.21) provides the limits to extraction from storage and condition (A.22) represents the working gas limitations.

s.t.

$$SALES^{SI}_{sdm} \le \overline{CAP}^{SI}_{s} + \sum_{m'<m}\Delta^{SI}_{sm'} \quad \forall m,d \quad \left(\alpha^{SI}_{sdm}\right) \qquad \textbf{(A.20)}$$

$$SALES^{SX}_{sdm} \le \overline{CAP}^{SX}_{s} + \sum_{m'<m}\Delta^{SX}_{sm'} \quad \forall m,d \quad \left(\alpha^{SX}_{sdm}\right) \qquad \textbf{(A.21)}$$

$$\sum_{d\in D} days_d SALES^{SX}_{sdm} \le \overline{WG}^{S}_{s} + \sum_{m'<m}\Delta^{SW}_{sm'} \quad \forall m \quad \left(\alpha^{SW}_{sm}\right) \qquad \textbf{(A.22)}$$

The limitations to allowable capacity expansions are modeled as follows:

$$\Delta^{SI}_{sm} \le \overline{\Delta}^{SI}_{sm} \quad \forall m \quad \left(\rho^{SI}_{sm}\right) \qquad \textbf{(A.23)}$$

$$\Delta^{SX}_{sm} \le \overline{\Delta}^{SX}_{sm} \quad \forall m \quad \left(\rho^{SX}_{sm}\right) \qquad \textbf{(A.24)}$$

$$\Delta^{SW}_{sm} \le \overline{\Delta}^{SW}_{sm} \quad \forall m \quad \left(\rho^{SW}_{sm}\right) \qquad \textbf{(A.25)}$$

Note that mass balance for each storage facility (the *storage cycle* constraint) including accounting for losses, is dealt with (for each separate trader) in equation (A.7).

Lastly, all variables are nonnegative:

$$SALES^{SI}_{sdm} \ge 0 \quad \forall m,d \qquad \textbf{(A.26)}$$

$$SALES^{SX}_{sdm} \ge 0 \quad \forall m,d \qquad \textbf{(A.27)}$$

$$\Delta^{SI}_{sm} \ge 0 \quad \forall m \qquad \textbf{(A.28)}$$

$$\Delta^{SX}_{sm} \ge 0 \quad \forall m \qquad \textbf{(A.29)}$$

$$\Delta^{SW}_{sm} \ge 0 \quad \forall m \qquad \textbf{(A.30)}$$

Market-Clearing Conditions

The following are the market-clearing conditions that tie the various optimization problems together into one equilibrium problem.

Market-clearing between producers and traders:

$$SALES^{P}_{pdm} = \sum_{t(p)} PURCH^{T}_{tn(p)dm} \quad \forall p,d,m \quad \left(\pi^{P}_{n(p)dm}\right) \tag{B.1}$$

Market-clearing for storage injection capacity and volumes:

$$SALES^{SI}_{sdm} = \sum_{t\in T(N(s))} INJ^{T}_{tsdm} \quad \forall s,d,m \quad \left(\tau^{SI}_{sdm}\right) \tag{B.2}$$

Market-clearing for storage extraction capacity and volumes:

$$SALES^{SX}_{sdm} = \sum_{t\in T(N(s))} XTR^{T}_{tsdm} \quad \forall s,d,m \quad \left(\tau^{SX}_{sdm}\right) \tag{B.3}$$

Market-clearing between the TSO and the traders for arc capacity and flows:

$$SALES^{A}_{adm} = \sum_{t} FLOW^{T}_{tadm} \quad \forall a,d,m \quad \left(\tau^{A}_{adm}\right) \tag{B.4}$$

The clearing of the final demand is represented as the inverse demand curve:

$$\left(\Pi^{W}_{ndm}(\cdot)=\right) \pi^{W}_{ndm} = INT^{W}_{ndm} + SLP^{W}_{ndm} \cdot \sum_{t} SALES^{T}_{tndm} \quad \forall n,d,m \quad \left(\pi^{W}_{ndm}\right) \tag{B.5}$$

Karush-Kuhn-Tucker Conditions

In the KKT's the left-hand sides (relative to the $\perp$-sign) are the equations, the right-hand sides the variables. Most primal variables are denoted as normal words in capitals, except for capacity expansions, which are denoted by Greek letter Δ; all dual variables are written as Greek symbols.

KKT conditions for the producer's problem

$$0 \le \gamma_m days_d \left(-\pi^{P}_{n(p)dm} + \frac{\partial c^{P}_{pm}(SALES^{P}_{pdm})}{\partial SALES^{P}_{pdm}}\right) + \alpha^{PR}_{pdm} + days_d \alpha^{PH}_{pdm} \perp SALES^{P}_{pdm} \ge 0, \forall d,m \tag{C.1}$$

$$0 \le \overline{PR}^{P}_{pm} - SALES^{P}_{pdm} \quad \perp \quad \alpha^{PR}_{pdm} \ge 0, \quad \forall d,m \tag{C.2}$$

$$0 \le \overline{PH}_{p} - \sum_{m\in M}\sum_{d\in D} days_d SALES^{P}_{pdm} \quad \perp \quad \alpha^{PH}_{pdm} \ge 0 \tag{C.3}$$

KKT conditions for the trader's problem

$$0 \le days_d \gamma_m \begin{pmatrix} \delta^C_{t,n} SLP^W_{ndm} SALES^T_{tndm} \\ -\left(\delta^C_{t,n}\Pi^W_{ndm} + (1-\delta^C_{t,n})\pi^W_{ndm}\right) \end{pmatrix} + \phi^T_{tndm} \perp SALES^T_{tndm} \ge 0, \quad \forall n,d,m \tag{C.4}$$

$$0 \le days_d \gamma_m \pi^P_{ndm} - \phi^T_{tndm} \quad \perp \quad PURCH^T_{tndm} \ge 0, \quad \forall n \in N(p(t)), d, m \tag{C.5}$$

$$0 \le days_d \gamma_m \left(\tau^{SI,reg}_{ndm} + \tau^{SI}_{ndm}\right) + \phi^T_{tndm} - \left(1 - loss_n\right) days_d \phi^S_{tnm} \perp INJ^T_{tdnm} \ge 0, \quad \forall n,m \tag{C.6}$$

$$0 \le days_d \gamma_m \tau^{SX}_{ndm} - \phi^T_{tndm} + days_d \phi^S_{tnm} \perp XTR^T_{tndm} \ge 0, \quad \forall n,m \tag{C.7}$$

$$0 \le \begin{matrix} days_d \left[\gamma_m \left(\tau^A_{adm} + \tau^{A,reg}_{adm}\right)\right] \\ +\phi^T_{tn_{a-}dm} - (1-loss_a)\phi^T_{tn_{a+}dm} - \varepsilon^T_{tadm} \end{matrix} \quad \perp \quad FLOW^T_{tadm} \ge 0, \quad \forall a = \left(n_{a-}, n_{a+}\right), d, m \tag{C.8}$$

$$0 = \begin{pmatrix} PURCH^T_{tndm} + \sum_{a \in a^+(n)} \left(1 - loss_a\right) FLOW^T_{tadm} + XTR^T_{tndm} \\ -SALES^T_{tndm} - \sum_{a \in a^-(n)} FLOW^T_{tadm} - INJ^T_{tndm} \end{pmatrix}, \quad \varphi^T_{tndm} free, \quad \forall n,d,m \tag{C.9}$$

$$0 = \left(1 - loss_s\right) \sum_d days_d INJ^T_{tsdm} - \sum_d days_d XTR^T_{tsdm}, \quad \varphi^S_{tsm} \; free, \forall n, s \in S\left(N\left(t\right)\right), d, m \tag{C.10}$$

$$0 \le FLOW^T_{tadm} - CON^T_{tadm} \quad \perp \varepsilon^T_{tadm} \ge 0, \forall a,d,m \tag{C.11}$$

KKT conditions for the transmission system operator's problem

$$0 \le -days_d \gamma_m \tau^A_{adm} + \alpha^A_{adm} \quad \perp \quad SALES^A_{adm} \ge 0 \quad \forall a,d,m \tag{C.12}$$

$$0 \le \overline{CAP}^A_{am} + \sum_{m'<m} \Delta^A_{am'} \quad - SALES^A_{adm} \perp \quad \alpha^A_{adm} \ge 0 \quad \forall a,d,m \tag{C.13}$$

$$0 \le \gamma_m b^A_{am} - \sum_{d \in D} \sum_{m'>m} \alpha^A_{adm'} + \rho^A_{am} \quad \perp \quad \Delta^A_{am} \ge 0 \quad \forall a,m \tag{C.14}$$

$$0 \le \overline{\Delta}^A_{am} - \Delta^A_{am} \quad \perp \quad \rho^A_{am} \ge 0 \quad \forall a,m \tag{C.15}$$

KKT conditions for storage operator's problem

$$0 \le -days_d \gamma_m \tau^{SI}_{sdm} + \alpha^{SI}_{sdm} \perp SALES^{SI}_{sdm} \ge 0, \quad \forall d,m \tag{C.16}$$

$$0 \le -days_d \gamma_m \tau^{SX}_{sdm} + \alpha^{SX}_{sdm} + days_d \alpha^{SW}_{sm} \perp SALES^{SX}_{sdm} \ge 0, \quad \forall d,m \tag{C.17}$$

$$0 \le \gamma_m b^{SI}_{sm} - \sum_{d \in D} \sum_{m'>m} \alpha^{SI}_{sdm'} + \rho^{SI}_{sm} \quad \perp \quad \Delta^{SI}_{sm} \ge 0, \quad \forall m \tag{C.18}$$

$$0 \le \gamma_m b^{SX}_{sm} - \sum_{d \in D} \sum_{m'>m} \alpha^{SX}_{sdm'} + \rho^{SX}_{sm} \quad \perp \quad \Delta^{SX}_{sm} \ge 0, \quad \forall m \tag{C.19}$$

$$0 \le \gamma_m b^{SW}_{sm} - \sum_{d \in D} \sum_{m'>m} \alpha^{SW}_{sm'} + \rho^{SW}_{sm} \quad \perp \quad \Delta^{SW}_{sm} \ge 0, \quad \forall m \tag{C.20}$$

$$0 \le \overline{CAP}^{SI}_{sm} + \sum_{m'<m} \Delta^{SI}_{sm'} - SALES^{SI}_{sdm} \quad \perp \quad \alpha^{SI}_{sdm} \ge 0 \qquad \forall m,d \tag{c.21}$$

$$0 \le \overline{CAP}_{sm}^{SI} + \sum_{m'<m} \Delta_{sm'}^{SX} - SALES_{sdm}^{SX} \perp \alpha_{sdm}^{SX} \ge 0 \quad \forall m,d \tag{C.22}$$

$$0 \le \overline{WG}_{s}^{S} + \sum_{m'<m} \Delta_{sm'}^{SW} - \sum_{d \in D} days_d SALES_{sdm}^{SX} \perp \alpha_{sm}^{SW} \ge 0 \quad \forall m \tag{C.23}$$

$$0 \le \overline{\Delta}_{sm}^{SI} - \Delta_{sm}^{SI} \perp \rho_{sm}^{SI} \ge 0 \quad \forall m \tag{C.24}$$

$$0 \le \overline{\Delta}_{sm}^{SX} - \Delta_{sm}^{SX} \perp \rho_{sm}^{SX} \ge 0 \quad \forall m \tag{C.25}$$

$$0 \le \overline{\Delta}_{sm}^{SW} - \Delta_{sm}^{SW} \perp \rho_{sm}^{SW} \ge 0 \quad \forall m \tag{C.26}$$

Market-clearing conditions

$$0 = SALES_{pdm}^{P} - \sum_{t(n) \in T(p)} PURCH_{t(n)n(p)dm}^{T} \quad , \quad \pi_{n(p)dm}^{P} \; free \quad \forall p,d,m \tag{C.27}$$

$$0 = SALES_{adm}^{A} - \sum_{t} FLOW_{tadm}^{T} \quad , \quad \tau_{adm}^{A} \; free \quad \forall a,d,m \tag{C.28}$$

$$0 = SALES_{sdm}^{SI} - \sum_{t \in T(N(s))} INJ_{tsdm}^{T} \quad , \quad \tau_{sdm}^{SI} \; free \quad \forall s,d,m \tag{C.29}$$

$$0 = SALES_{sdm}^{SX} - \sum_{t \in T(N(s))} XTR_{tsdm}^{T} \quad , \quad \tau_{sdm}^{SX} \; free \quad \forall s,d,m \tag{C.30}$$

$$0 = \pi_{ndm}^{W} - \left(INT_{ndm}^{W} - SLP_{ndm}^{W} \cdot \sum_{t \in T(n)} SALES_{tndm}^{T} \right) \quad , \pi_{ndm}^{W} free \;\; \forall n,d,m \tag{C.31}$$

The combination of all the Karush-Kuhn-Tucker conditions, the market-clearing conditions and inverse demand curves form the MCP. All minimization objective functions are convex and differentiable and all feasible regions are polyhedral, thus, the KKT points for this system are necessary and sufficient for optimal solutions.

Appendix B

This Appendix provides tabular data to support the figures and conclusions.

Table 6 Prices by region in $/MMBTU for 2020, Cartel Cases

Region	Base	GECF	GECF+Caspian	GECF+Caspian+Middle East
Africa	2.45	2.05	2.08	2.12
Asia-Pacific	5.64	5.96	6.10	6.34
Caspian	2.37	2.83	1.70	1.70
Europe	8.39	9.45	10.50	11.11
Mid-East	2.90	3.15	3.22	2.69
N. America	6.76	6.79	6.80	6.80
Russia	2.53	2.31	2.41	2.43
S. America	7.42	7.37	7.42	7.61

Table 7 Prices by region in $/MMBTU for 2030, Cartel Cases

Region	Base	GECF	GECF+Caspian	GECF+Caspian+Middle East
Africa	2.51	2.20	2.22	2.27
Asia-Pacific	7.20	7.73	7.99	8.33
Caspian	3.09	3.93	2.20	2.24
Europe	10.13	11.61	12.85	13.82
Mid-East	3.45	3.68	3.79	3.14
N. America	8.01	8.02	8.03	8.04
Russia	3.32	2.95	3.05	3.10
S. America	7.77	8.51	8.59	8.78

Table 8 Consumption by region in billions of cubic meters for 2020, Cartel Cases

Region	Base	GECF	GECF+Caspian	GECF+Caspian+Middle East
Africa	118.6	125.2	124.6	124
Asia-Pacific	504	487.2	480.8	466.6
Caspian	130.4	123.5	140.4	140.4
Europe	707.4	660.5	610.2	584.1
Mid-East	377.2	359.8	352.1	387
N. America	744.2	742.7	742.5	742.5
Russia	439.3	465.8	454.8	451.9

Table 9 Consumption by region in billions of cubic meters for 2030, Cartel Cases

Region	Base	GECF	GECF+Caspian	GECF+Caspian+Middle East
Africa	136.6	141.6	141.2	140.2
Asia-Pacific	613.8	586.8	572.7	552.8
Caspian	161.7	147.8	176.3	175.8
Europe	761.6	700	643.7	604.5
Mid-East	550.3	527.5	512.5	568.7
N. America	825.7	825.4	825	824.4
Russia	461.6	506.1	494.3	488.4
S. America	193.7	186.3	185.4	183.1

Table 10 Production by region in billions of cubic meters for 2020, Cartel Cases

Region	Base	GECF	GECF+Caspian	GECF+Caspian+Middle East
Africa	312.5	268.4	273.2	276.9
Asia-Pacific	437.3	422.4	424.8	429.8
Caspian	262.3	285.1	183.3	183.4
Europe	275.7	293.2	301	306
Mid-East	476.5	490.3	481.6	440.7
N. America	725.6	728.2	728.6	728.6
Russia	647.4	594.5	615.6	620.7
S. America	163.2	150.5	151.1	152.4

Table 11 Production by region in billions of cubic meters for 2030, Cartel Cases

Region	Base	GECF	GECF+Caspian	GECF+Caspian+Middle East
Africa	389.8	299.6	303.7	313.4
Asia-Pacific	476.2	480.3	481.9	484.7
Caspian	327.3	345.6	255.1	259.3
Europe	245.5	257.8	259.8	260.3
Mid-East	684.7	693.5	676.9	623.6
N. America	821	821.6	822.1	822.8
Russia	702.9	659.4	672.9	678.5
S. America	198.9	190.3	190.2	192.3

Table 12 Prices by Region in 2020, in $/million BTU, Sensitivity Cases

Region	Base	GECF	Base Low Unconv	GECF Low Unconv	Base Low Tr.cost	GECF Low Tr.cost
Africa	2.45	2.05	2.48	2.05	2.61	2.04
Asia-Pacific	5.64	5.96	5.65	5.96	5.51	5.92
Caspian	2.37	2.83	2.38	2.83	2.50	3.09
Europe	8.39	9.45	8.40	9.46	8.01	9.12
Mid-East	2.90	3.15	2.90	3.15	2.95	3.24
N. America	6.76	6.79	7.05	7.12	6.58	6.61
Russia	2.53	2.31	2.54	2.31	2.56	2.33
S. America	7.42	7.37	7.44	7.40	7.27	7.29

Table 13 Prices by Region in 2030, in $/million BTU, Sensitivity Cases

Region	Base	GECF	Base Low Unconv	GECF Low Unconv	Base Low Tr.cost	GECF Low Tr.cost
Africa	2.51	2.20	2.56	2.20	2.67	2.19
Asia-Pacific	7.20	7.73	7.23	7.77	6.97	7.63
Caspian	3.09	3.93	3.10	3.94	3.33	4.33
Europe	10.13	11.61	10.18	11.63	9.52	11.02
Mid-East	3.45	3.68	3.47	3.70	3.55	3.85
N. America	8.01	8.02	8.72	8.85	7.69	7.72
Russia	3.32	2.95	3.33	2.95	3.34	2.99
S. America	7.77	8.51	7.78	8.55	7.70	8.28

Table 14Consumption by Region in 2020, in BCM, Sensitivity Cases

Region	Base	GECF	Base Low Unconv	GECF Low Unconv	Base Low Tr.cost	GECF Low Tr.cost
Africa	118.6	125.2	118.1	125.2	116	125.3
Asia-Pacific	504	487.2	503.8	487.1	509.7	489.9
Caspian	130.4	123.5	130.3	123.5	128.4	119.7
Europe	707.4	660.5	706.9	660.2	723.6	674.7
Mid-East	377.2	359.8	376.9	359.8	374.3	354.1
N. America	744.2	742.7	730.8	727.4	751.6	749.9
Russia	439.3	465.8	439.1	465.7	436.2	464.2
S. America	151.3	150.8	151.2	150.6	152.6	151.7

Table 15 Consumption by Region in 2030, in BCM, Sensitivity Cases

Region	Base	GECF	Base Low Unconv	GECF Low Unconv	Base Low Tr.cost	GECF Low Tr.cost
Africa	136.6	141.6	135.8	141.6	134	141.7
Asia-Pacific	613.8	586.8	612.6	585.2	623.9	592.9
Caspian	161.7	147.8	161.5	147.6	157.8	141.2
Europe	761.6	700	759.6	699	786.6	723.9
Mid-East	550.3	527.5	549.2	526.1	543.5	513.7
N. America	825.7	825.4	793.5	788	838.6	837.5
Russia	461.6	506.1	460.9	505.9	460	500.5
S. America	193.7	186.3	193.7	186.1	194.3	188.9

Table 16 Production by Region in 2020, in BCM, Sensitivity Cases

Region	Base	GECF	Base Low Unconv	GECF Low Unconv	Base Low Tr.cost	GECF Low Tr.cost
Africa	312.5	268.4	313.8	268.5	319.8	267.4
Asia-Pacific	437.3	422.4	437.6	422.5	438.8	423.7
Caspian	262.3	285.1	262.5	285.3	270.6	291
Europe	275.7	293.2	275.9	293.3	271.3	292.6
Mid-East	476.5	490.3	477.1	490.2	483.1	495.2
N. America	725.6	728.2	707.6	711.1	731	733.7
Russia	647.4	594.5	647.7	594.6	651.1	597.8
S. America	163.2	150.5	163.3	151.3	163	151.3

Table 17 Production by Region in 2030, in BCM, Sensitivity Cases

Region	Base	GECF	Base Low Unconv	GECF Low Unconv	Base Low Tr.cost	GECF Low Tr.cost
Africa	389.8	299.6	397.1	299.7	409.5	297.9
Asia-Pacific	476.2	480.3	476.5	482.2	476.7	480.6
Caspian	327.3	345.6	327.7	345.7	335.1	350.2
Europe	245.5	257.8	246.5	257.9	241.6	257.1
Mid-East	684.7	693.5	687	696.5	698.2	705.2
N. American	821	821.6	771.5	773.5	827.7	828.6
Russia	702.9	659.4	703.7	659.6	703.8	665.9
S. America	198.9	190.3	199.1	192	200.2	193