A Market Equilibrium Approach to Modeling Gas Markets Using the World Gas Model

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CONFERENCE: THE ECONOMICS OF NATURAL GAS, NEW RESEARCH PERSPECTIVES FOR A RAPIDLY-CHANGING WORLD

PARIS

MINES PARISTECH

JUNE 27, 2017

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Outline

1. Brief Overview of International Natural Gas Markets

2. Brief Overview of Optimization/Equilibrium and Game Theory Modeling

3. Highlighted Research Project : Large-scale Nash-Cournot equilibrium model, “Energy Security and the Influence of the Panama Canal on Natural Gas Markets Worldwide” (for Électricité de France, Paris, France)

4. Conclusions

Brief Overview of Natural Gas Markets

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Natural Gas Consumption Projected to Rise Globally

- According to the Energy Information Administration (EIA) at the U.S. Dept. of Energy International Energy Outlook 2016 (IEO 2016), Reference Case
    - Consumption to increase 69% from 3398 billion cubic meters (BCM) in 2012 to 5748 BCM in 2040 (120 trillion cubic feet to 203 Tcf)
    - This is the largest increase in global primary energy consumption

Source: https://www.eia.gov/outlooks/ieo/nat_gas.cfm

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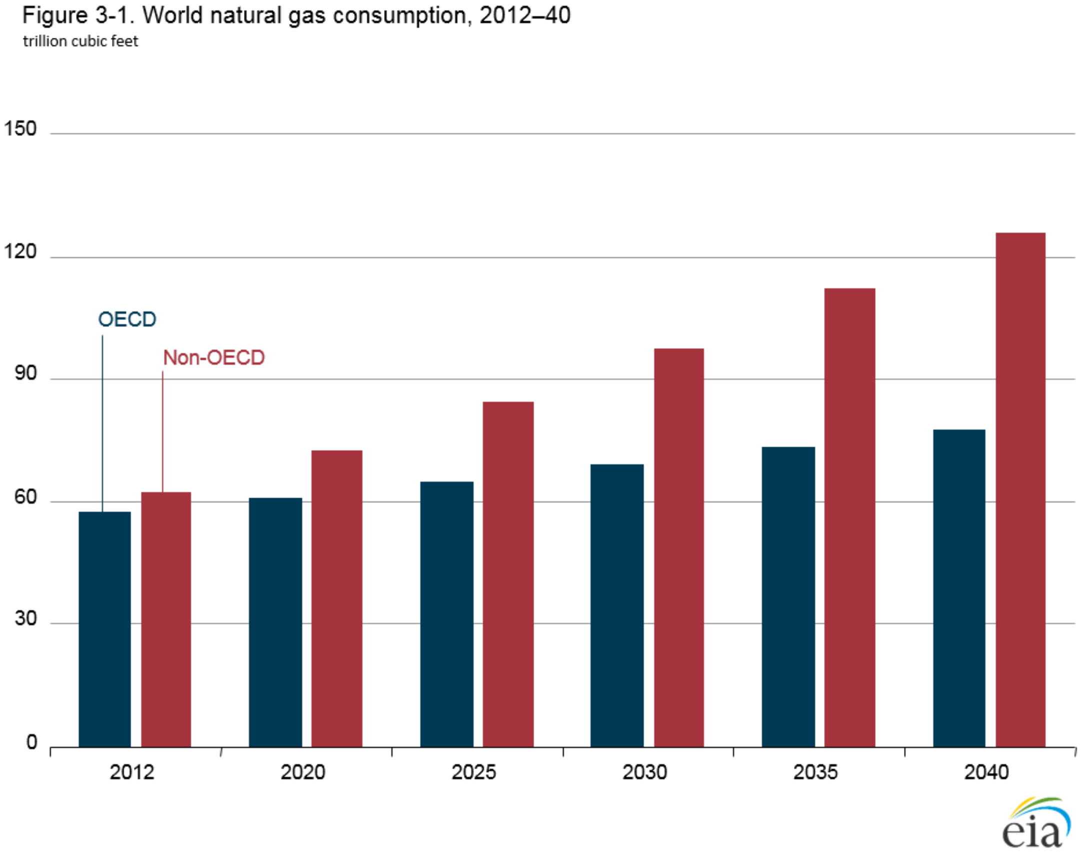
Natural Gas Consumption Projected to Rise Globally

EIA reports

- Every IEO region sees an increase in natural gas consumption
- Consumpton outside the Organization for Economic Cooperation and Development (non-OECD) increasing more than twice as fast as in the OECD
- The strongest growth non-OECD Asia



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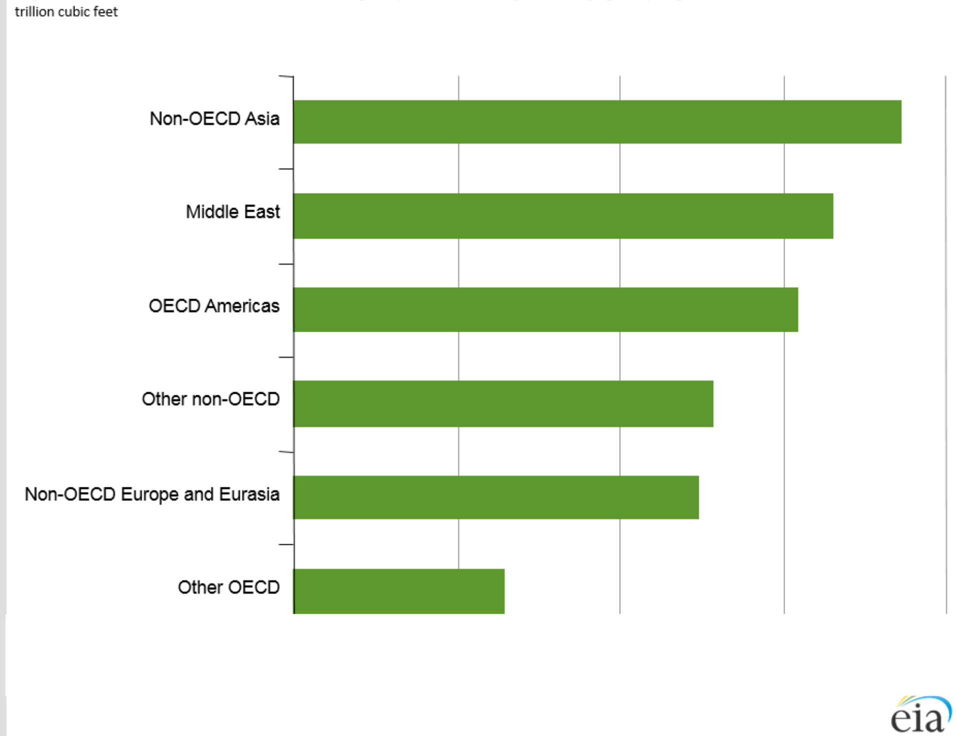
Natural Gas Supply Projections

EIA reports

- Commensurate 69% increase in natural gas supplies globally
- Largest production increases from:
  - Non-OECD Asia (529 BCM)
  - Middle East (470 BCM)
  - OECD Americas (439 BCM)
  - China (425 BCM), shale resources
  - U.S. (320 BCM), shale resourcese
  - Russia (283 BCM), from Arctic & eastern regions

44% of overall increase in global gas production

Figure 3-2. World increase in natural gas production by country grouping, 2012–40

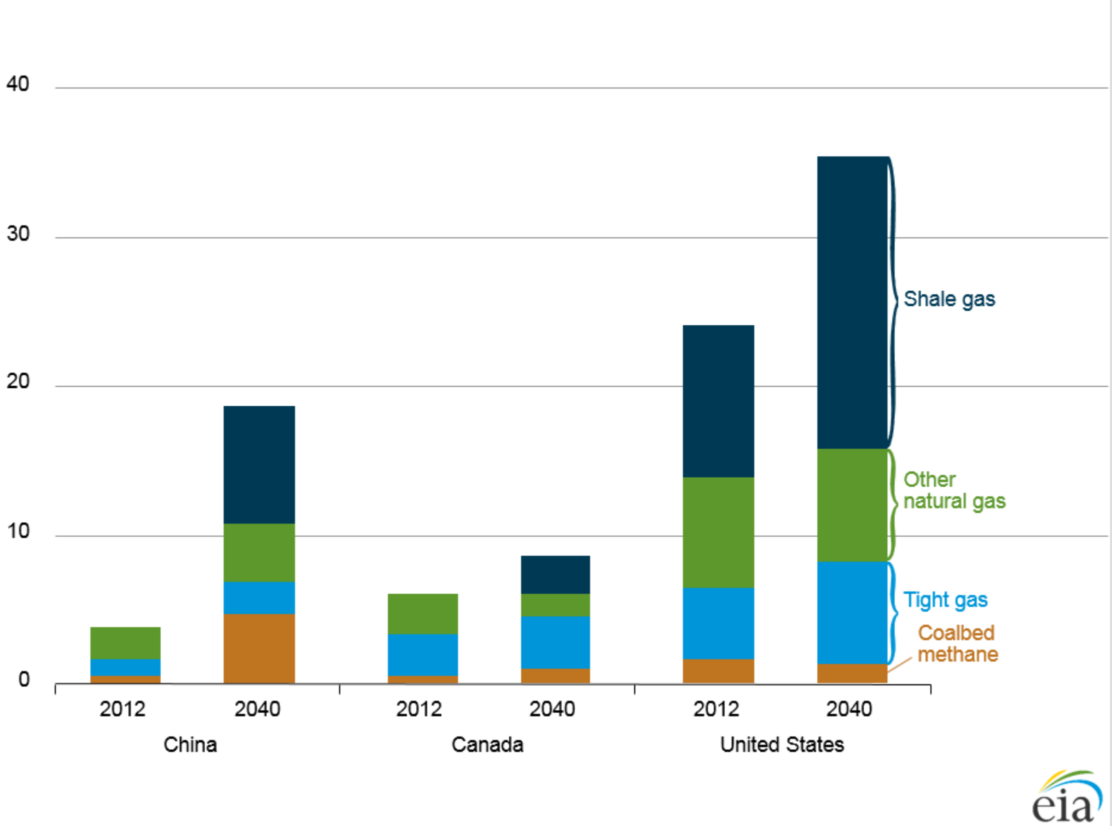


Natural Gas Supply Projections for: Tight Gas, Shale Gas, Coalbed Methane

EIA reports

- China, U.S., Canada large producers of these types of natural gas
- Horizontal drilling and hydraulic fracturing ➔nearly doubling of estimates for total U.S. technically recoverable natural gas resources over the past decade.
- Shale gas more than ½ U.S. production in IEO2016 Reference Case
- Tight gas, shale gas, and coalbed methane resources in Canada and China about 80% of total production in 2040 in those countries.

Figure 3-3. Natural gas production by type in China, Canada, and the United States, 2012 and 2040

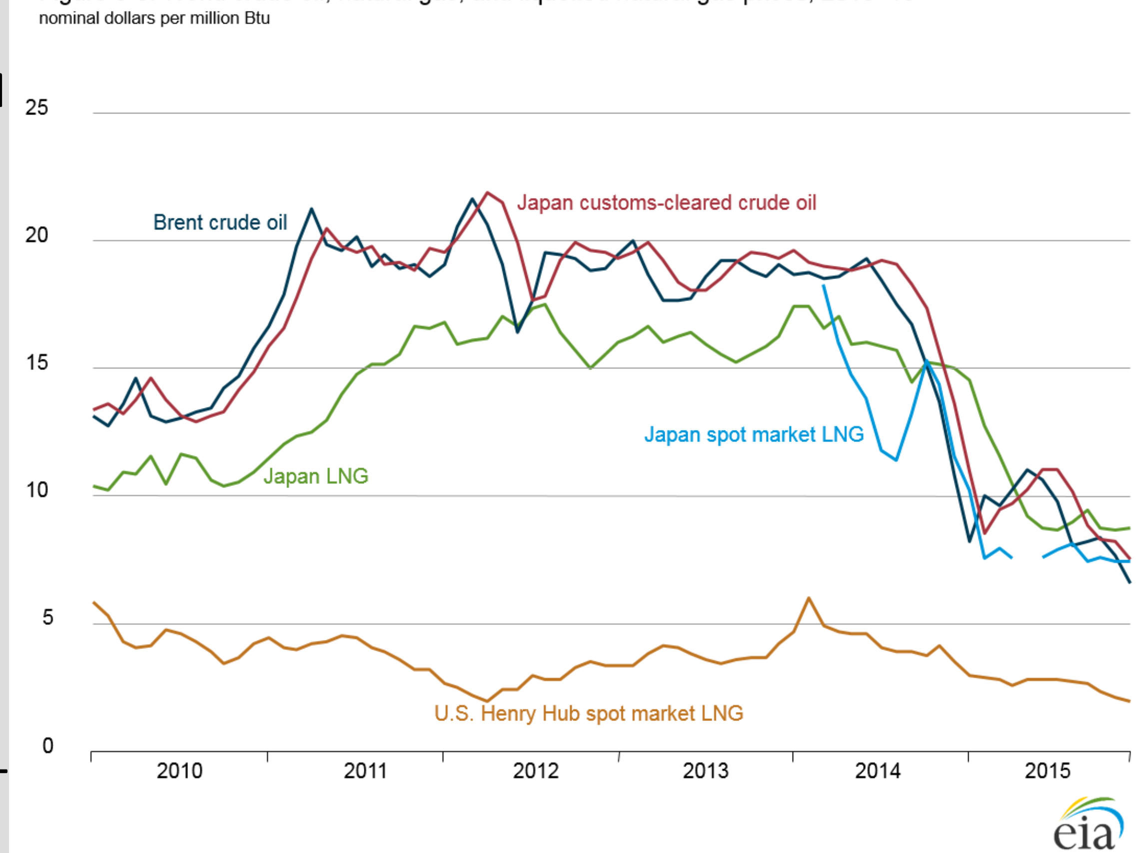


Liquefied Natural Gas (LNG) Trade

EIA reports

- World LNG trade more than doubles, from about 340 BCM in 2012 to 821 BCM in 2040
- Majority of liquefaction in Australia and North America (new projects)
- Decline of existing projects in North Africa and Southeast Asia (underutilized/shutting down) NG consumption higher value than exports
- Japan, China, and Singapore—are developing regional trading hubs for better price formation transparency

Figure 3-8. World crude oil, natural gas, and liquefied natural gas prices, 2010–15



Natural Gas and Renewables

- Many countries striving to reduce greenhouse gases in light of climate change issues
- Main renewables in many places: intermittent wind and solar (also biomass)
- May still need a fossil fuel back-up (at least in the "short-term")
- Natural gas much cleaner than coal and other hydrocarbons– thus the rising importance of this fuel

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Selected Aspects of Energy Security/Insecurity: Focus on Natural Gas

- Physical Security
    - Natural gas (LNG) shipments and pirates
- Supply/Demand Security
    - Russian natural gas demand security issues
    - European natural gas supply diversity, how to achieve supply diversity including U.S. exports of LNG to Europe and Asia
- Environmental/Energy Efficiency Programs Security
- For example, want models that take into account :
    - Stochasticity
    - Investments
    - Operations
    - Learning by the players in response to changing market conditions e.g., energy insecurity
    - Market equilibrium aspects

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Russia, Europe and Natural Gas Demand Insecurity: Looking West

- European demand/geopolitical insecurity for Gazprom and Russia
- The European Commission abuse of dominance in natural gas, charging higher prices in Bulgaria, Estonia, Latvia, Lithuania, Poland (countries with a large dependence on natural gas)
- Regulators: Gazprom is trying to partition Central and Eastern European gas markets by “reducing customer’s ability to resell the gas to other countries”.
- Siberian pipeline gas to European utilities down 20% in Q1 (compared with historical average) – LNG from Qatar and elsewhere cheaper including U.S. shale gas.

Gazprom Faces Effects of Politics on Its Bottom Line

By ANDREW E. KRAMER APRIL 22, 2015

The Gaz-System distribution station in Gustorzyn, Poland. Poland and some other European countries are largely dependent on Russian gas. Agencja Gazeta/Reuters

http://www.nytimes.com/2015/04/23/business/international/gazprom-faces-effects-of-politics-on-its-bottom-line.html?smprod=nytcore-iphone&smid=nytcore-iphone-share&_r=0

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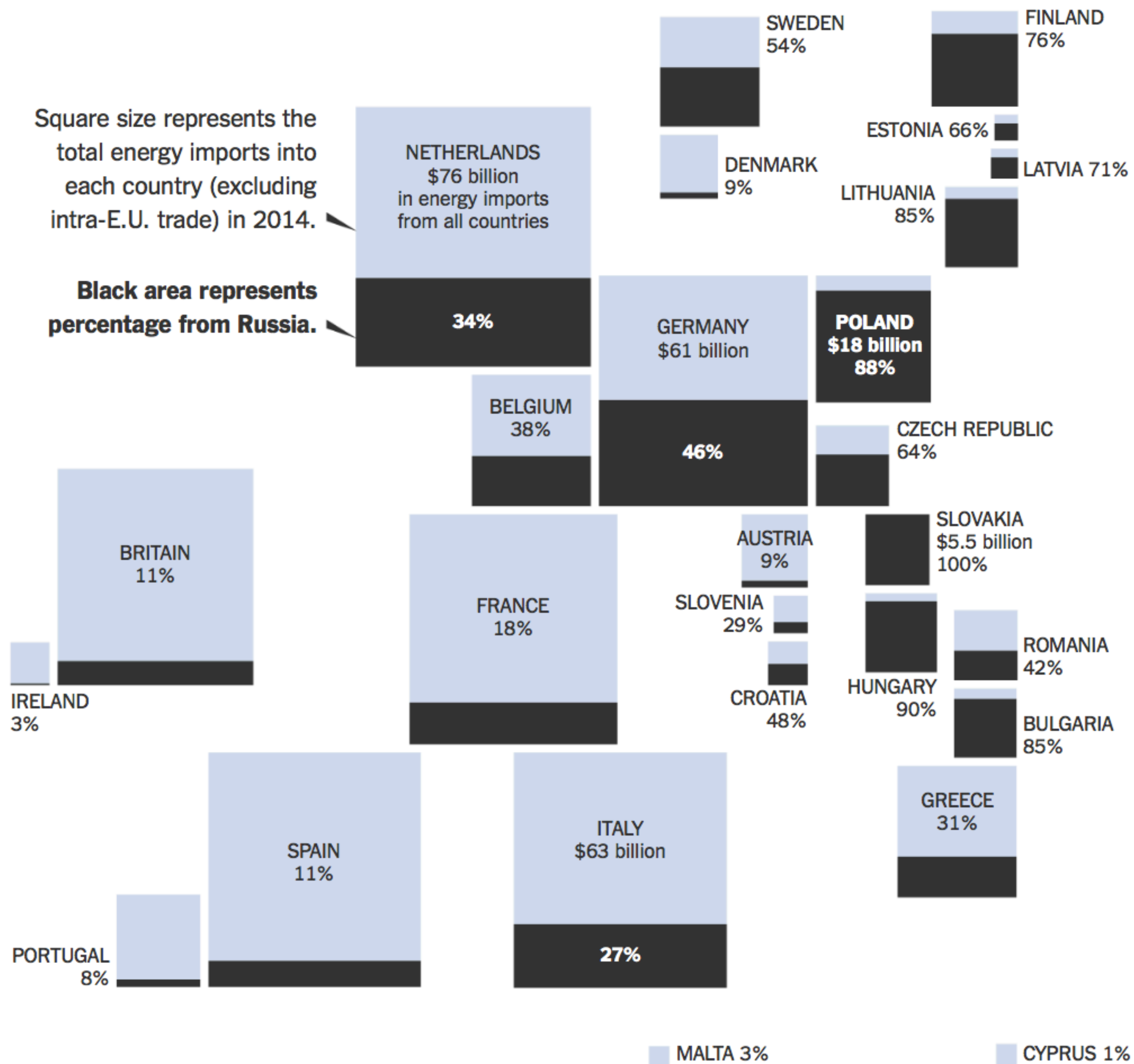
Russia, Europe and Natural Gas Demand Insecurity: Looking West

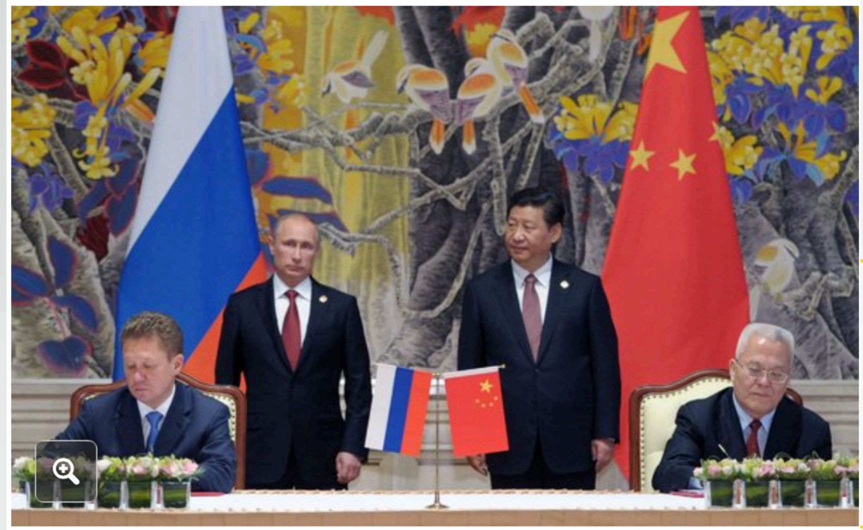
How Russian Energy Flows to Europe

While Europe is moving to diversify its supplies, the European Union still depends heavily on Russia for its energy needs. Such dominance is now under scrutiny by antitrust regulators, which accused the Russian natural gas giant Gazprom of inflating prices and quashing competition.

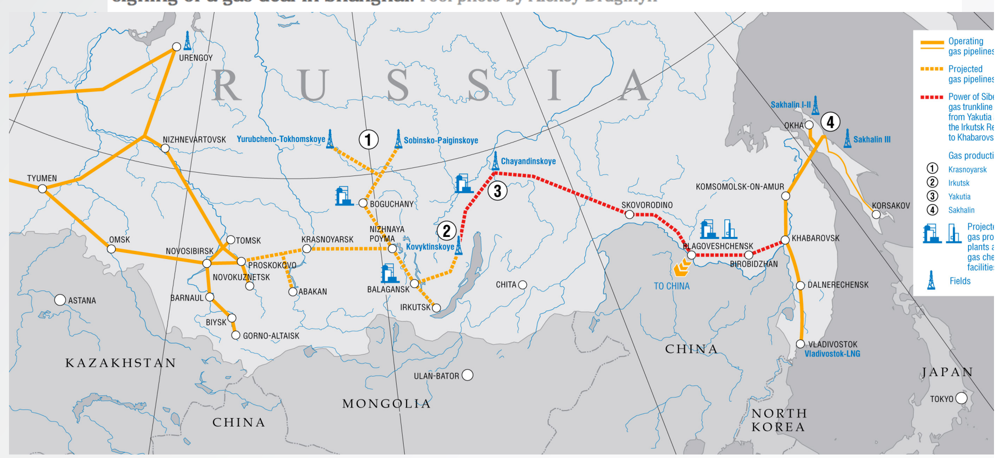


Russia, China and Natural Gas Demand Insecurity: Looking East

- Gazprom made deals to supply gas to China for 30 years from Siberia, new pipelines, gas to flow starting in 2019, 38 BCM/year.
- Eventually China could get more Russian gas than Germany (largest customer at present)
- Gazprom -$50 billion commitment to build a new pipeline to China that will take years to produce profits, Chinese financing is slow to happen
- Projected natural gas consumption in the PRC 300-350 bcm a year by 2020, and at a level around 500 bcm a year by 2030.



Vladimir V. Putin, second from left, stood next to President Xi Jinping of China at last May's signing of a gas deal in Shanghai. Pool photo by Alexey Druginyn



http://www.gazprom.com/press/news/2014/may/article191451/
http://www.gazpromexport.ru/en/partners/china/
http://www.chinadaily.com.cn/business/2017-03/16/content_28581640.htm

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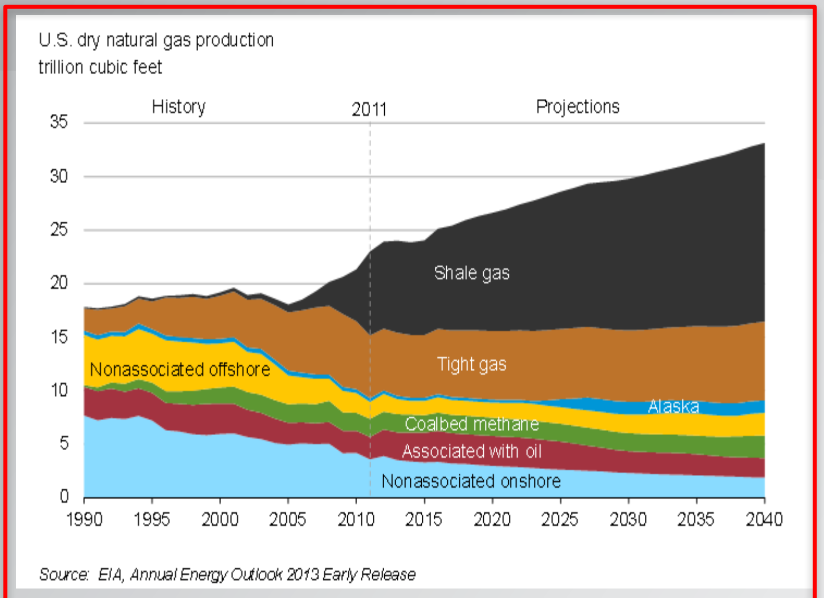
North American Gas Market
Shale Gas Revolution

U.S. Shale Gas Production Through 2040 (TCF)



- The share of U.S. shale gas in the total production is increasing
- U.S. LNG exports rise to approximately 45 BCM (1.6 Tcf) in 2027
- Hydrofracking environmental issue considered by each U.S. State and EPA

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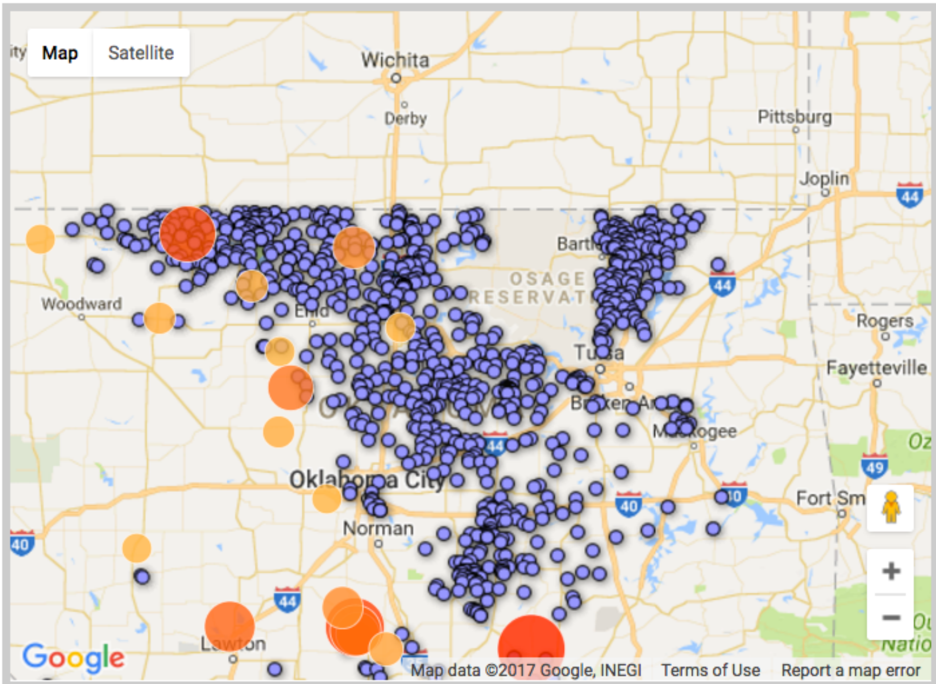
Earthquakes from Wells? 1980-1999

EARTHQUAKES IN OKLAHOMA

EARTHQUAKE MAP



Note: Only Earthquakes with a magnitude of 3.0 and higher are displayed.

- [ ] Earthquakes - Past 7 days
- [ ] Earthquakes - 2017 (YTD)
- [ ] Earthquakes - 2016
- [ ] Earthquakes - 2015
- [ ] Earthquakes - 2014
- [ ] Earthquakes - 2013
- [ ] Earthquakes - 2012
- [ ] Earthquakes - 2011
- [ ] Earthquakes - 2010
- [ ] Earthquakes - 2000 through 2009
- [x] Earthquakes - 1990 through 1999
- [x] Earthquakes - 1980 through 1989
- [x] Arbuckle Waste Water Disposal Wells

http://earthquakes.ok.gov/what-we-know/earthquake-map/

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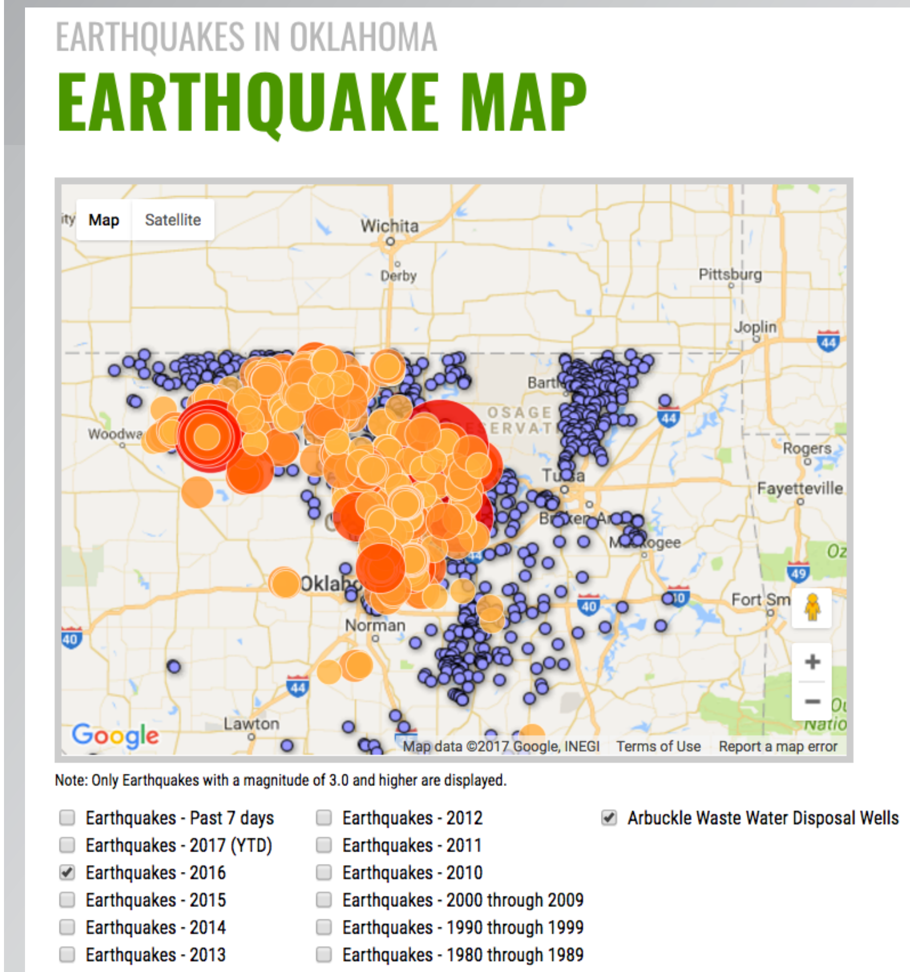
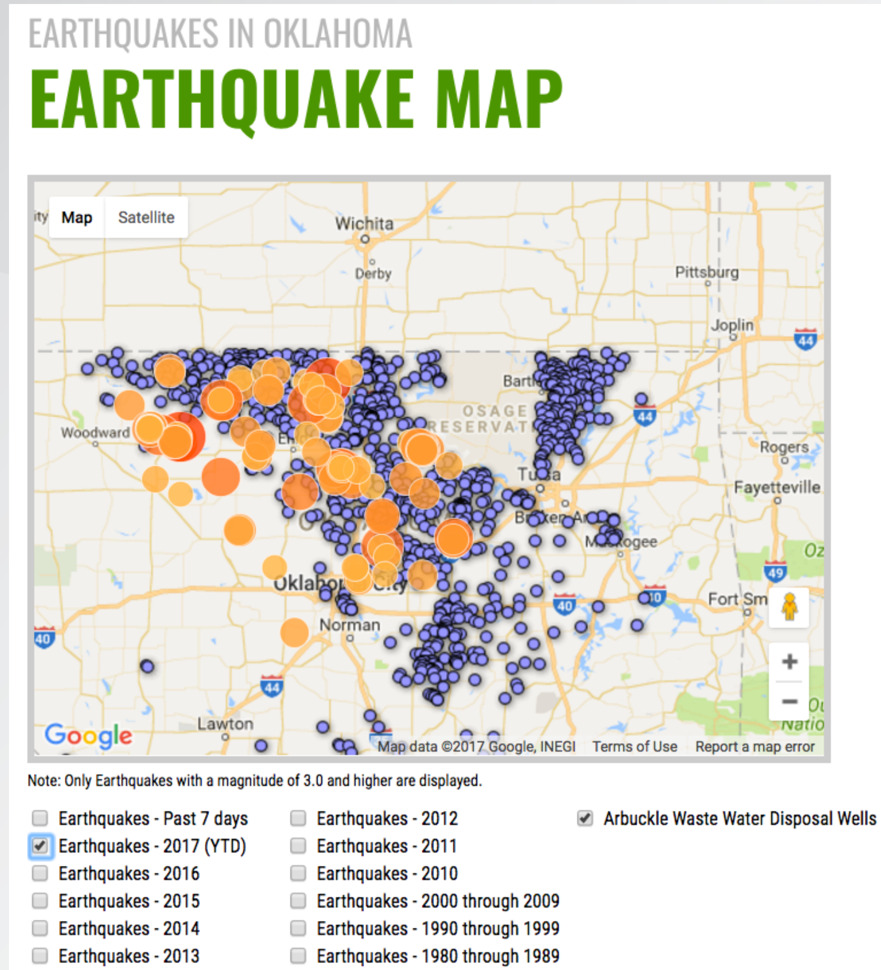
Earthquakes from Wells?

2016



2017



http://earthquakes.ok.gov/what-we-know/earthquake-map/

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Earthquakes from Wells? Summary

- "The Oklahoma Geological Survey has determined that the majority of recent earthquakes in central and north-central Oklahoma are very likely triggered by the injection of produced water in disposal wells."
- Magnitude 3+ Earthquakes
    - 2016: 623
    - 2015: 903
    - 2014: 579
    - 2013: 110
    - 2012: 35
    - 2011: 67
    - 2010: 41

https://earthquakes.ok.gov/what-we-know/

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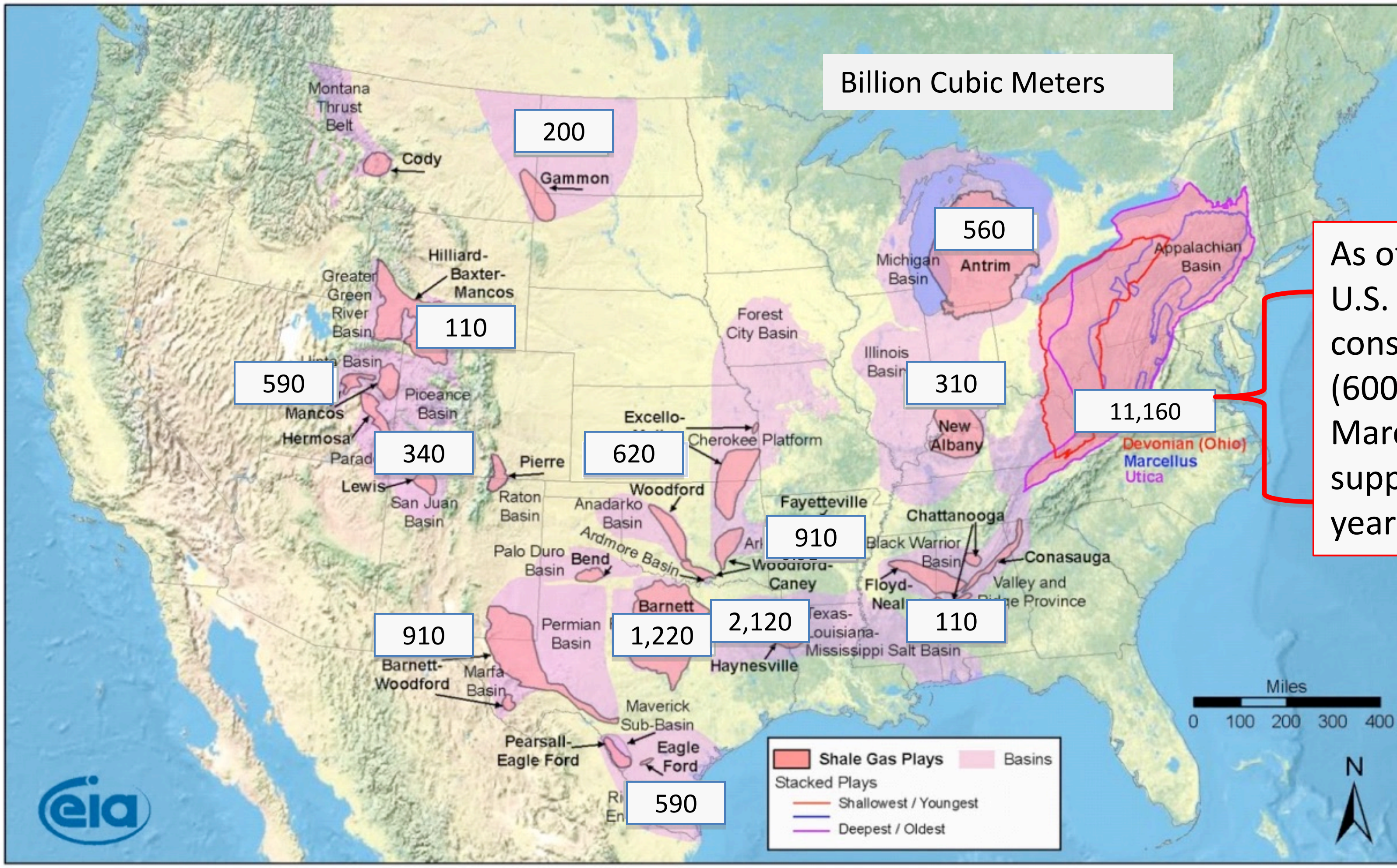
U.S. Environmental Protection Agency (EPA) Major Findings on Hydrofracking

- EPA found scientific evidence that hydrofracturing can impact drinking water resources under some circumstances for example:
- "Water withdrawals for hydraulic fracturing in times or areas of low water availability, particularly in areas with limited or declining groundwater resources"
- "Spills during the handling of hydraulic fracturing fluids and chemicals or produced water that result in large volumes or high concentrations of chemicals reaching groundwater resources"
- "Injection of hydraulic fracturing fluids into wells with inadequate mechanical integrity, allowing gases or liquids to move to groundwater resources", etc.
- However, some gaps in data and uncertainties limited EPA's ability to fully assess the potential impacts on drinking water resources locally and nationally.

https://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=332990

US Shale Gas Plays, Lower 48 States



Source: Energy Information Administration based on data from various published studies
Updated: May 28, 2009

As of 2010 U.S. consumption (600BCM*), Marcellus can supply for 20 years

*BP Statistical Review, 2011

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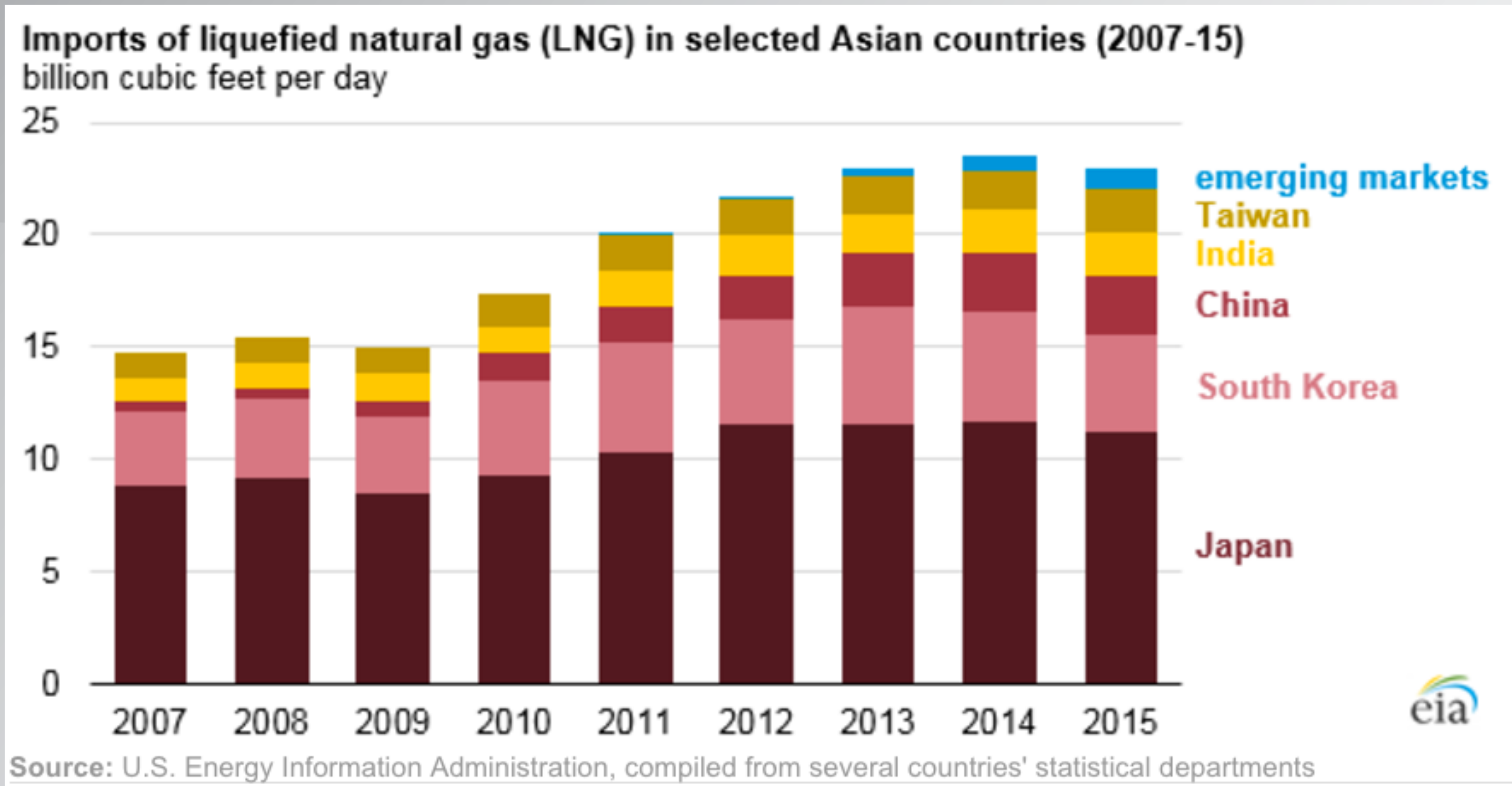
Overview of LNG Markets



Source:https://www.eia.gov/todayinenergy/detail.php?id=27652

- Japan, South Korea, China imported more than half of all global LNG in 2015
- These three countries combined for 18.2 Bcf/day (515 million cubic meters) in 2015

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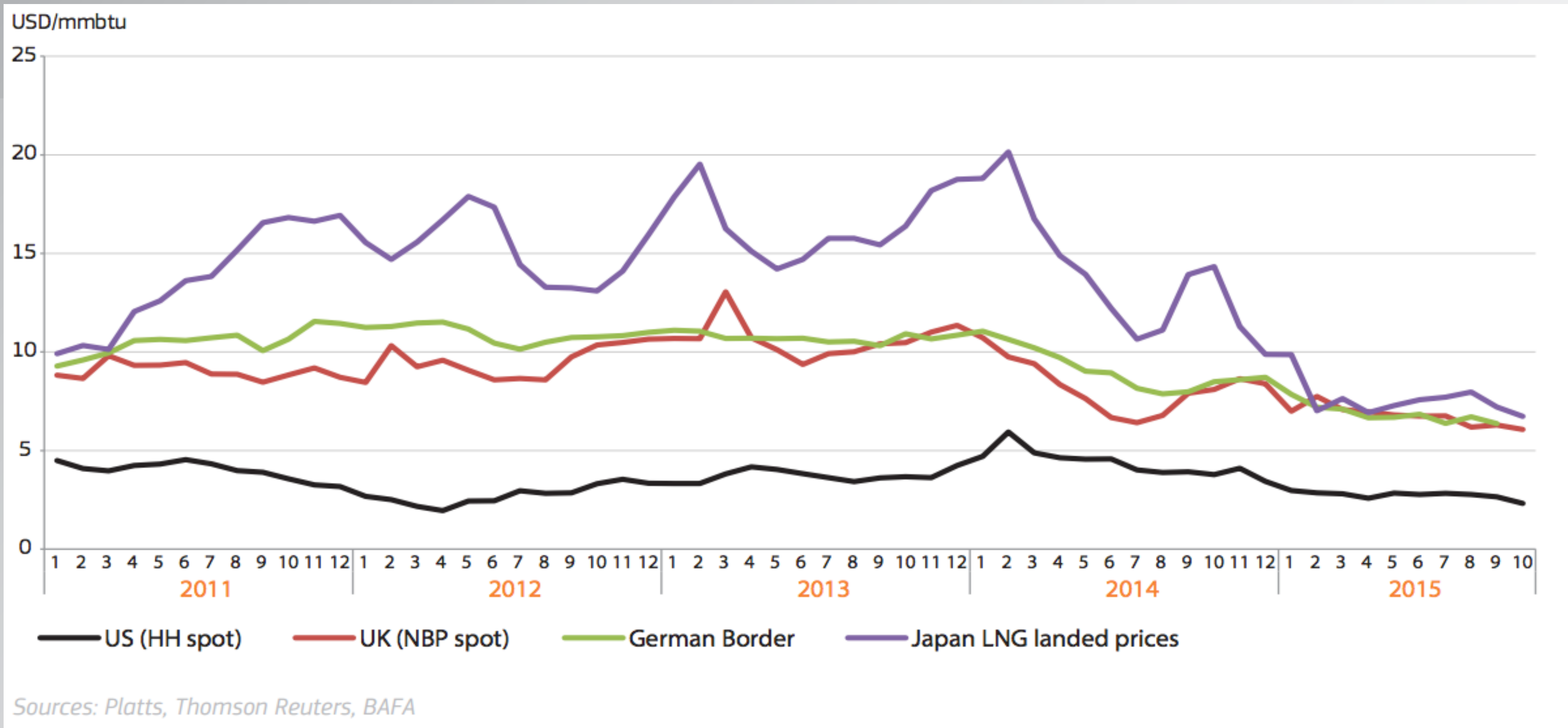
International Comparison of Wholesale Gas Prices



Source: https://ec.europa.eu/energy/sites/ener/files/documents/quarterly_report_on_european_gas_markets_q3_2015.pdf

U.S. LNG Export Status as of March 1, 2017
Total of All Applications Received

	Total (per day)	Total (per year)
FTA application	54.72 Bcf/day or 1.54 BCM/day	19.97 Tcf/year or 565 BCM/year
Non-FTA application	51.13 Bcf/day or 1.45 BCM/day	18.74 Tcf/year or 530 BCM/year

FTA with the U.S. requires national treatment for trade in natural gas, including Australia, Bahrain, Canada, Chile, Colombia, Dominican Republic, El Salvador, Guatemala, Honduras, Jordan, Mexico, Morocco, Nicaragua, Oman, Peru, Republic of Korea and Singapore

Source: https://energy.gov/sites/prod/files/2017/03/f34/Summary%20of%20LNG%20Export%20Applications.pdf

Much Shorter Distances for U.S. Gulf of Mexico LNG Exports to Asia via the Panama Canal

Origin	Via Panama	Via Suez	Around Cap Horn	Around Good Hope	Destination
Gulf of Mexico	3,733	21,637	9,783	19,713	Mexico West
	4,449	19,723	13,476	20,266	Chile
	9,756	14,449	17,060	15,697	Japan
	12,147	11,910	16,900	13,157	Singapore
Trinidad	3,331	20,272	7,643	17,573	Mexico West
	4,048	18,358	11,336	18,126	Chile
	9,355	13,054	14,920	13,557	Japan
	11,746	10,545	14,761	11,027	Singapore
Norway	7,471	19,474	10,801	19,601	Mexico West
	8,188	17,559	14,493	20,155	Chile
	13,494	12,285	18,078	15,585	Japan
	15,886	9,746	17,918	13,046	Singapore

Popils,2011

- Massive time saving on voyages to Japan, South Korea, Taiwan and China
- Avoid Cape Horn during winter season for potential deliveries to western coast of North and Central America
- Panama Canal expansion (ongoing) to be able to handle more and larger ships

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Overview of Optimization/Equilibrium and Game Theory Modeling

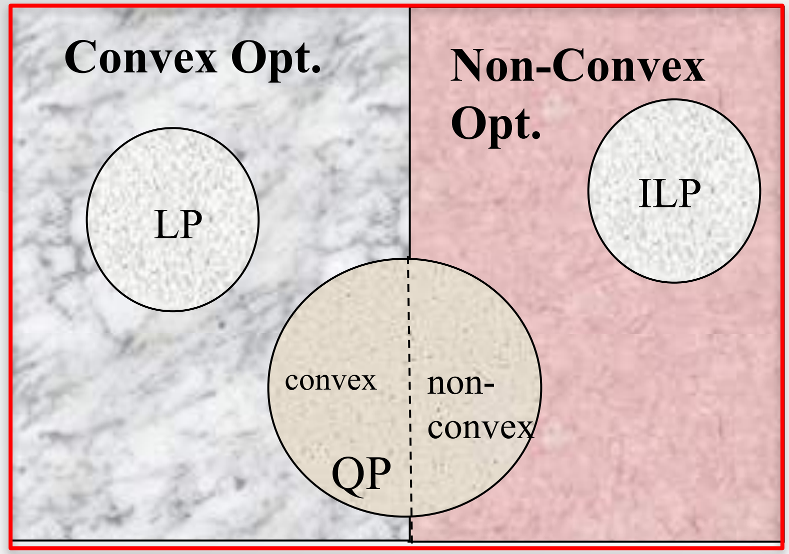
Optimization and Equilibrium Modeling: Engineering-Economic System Focus

General Form of an Optimization Problem

$$\min\ f(x) \quad \text{Objective Function}$$

$$s.t. \quad \text{Feasible Region}$$

$$\begin{pmatrix} g_i(x) \le 0, i = 1,2,\ldots,m \\ h_j(x) = 0, j = 1,2,\ldots,p \end{pmatrix} = S$$



- Many engineering problems have either *f* a non-convex function of *S* a non-convex usually making the problem much harder to solve, examples:
    - Unit commitment in power (binary-constrained problem)
    - Design optimization (on/off plus continuous design variables)

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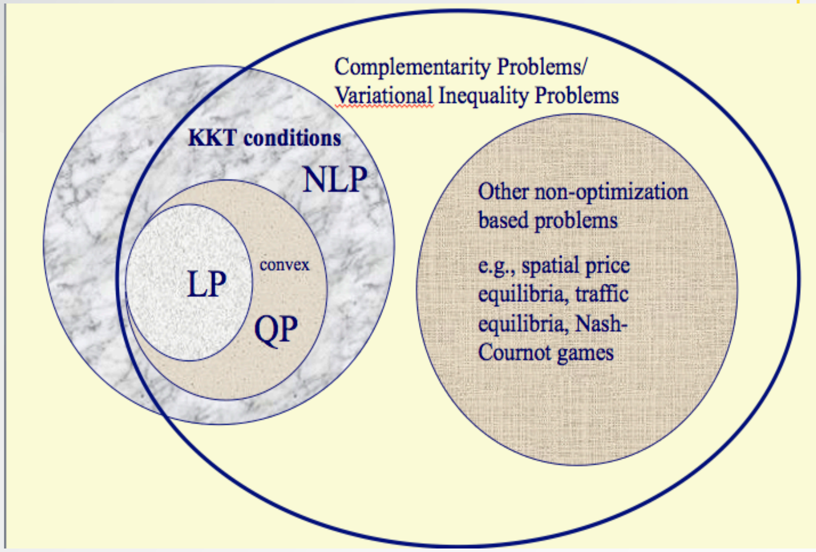
Optimization and Equilibrium Modeling: Engineering-Economic System Focus

General Form of an Equilibrium Problem, simultaneous agent-based optimization problems to solve

$$\min f_p(x^p; x^{-p})$$

$$s.t.$$

$$\begin{pmatrix} g_{ip}(x^p; x^{-p}) \le 0, i = 1,2,\ldots,m \\ h_{jp}(x^p; x^{-p}) = 0, j = 1,2,\ldots,p \end{pmatrix}$$



- Each player (agent) p optimizes their own set of design variables x^p while taking in to account those of the other players x^{-p}
- Nash-Cournot non-cooperative games, generalized Nash-Cournot non-cooperative games
- Can be multilevel with planner at top level protecting against/anticipating lower-level players' actions

Optimization and Equilibrium Modeling: Engineering-Economic System Focus

optimization problem (P)

min $f(x)$

$s.t.$

$g_i(x) \le 0, i = 1,2,\ldots,m$

$h_j(x) = 0, j = 1,2,\ldots,p$

KKT conditions, find $\bar{x} \in R^n, \bar{u} \in R^m, \bar{v} \in R^p \ s.t.$

$$\left\{\begin{array}{l} (i) \nabla f(\bar{x}) + \sum_{i=1}^{m} \bar{u}_i \nabla g_i(\bar{x}) + \sum_{j=1}^{p} \bar{v}_i \nabla h_j(\bar{x}) = 0 \\ (ii) g_i(\bar{x}) \le 0, \bar{u}_i \ge 0, g_i(\bar{x})\bar{u}_i = 0, \text{ for all } i = 1,\ldots,m \\ (iii) h_j(\bar{x}) = 0, \bar{v}_j \text{ free, for all } j = 1,\ldots,p \end{array}\right\}$$

- (i) is stationarity
- (ii) is feasibility and complementarity for the inequalities
- (iii) is feasibility for the equalities

Two-Person Non-Cooperative Games (Shy)

Equilibrium Concepts

Definition

A set of joint strategies $\left(\hat{s}_1,\ldots,\hat{s}_N\right)\in S_1\times\ldots S_N$ is said to be a **Nash equilibrium (NE)** if no player would find it beneficial to deviate provided that all other players do not deviate from their strategies played at the NE outcome. Formally, for every player

$p\in P$

$f_p\left(\hat{s}_p,\hat{s}^{-p}\right)\geq f_p\left(s_p,\hat{s}^{-p}\right)$ for all $s_p\in S_p$.

That is, player *p* has no profitable unilateral incentive to deviate from the NE solution.

Equilibrium Problems Expressed as Mixed Nonlinear Complementarity Problems

Mixed Nonlinear Complementarity Problem (MCP)

Having a function $F: R^n \to R^n$, find an $x \in R^{n_1},\ y \in R^{n_2}$ such that

$$F_i(x,y) \ge 0, x_i \ge 0, F_i(x,y) * x_i = 0 \ for\ i = 1,\ldots,n_1$$

$$F_i(x,y) = 0, y_i \text{ free}, \ for\ i = n_1+1,\ldots,n$$

Example

$$F(x_1,x_2,y_1) = \begin{pmatrix} F_1(x_1,x_2,y_1) \\ F_2(x_1,x_2,y_1) \\ F_3(x_1,x_2,y_1) \end{pmatrix} = \begin{pmatrix} x_1 + x_2 \\ x_1 - y_1 \\ x_1 + x_2 + y_1 - 2 \end{pmatrix}$$ so we want to find x_1, x_2, y_1 s.t.

$$x_1 + x_2 \ge 0 \qquad x_1 \ge 0 \qquad (x_1 + x_2) * x_1 = 0$$

$$x_1 - y_1 \ge 0 \qquad x_2 \ge 0 \qquad (x_1 - y_1) * x_2 = 0$$

$$x_1 + x_2 + y_1 - 2 = 0 \qquad y_1 \text{ free}$$

One solution: $(x_1,x_2,y_1) = (0,2,0)$, why? Any others?

If all functions (linear) affine, we get the linear complementarity problem (LCP)

Nonlinear Programs Expressed as Mixed Nonlinear Complementarity Problems

Consider a generic nonlinear program and its resulting KKT conditions

$$\min\ f(x)$$

$$s.t.\ g_i(x) \le 0, i = 1,\ldots,m \quad (u_i)$$

$$h_j(x) = 0, j = 1,\ldots,p \quad (v_j)$$

KKT conditions, find $\bar{x} \in R^n, \bar{u} \in R^m, \bar{v} \in R^p\ s.t.$

$$\begin{Bmatrix} (i)\nabla f(\bar{x}) + \sum_{i=1}^{m} \bar{u}_i \nabla g_i(\bar{x}) + \sum_{j=1}^{p} \bar{v}_i \nabla h_j(\bar{x}) = 0 \\ (ii) g_i(\bar{x}) \le 0, \bar{u}_i \ge 0, g_i(\bar{x})\bar{u}_i = 0, \text{ for all } i = 1,\ldots,m \\ (iii) h_j(\bar{x}) = 0, \bar{v}_j \text{ free, for all } j = 1,\ldots,p \end{Bmatrix}$$

Nonlinear Programs Expressed as Mixed Nonlinear Complementarity Problems

Thus, we get a mixed NCP as follows:

$$F\begin{pmatrix} x \\ u \\ v \end{pmatrix} = \begin{pmatrix} \nabla f(x) + \sum_{i=1}^{m} u_i \nabla g_i(x) + \sum_{j=1}^{p} v_j \nabla h_j(x) \\ -g_i(x), i = 1, \ldots, m \\ h_j(x), j = 1, \ldots, p \end{pmatrix}$$

$$\nabla f(x) + \sum_{i=1}^{m} u_i \nabla g_i(x) + \sum_{j=1}^{p} v_j \nabla h_j(x) = 0 \qquad x \text{ free}$$

$$-g_i(x) \geq 0, i = 1, \ldots, m \qquad u_i \geq 0, \left(-g_i(x)\right) * u_i = 0$$

$$h_j(x) = 0, j = 1, \ldots, p \qquad v_j \text{ free}$$

Case Study Results: Supply Security in International Natural Gas Markets and the Effects of Expanding the Panama Canal on Liquefied Natural Gas (LNG) Flow Using the World Gas Model

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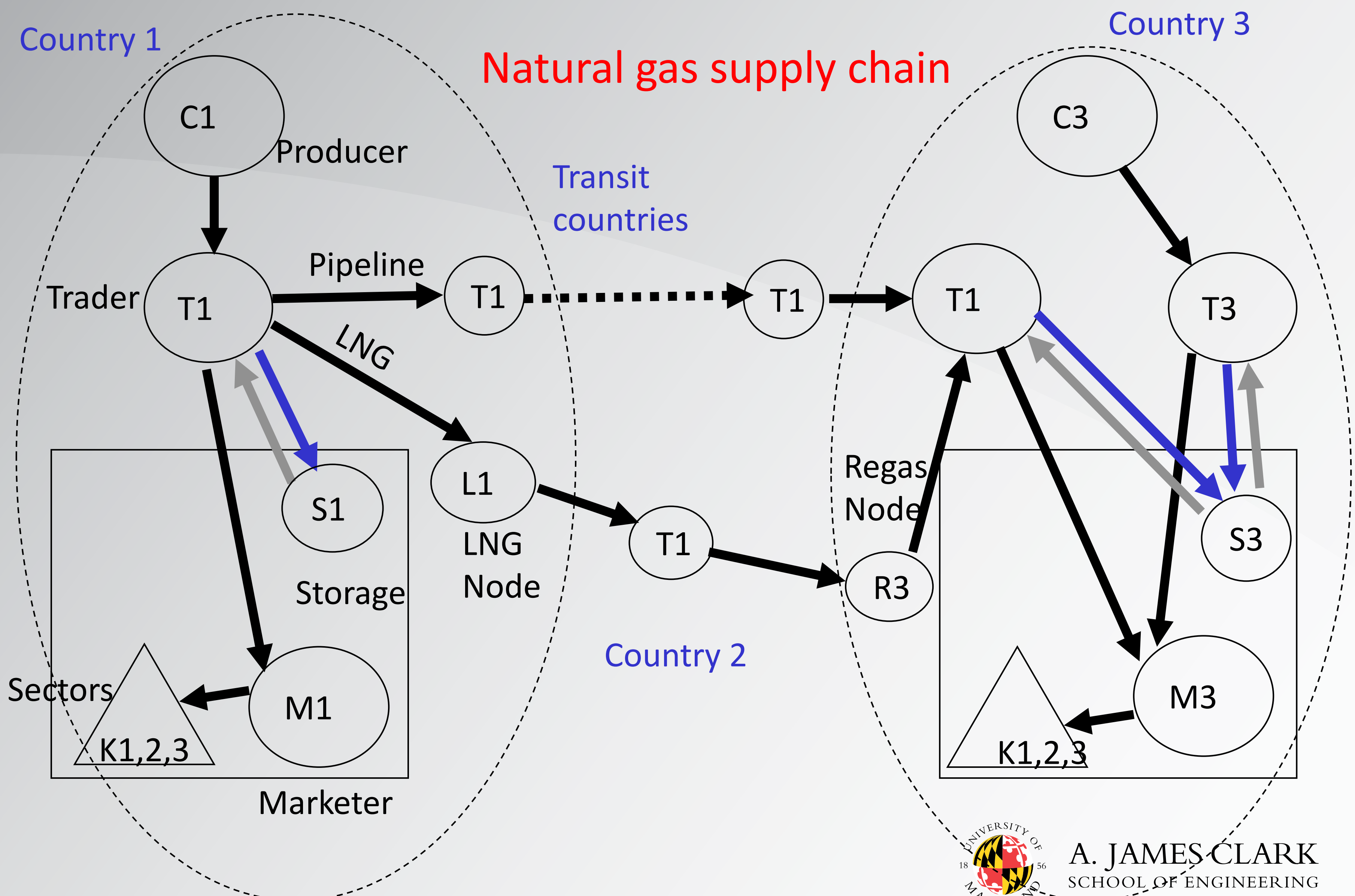
Representation of Gas Market in World Gas Model to Analyze LNG Issues and Panama Canal's Influence



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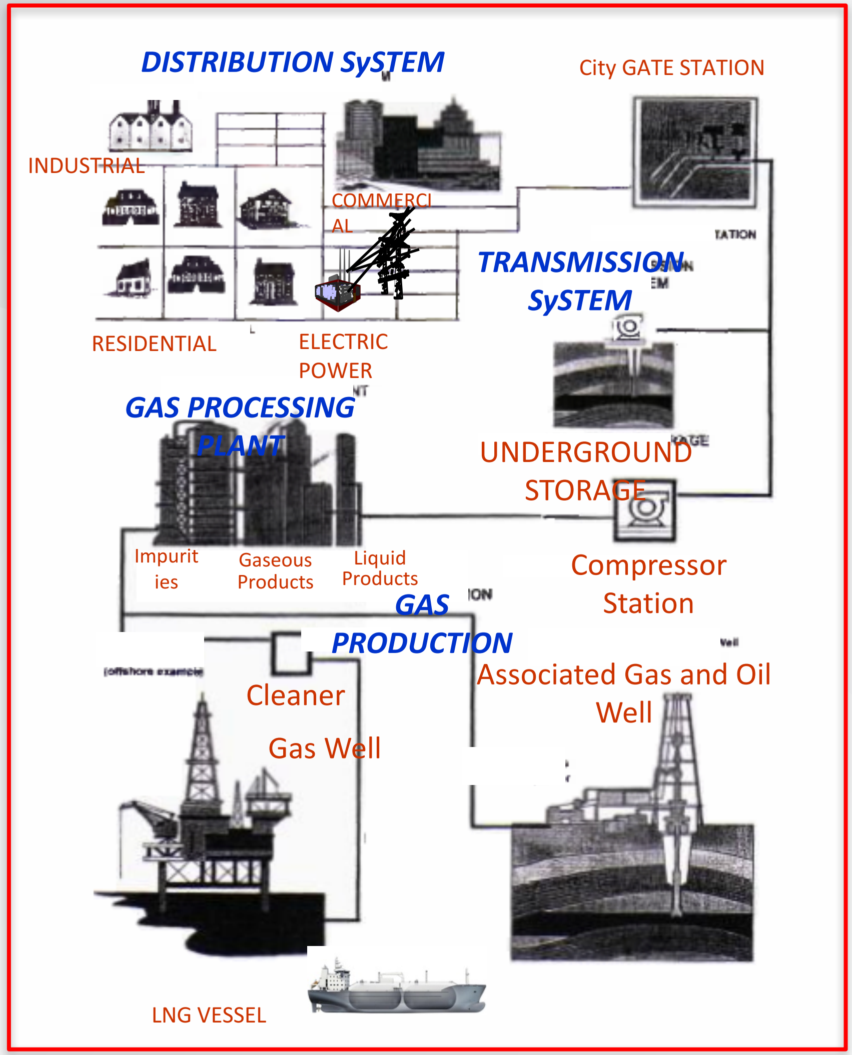
The World Gas Model

- Production/Consumption Nodes: 41 (Groups of countries, countries, regions)
- Covers over 95% of worldwide consumption
- 10 periods: 2005-2050, calibration year 2010
- Typical decision variables
  - Operating levels (e.g., production, storage injection)
  - Investment levels (e.g., pipeline, liquefaction capacity)
- Other
  - Market power aspects (traders)
  - LNG contracts database
  - Seasonality of demand: low and high demand
  - Environmental policy consideration: Carbon costs for supply chains
- Computational aspects
  - Large-scale complementarity problem (KKT optimality conditions for all players + market-clearing conditions)
  - ~78,000 vars. Solves in ~240 mins (8GB, 3.0 GHz)
  - MCPs are examples of non-convex problems (via the complementarity constraints)
  - Improved WGM, S. Moryadee Ph.D. thesis 2015

Natural gas supply chain



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The World Gas Model (WGM)
WGM 2012 vs. WGM 2014
(S. Moryadee, S.A. Gabriel, 2015)

	WGM 2012	WGM 2014
Market players with separate optimization problems	Producers Traders Pipeline operator Storage operator Marketers	Producers Traders Pipeline operator Storage operator Marketers Liquefier Regasifiers LNG shipping operator Canal operators
LNG shipping cost	$8 kcm/1000 nautical miles	Endogenous
Investment for producers	Exogenous	Endogenous
Investment for LNG tanker	No	Yes
Limitation on LNG shipping	No limit	Constraint on LNG Shipping operator
LNG routes	Only1 route origin-destination	Flexible up to 3 routes
Number of variables	~ 60,000 vars	~ 110,000 vars

RK
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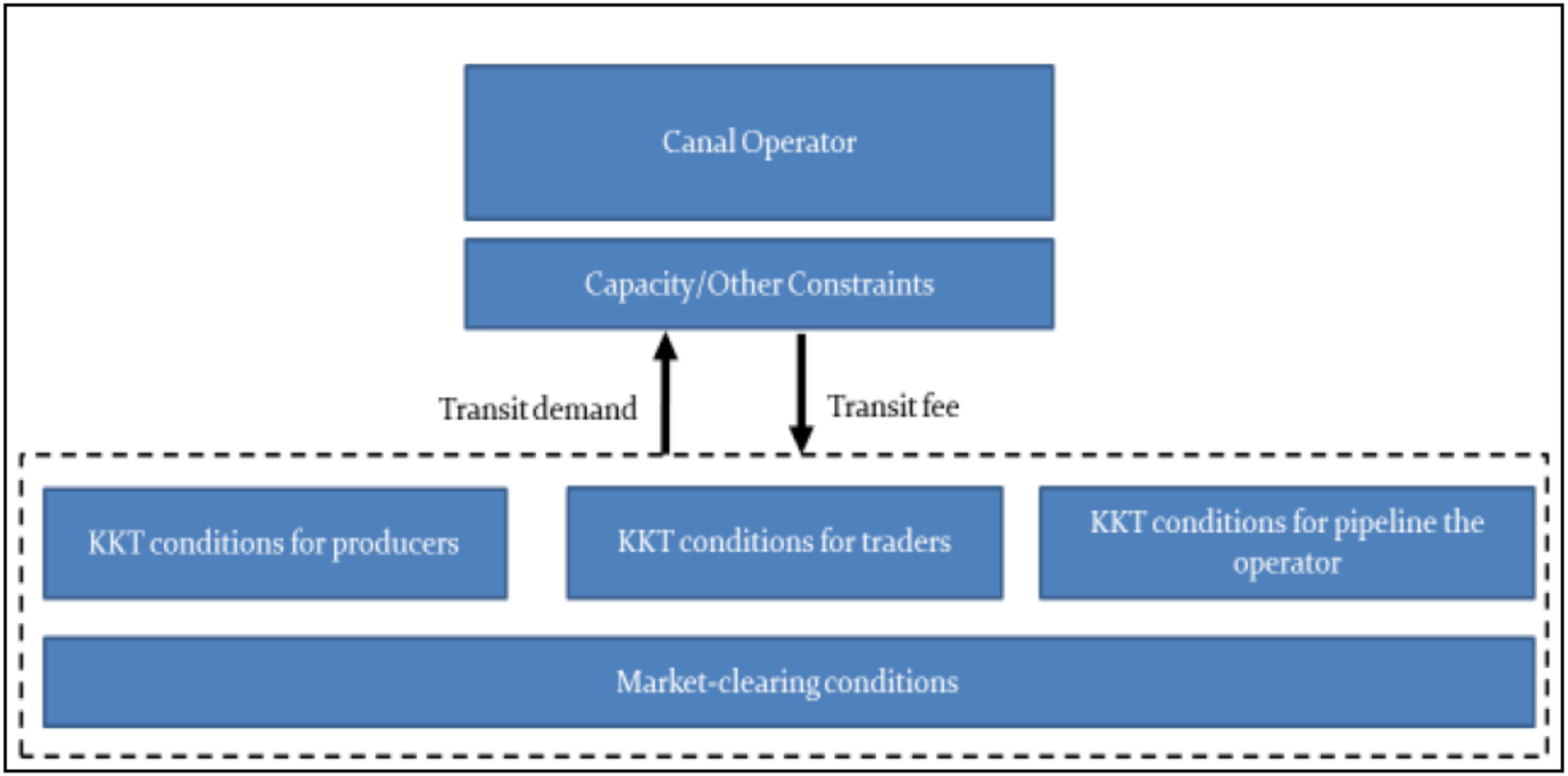
The World Gas Model Mathematical Program with Equilibrium Constraints (MPEC) Version (S. Moryadee, Ph.D. Thesis 2015)



The World Gas Model 2012 Version

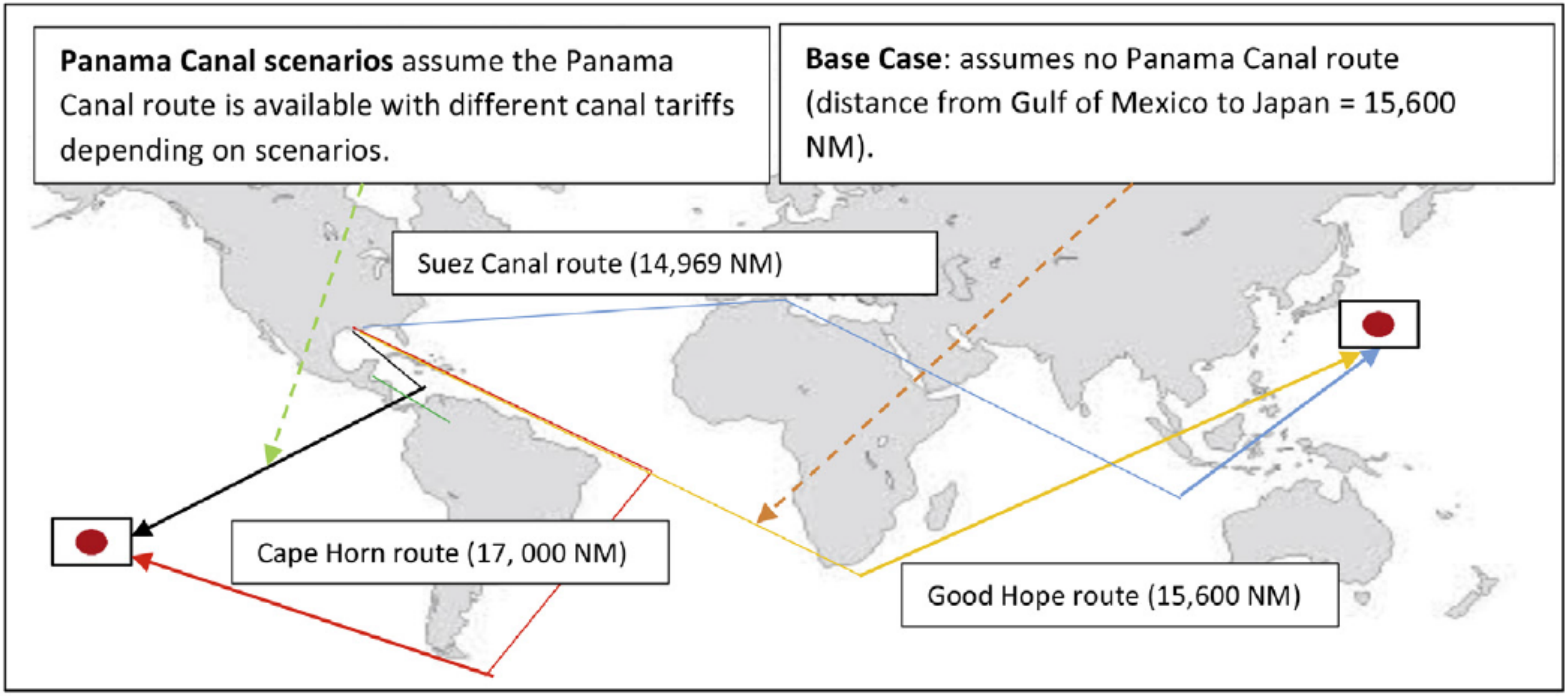


Fig. 1. The difference between Panama Canal scenarios and the calibration Base Case.

S. Moryadee, S.A. Gabriel, F. Rehulka, F. 2014. "The Influence of the Panama Canal on Global Gas Trade," *Journal of Natural Gas Science & Engineering*, 20, 161-174.

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Selected Market Players: Producer Optimization Problem

Revenues

Production Costs

$$\max_{SALES^P_{pdm}} \sum_{m\in M} \gamma_m \sum_{d\in D} days_d \left[\pi^P_{n(p)dm} SALES^P_{pdm} - c^P_{pm}(SALES^P_{pdm}) \right]$$

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

Production Capacity

$$\sum_{m\in M}\sum_{d\in D} days_d SALES^P_{pdm} \le \overline{PH}_p \quad \forall m \quad \left(\alpha^{PH}_p\right)$$

Reserve Limits

$$SALES^P_{pdm} \ge 0 \quad \forall d,m$$

- Producers maximize their profit
- Three types of producers for N. America: conventional, shale, non-shale
- Golombek production (convex) cost function with producer-specific parameters
- Convex program, take KKT conditions
- Other players' KKT conditions as well, combined with market-clearing conditions to get overall MCP market equilibrium

Selected Market Players: Trader Optimization Problem

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

Revenue

Natural Gas Cost

Storage Cost

Transport Cost

s.t.

$$PURCH^T_{tndm} + \sum_{a\in a^+(n)} (1-loss_a) FLOW^T_{tadm} + XTR^T_{tndm} = SALES^T_{tndm} + \sum_{a\in a^-(n)} FLOW^T_{tadm} + INJ^T_{tndm} \quad \forall n,d,m \quad (\varphi^T_{tndm})$$

Mass Balance constraint

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

Storage Cycle Con

$$FLOW^T_{tadm} \geq CON^T_{tadm} \quad \forall a,d,m \quad (\varepsilon^T_{tadm})$$

Contractual obligations

$$SALES^T_{tndm} \geq 0 \quad \forall n,d,m$$

$$PURCH^T_{tndm} \geq 0 \quad \forall n,d,m$$

$$FLOW^T_{tadm} \geq 0 \quad \forall a,d,m$$

$$INJ^T_{tndm} \geq 0 \quad \forall n,d,m$$

$$XTR^T_{tndm} \geq 0 \quad \forall n,d,m$$

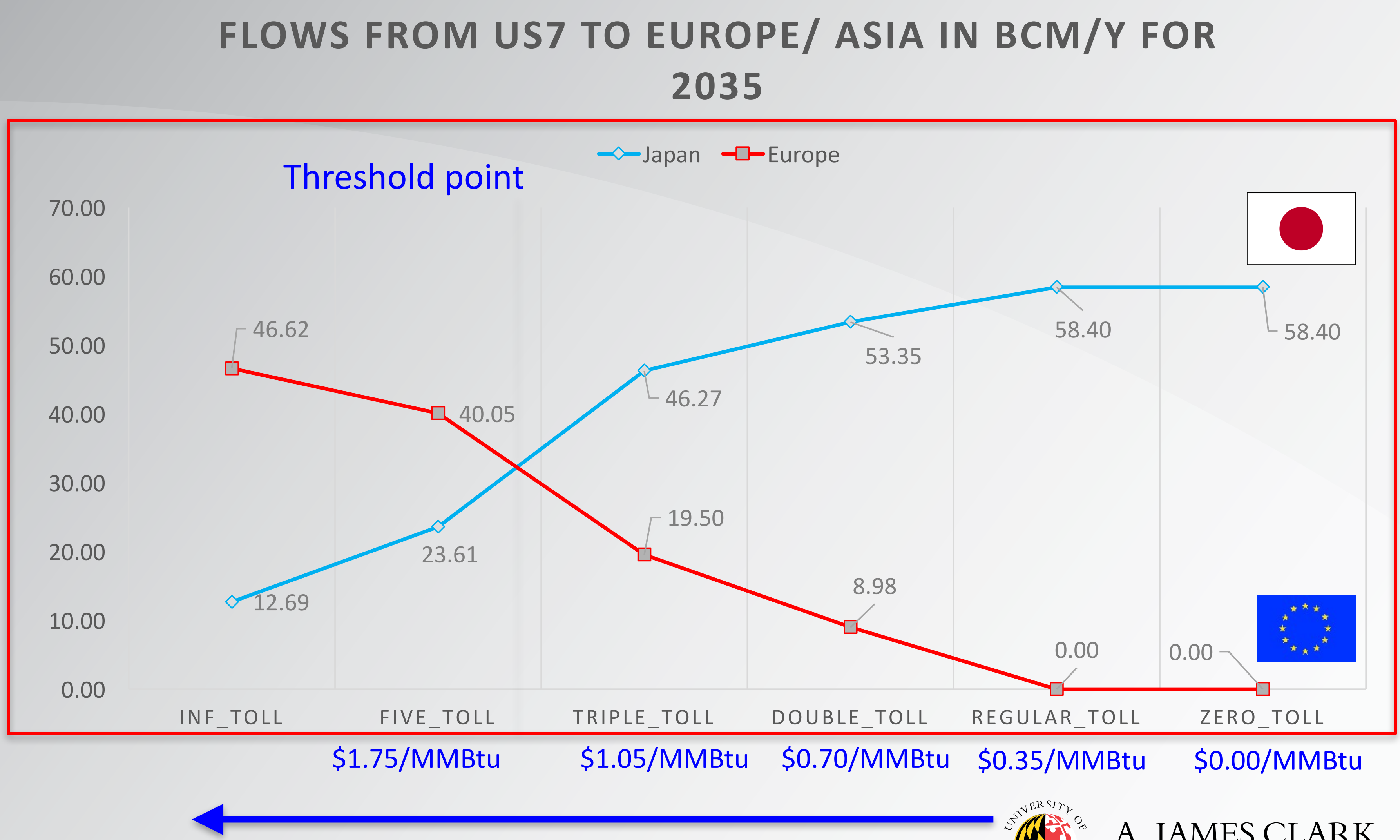
Trader

- Buys gas from producer
- Exerts market power
- Controls usage of storage
- Responsible for regulated and congestion fee

EDF-WGM Sensitivity Analysis Scenarios

Scenarios	Assumptions
Zero_Toll	"Zero Tariff" :tariff is $0/trip or $0.00/MMBtu
Regular_Toll	"Regular Tariff" : Canal Tariff tariff = $/trip or $0.35 /MMBtu
Double_Toll	“Double Tariff” :Canal tariff=Regular tariff X 2 = $0.70 /MMBtu
Triple_Toll	“Triple Tariff” :Canal tariff=Regular tariff X 3 = $1.05 /MMBtu
Fivefold_Toll	“Fivefold Tariff” :Canal tariff=Regular tariff X 5= $1.75 /MMBtu
Inf_Toll	"Infinite Tariff” : Canal tariff= large number $9,999/kcm

Impacts of Canal Tolls on Flows from U.S. Gulf of Mexico (US7 Node)



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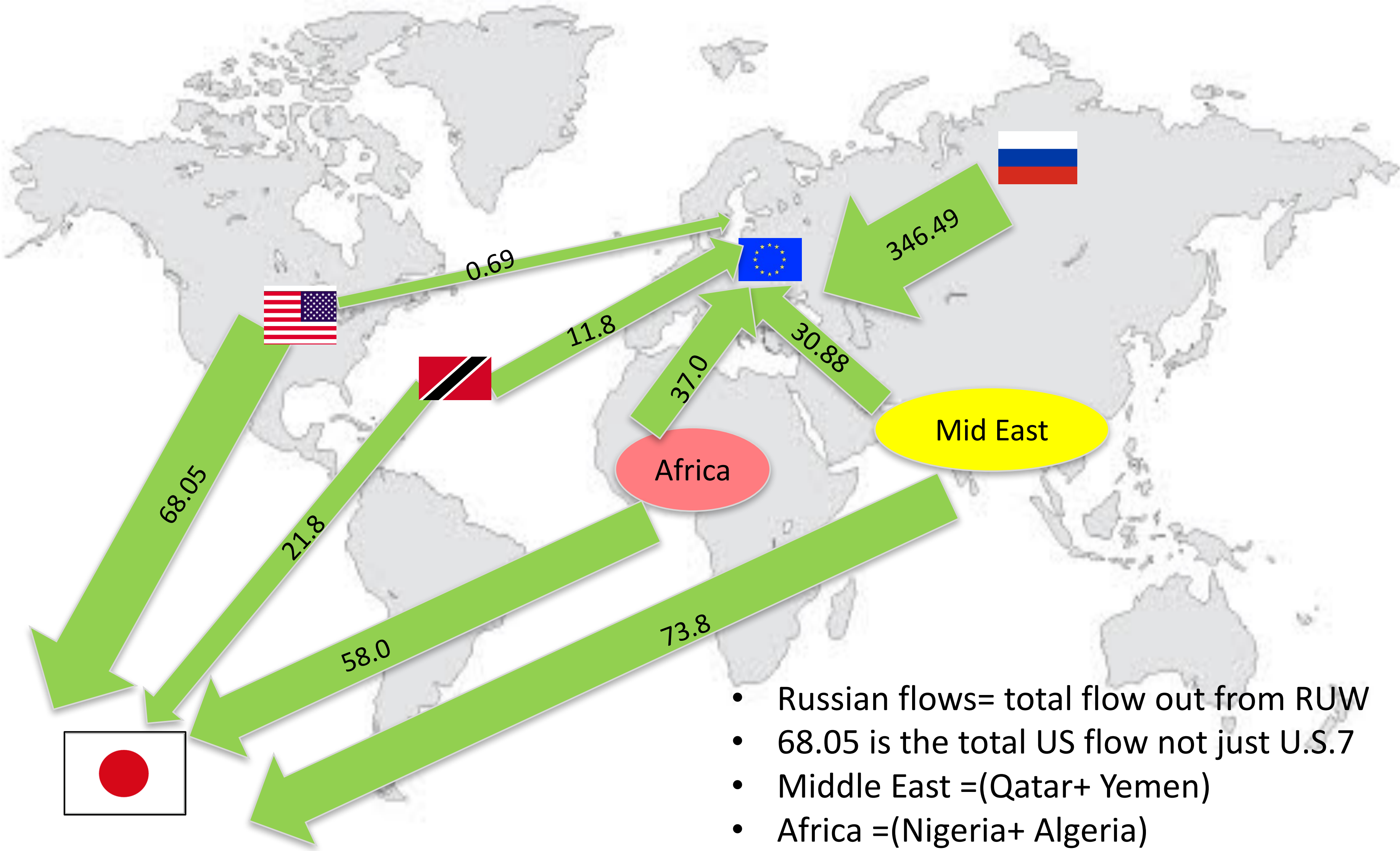
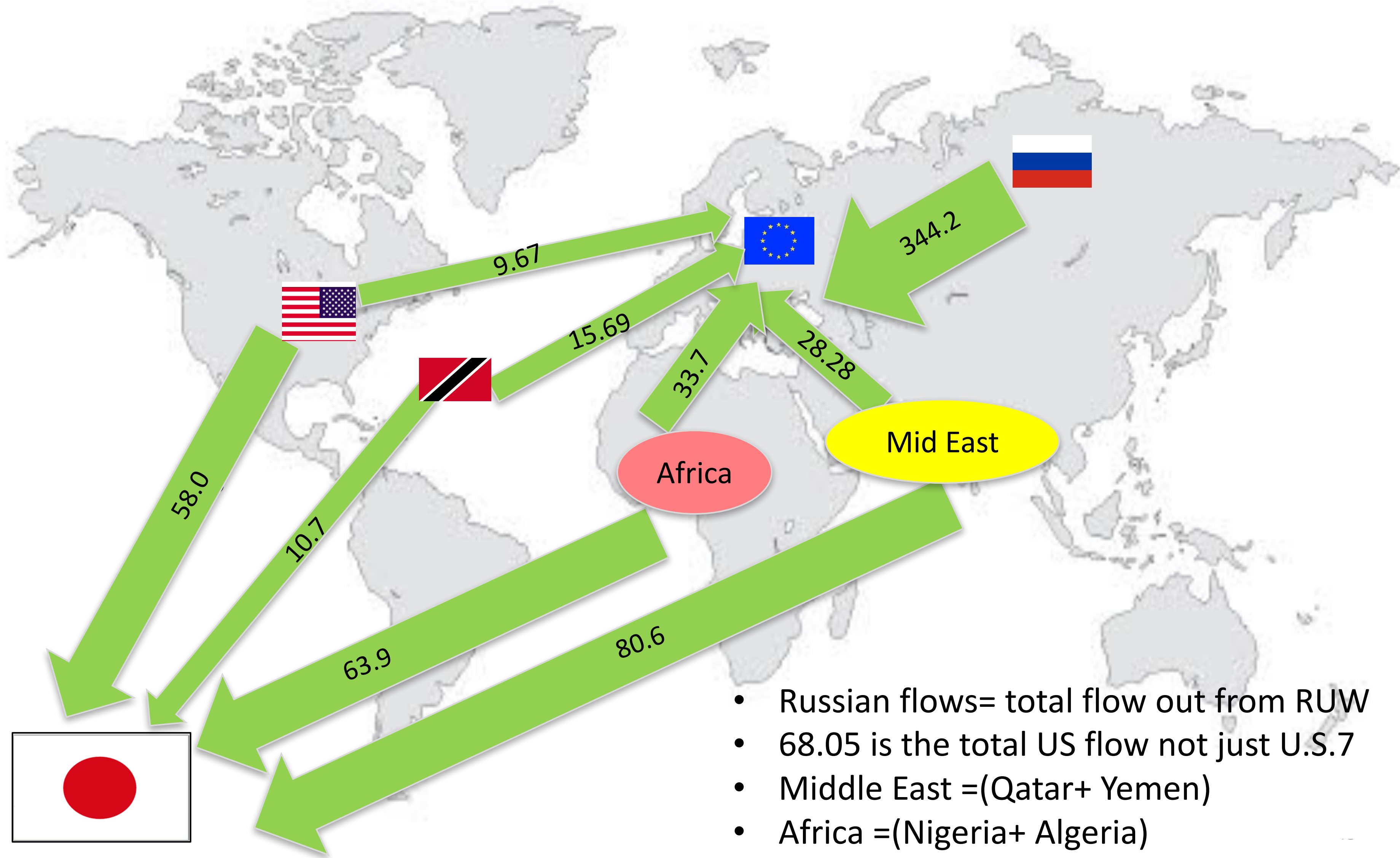
Dynamics of Flows: Regular Tariff Scenario, Flows in Bcm/y for 2035



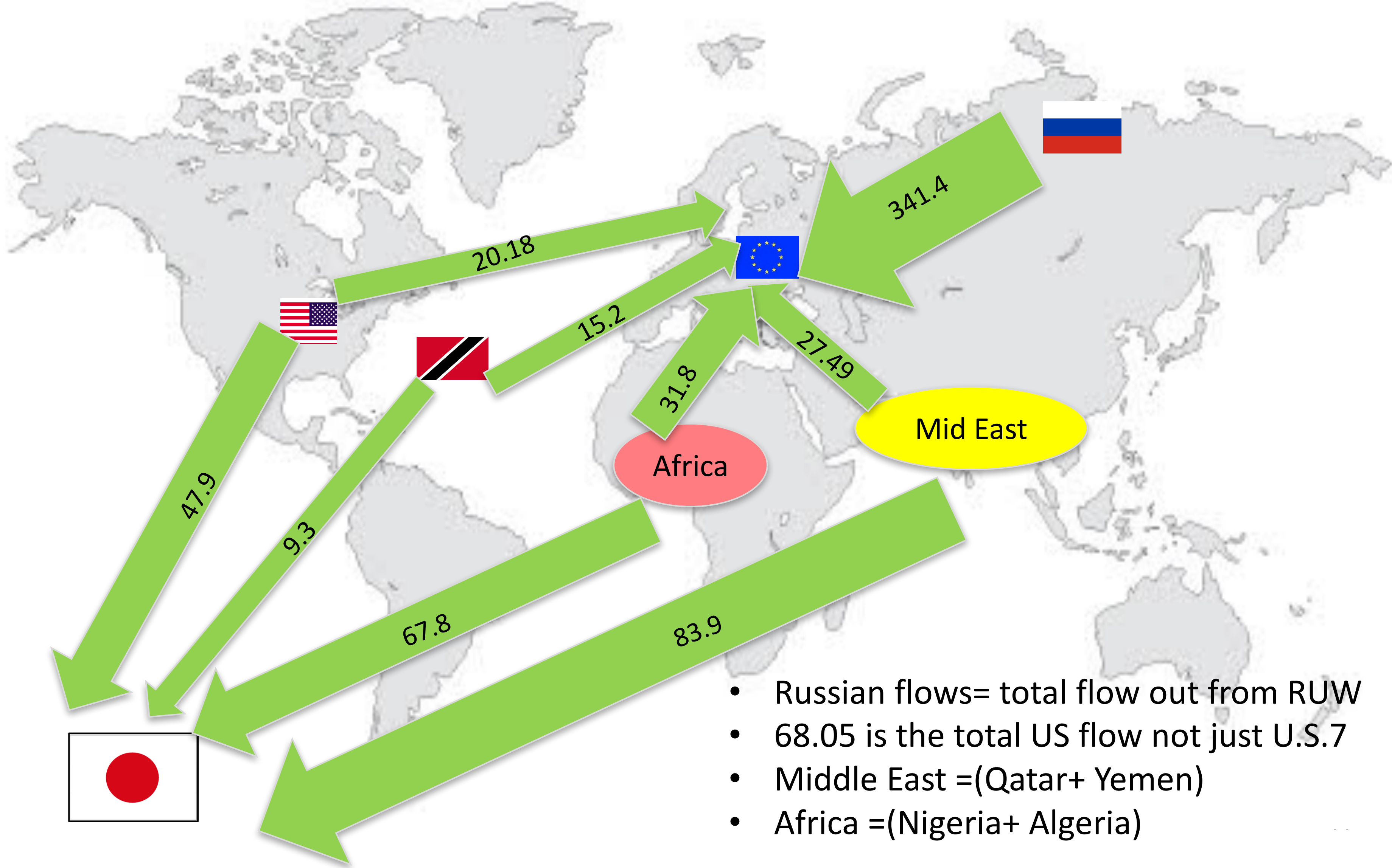
- Russian flows= total flow out from RUW
- 68.05 is the total US flow not just U.S.7
- Middle East =(Qatar+ Yemen)
- Africa =(Nigeria+ Algeria)

Dynamics of Flows: Double Tariff Scenario, Flows in Bcm/y for 2035



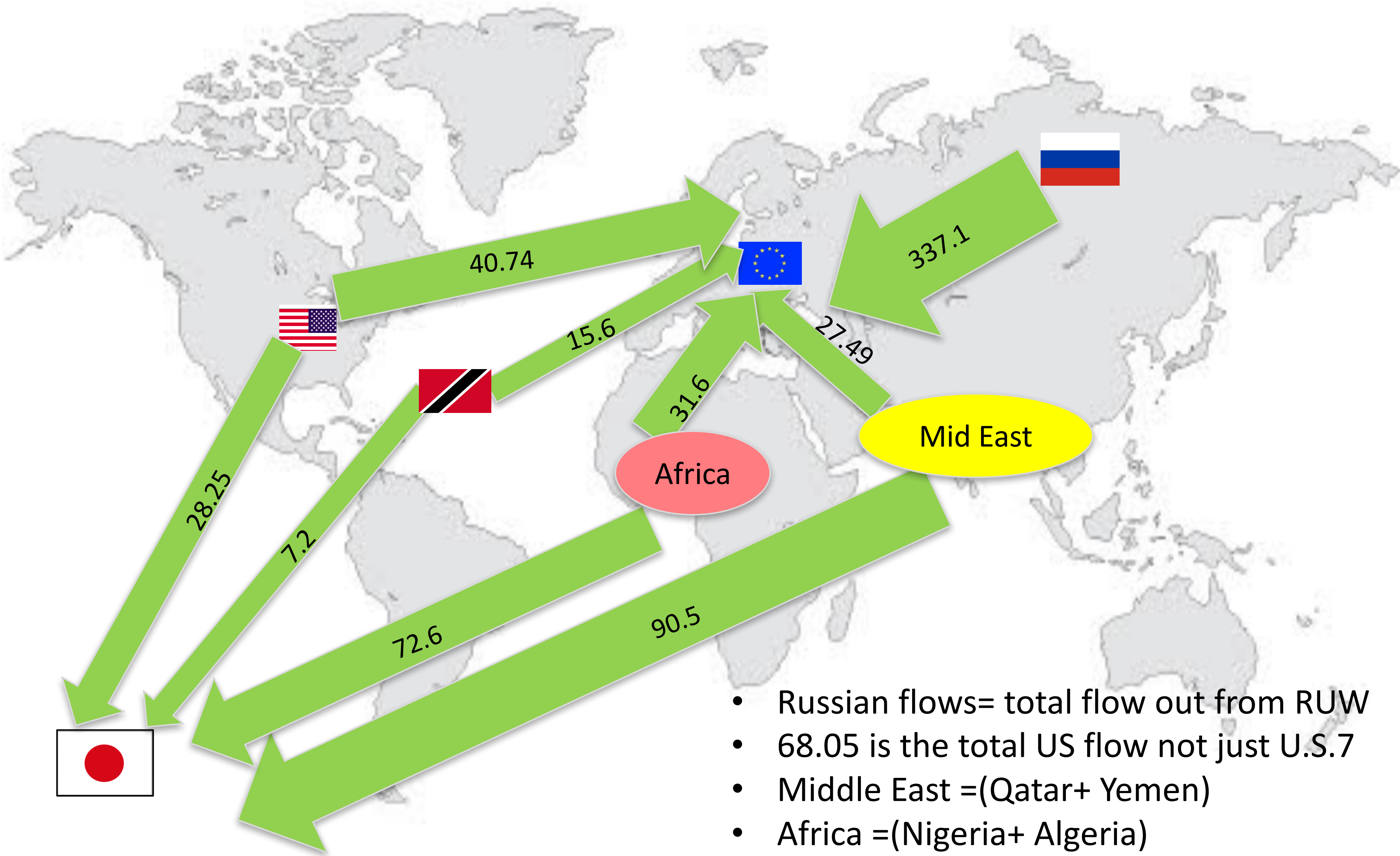
- Russian flows= total flow out from RUW
- 68.05 is the total US flow not just U.S.7
- Middle East =(Qatar+ Yemen)
- Africa =(Nigeria+ Algeria)

Dynamics of Flows: Triple Tariff Scenario, Flows in Bcm/y for 2035



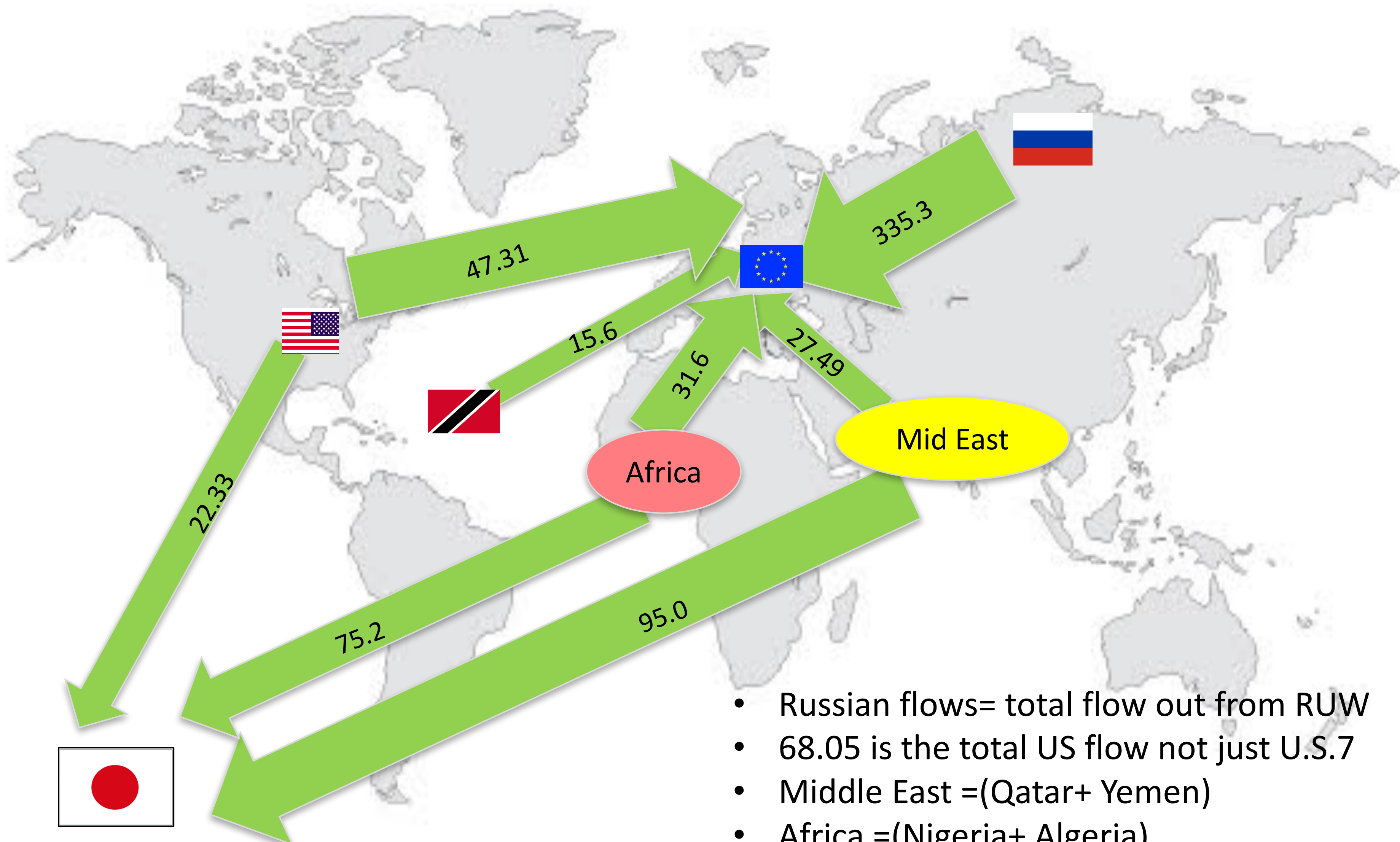
- Russian flows= total flow out from RUW
- 68.05 is the total US flow not just U.S.7
- Middle East =(Qatar+ Yemen)
- Africa =(Nigeria+ Algeria)

Dynamics of Flows: Five-fold Tariff Scenario, Flows in Bcm/y for 2035



- Russian flows= total flow out from RUW
- 68.05 is the total US flow not just U.S.7
- Middle East =(Qatar+ Yemen)
- Africa =(Nigeria+ Algeria)

Dynamics of Flows: Infinite Tariff Scenario, Flows in Bcm/y for 2035



- Russian flows= total flow out from RUW
- 68.05 is the total US flow not just U.S.7
- Middle East =(Qatar+ Yemen)
- Africa =(Nigeria+ Algeria)

Prices

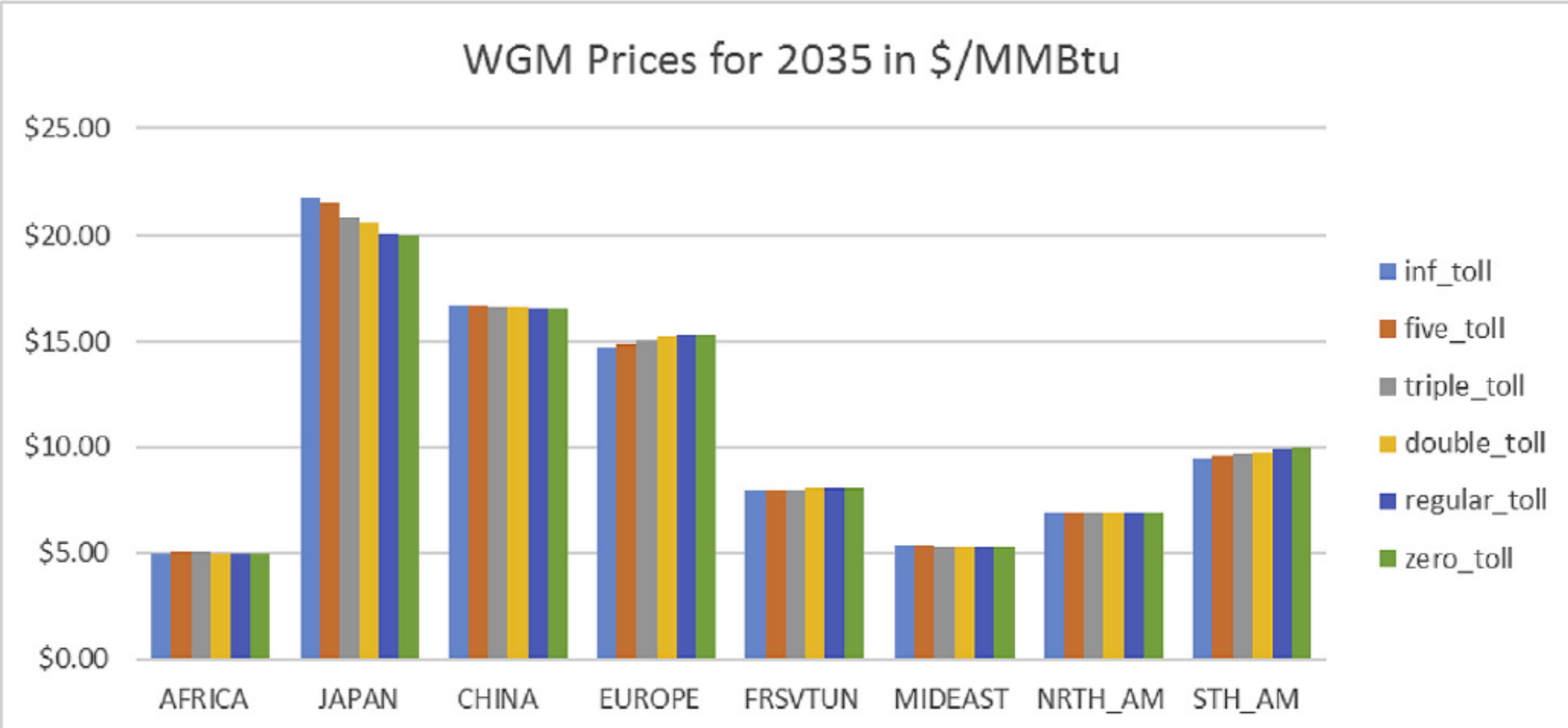


Fig. 6. WGM prices for 2035 in $/MMBtu.

Conclusions

- Nash-Cournot approach to large-scale energy security can provide useful results for modelers, private and public sector decision-makers
- An increase in the Panama Canal tariff causes dynamic changes in flows between Europe and Asia for Trinidad and US, e.g.,
  - As the tariff increases, the flows from U.S. and Trinidad to Japan decrease, but the flows from these two countries to Europe go up
  - U.S. and Trinidad flows slightly displace flows from Middle East, African , and Asian suppliers to Japan node
  - When the canal is available, Qatar, Yemen, Algeria, Indonesia, and Nigeria will lose their market shares
  - Russian flows to Europe are affected by the direction of U.S. LNG Exports (2-3% change)
  - Russia does not utilize South Stream in any scenarios
- Panama Canal operator has some sort of market power (two-level optimization in Seksun Moryadee's (Ph.D. thesis)

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