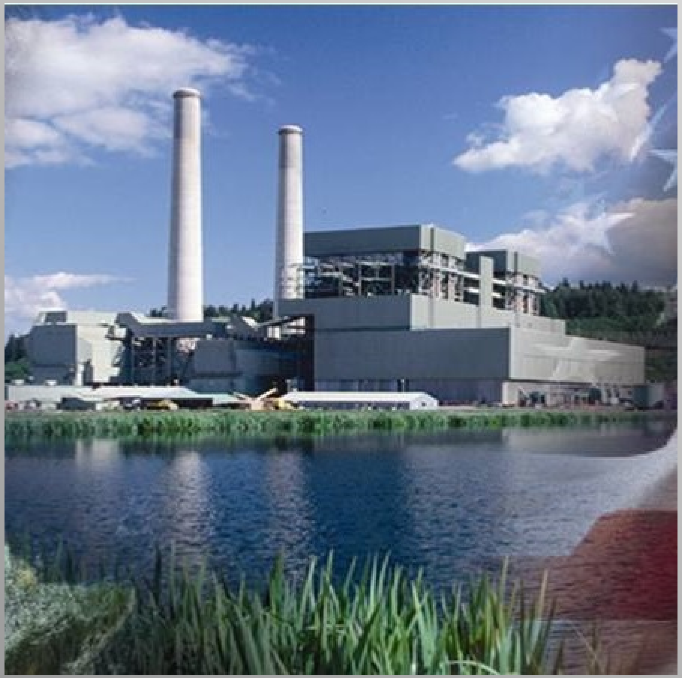

Life Cycle GHG Footprint of a U.S. Energy Export Market for Coal and Natural Gas

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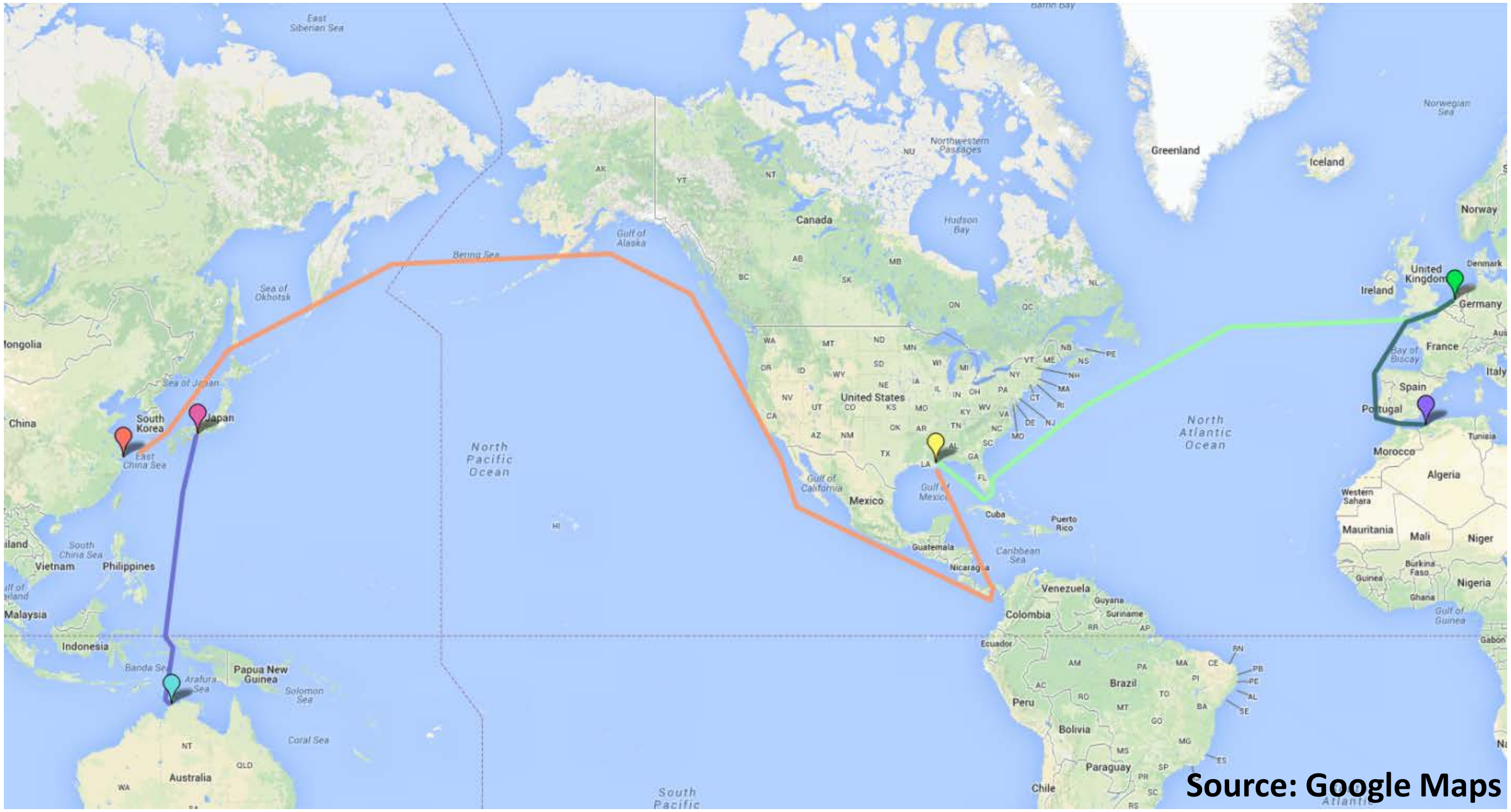
Two questions – from a life cycle GHG perspective

1. **How does exported liquefied natural gas (LNG) from U.S. compare with regional coal for electric power generation in Europe and Asia?**
2. **How do results compare with natural gas (NG) extracted in Russia and delivered via pipeline to European and Asian markets?**

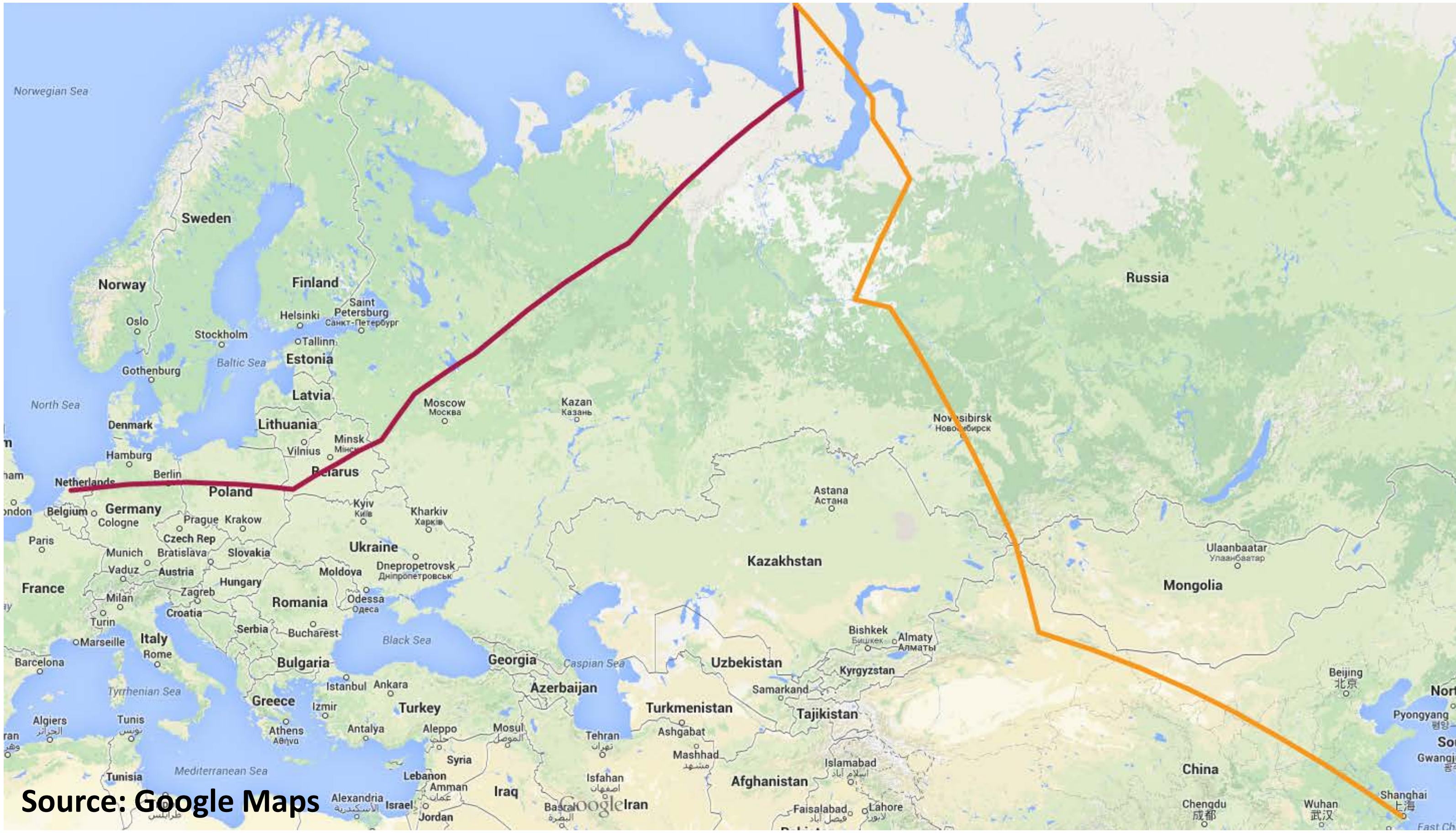
Image source: Energy Information Administration (EIA)
(http://cms.doe.gov/fe/science-innovation/oil-gas/liquefied-natural-gas)

LNG scenarios include U.S. exports as well as business-as-usual LNG scenarios



- LNG requires liquefaction, ocean transport, and regasification
- Panama Canal is viable route for LNG tankers
- U.S. export terminal is near New Orleans, with import terminals in Rotterdam and Shanghai
- Business-as-usual LNG scenarios are Algeria to Rotterdam and Australia to Osaka

Traditional overland transport of NG is also modeled as basis for comparison



Source: Google Maps

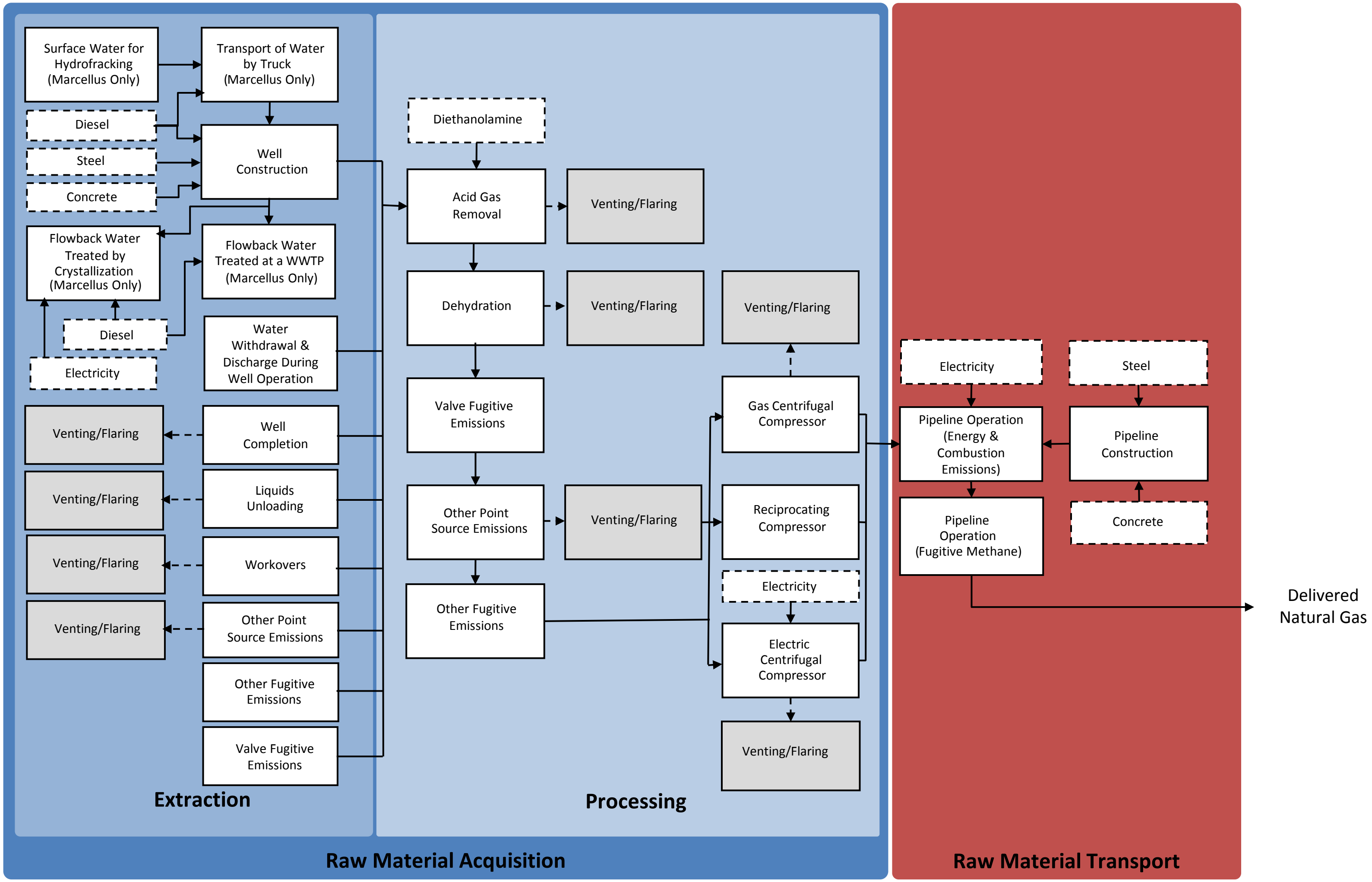
- Natural gas extracted in Russia is sent to Europe and Asia
- Pipeline distance estimated by adding 1,000 km to the great circle distance between source and destinations

Options for natural gas and coal supply chains result in 4 general scenarios

	Scenarios →	1. U.S. NG (Marcellus Shale) via LNG	2. Regional supply of NG via LNG	3. Regional supply of NG via pipeline	4. Regional Coal
	Geographies	U.S. supplies Europe and Asia	Algeria supplies Europe/ Australia supplies Asia	Russia supplies Europe and Asia	Russia supplies Europe and Asia
Life Cycle Steps	Extraction and processing	• Shale gas extraction • Processing	• Conventional NG extraction • Processing	• Conventional NG extraction • Processing	• Coal surface mining
	LNG supply chain	• Liquefaction • Ocean transport • Regasification		Not applicable	
	Pipeline or rail transport	Pipeline transport from regasification to power plant		Pipeline transport from processing to power plant	Rail transport from mine to power plant
	Energy Conversion	Fleet NG power plant			Fleet coal power plant
	Electricity Transmission & Distribution	Electricity transmission and distribution (Functional unit: 1 MWh of delivered electricity)			

These 4 scenarios bound the likely life cycle GHG emissions from natural gas and coal power – demand interactions between different options are outside of study scope.

Our upstream NG model is an important component of our power LCAs



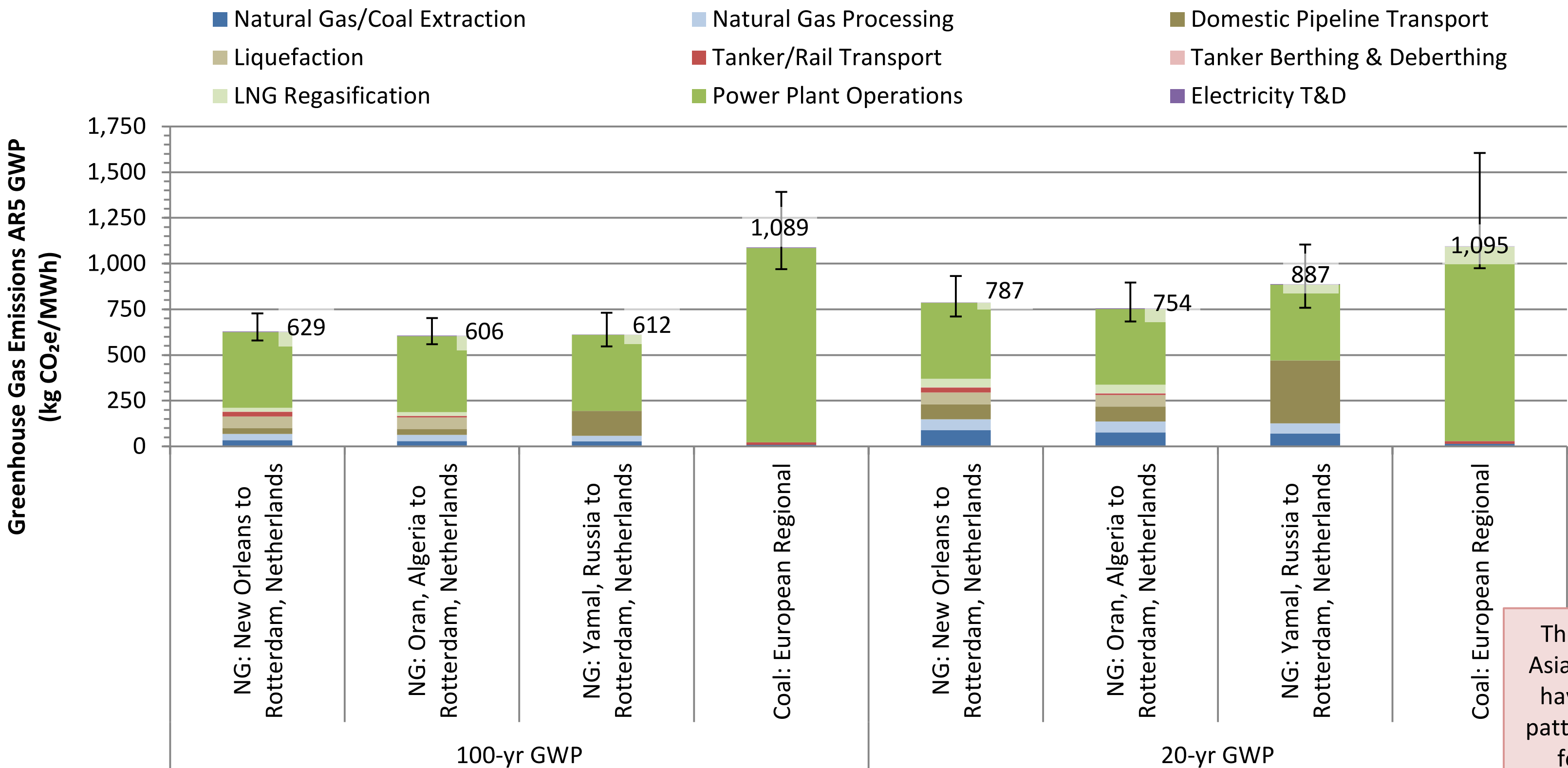
Over 20 unique unit processes directly related to upstream NG – bottom-up and parameterized

Parameters allow analysis of uncertainty

Supply Chain Activity	Model Parameter		Low	Expected	High
LNG					
NG extraction, processing, and transport	Methane Leakage (cradle-to-liquefaction)	Marcellus Shale Gas	1.20%	1.40%	1.60%
		Conventional Onshore Gas	1.10%	1.30%	1.60%
	Gas Type		Marcellus Shale – U.S. Gas Conventional Onshore – Regional Gas		
	Pipeline Distance (Extraction to LNG Facility) (km)		777	971	1,166
	Transport distances (nautical miles)	New Orleans to Rotterdam, Netherlands	4,301	4,801	5,301
		Oran, Algeria to Rotterdam, Netherlands	1,082	1,582	2,082
		New Orleans to Shanghai, China	9,497	9,997	14,844
		Darwin, Australia to Osaka, Japan	2,385	2,885	3,385
Power plant	Power Plant Net Efficiency		41.2%	46.4%	49.2%
Electricity transport	Transmission and Distribution (T&D) Loss		7%		
Overland Natural Gas					
NG extraction, processing, and transport	Methane Leakage (cradle-to-delivered)	Yamal, Russia to Rotterdam, Netherlands	2.80%	3.40%	4.10%
		Yamal, Russia to Shanghai, China	3.70%	4.30%	5.00%
	Gas Type		Conventional Onshore		
	Pipeline Distance (km)	Yamal, Russia to Rotterdam, Netherlands	3,792	4,792	5,792
		Yamal, Russia to Shanghai, China	5,447	6,447	7,447
Power plant	Power Plant Net Efficiency		41.2%	46.4%	49.2%
Electricity transport	Transmission and Distribution (T&D) Loss		7%		
Coal					
Coal extraction	Coal Mine Methane (scf/ton)		8	8	360
	Coal Type		PRB	PRB	I-6
Transport	Rail Transport Distance (miles)		225	725	1,225
Power plant	Power Plant Net Efficiency		28.30%	33.00%	36.70%
Electricity transport	Transmission and Distribution (T&D) Loss		7%		

- Natural gas model has more parameters than coal model – natural gas life cycle chain has more sources of methane emissions than coal life cycle
- Leakage rate is not an input, but an output based on a mix of emission factors, flaring rates, NG composition, etc.
- Low and high bounds for coal mine methane account for variability demonstrated by different coal sources

Power plants account for majority of GHG emissions, but upstream methane is an important variable

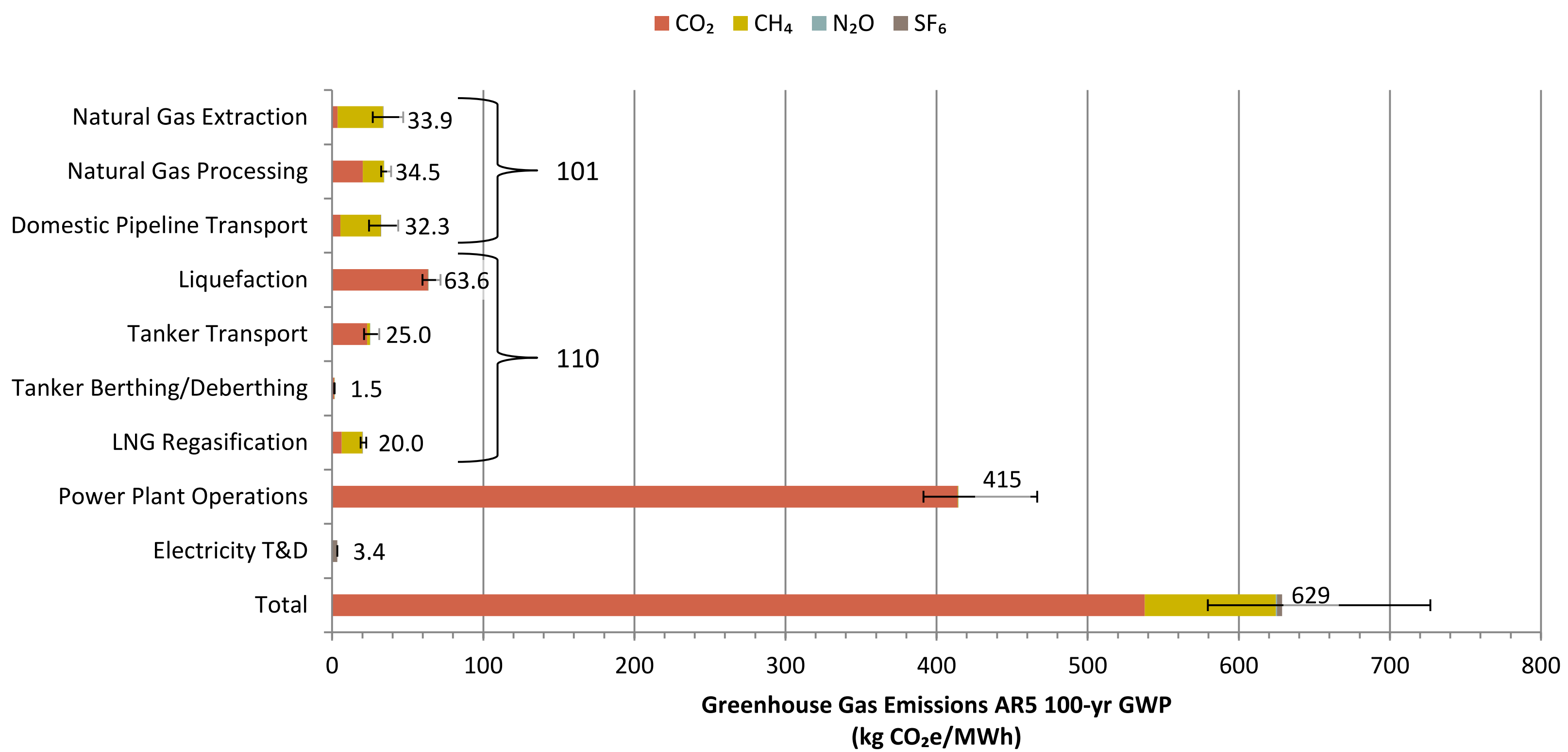


The results for Asia (not shown) have the same patterns as those for Europe.

- Power plant operations account for majority of life cycle GHG emissions
- Uncertainty comprises power plant efficiencies, transport distances, and upstream methane emissions
- Global warming potential (GWP) timeframe matters
  - 100-yr GWP: All NG scenarios are lower than coal
  - 20-yr GWP: Uncertainty overlaps between NG and coal

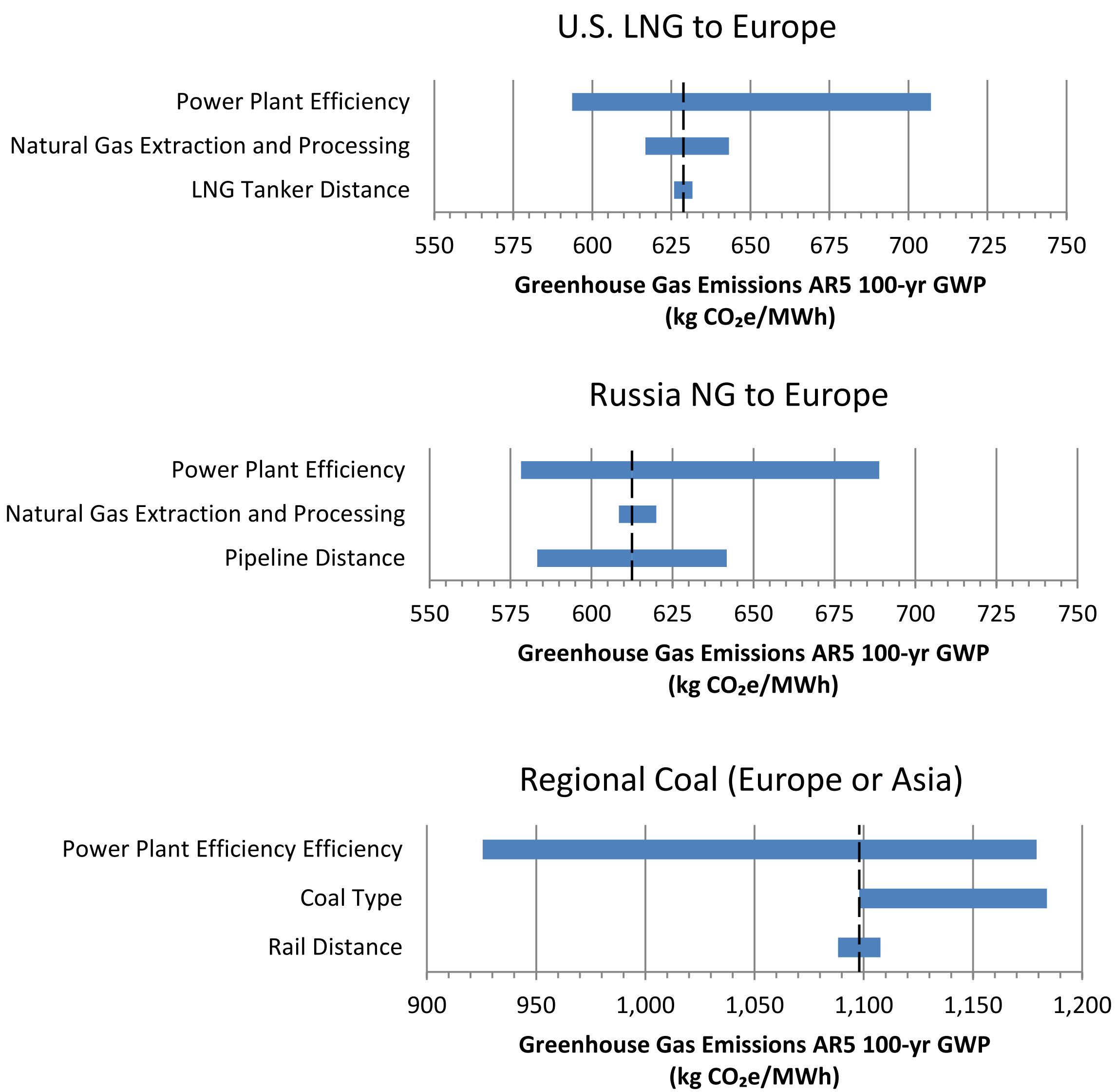
Detailed results show key drivers and opportunities

(Example: LNG exported to Europe)



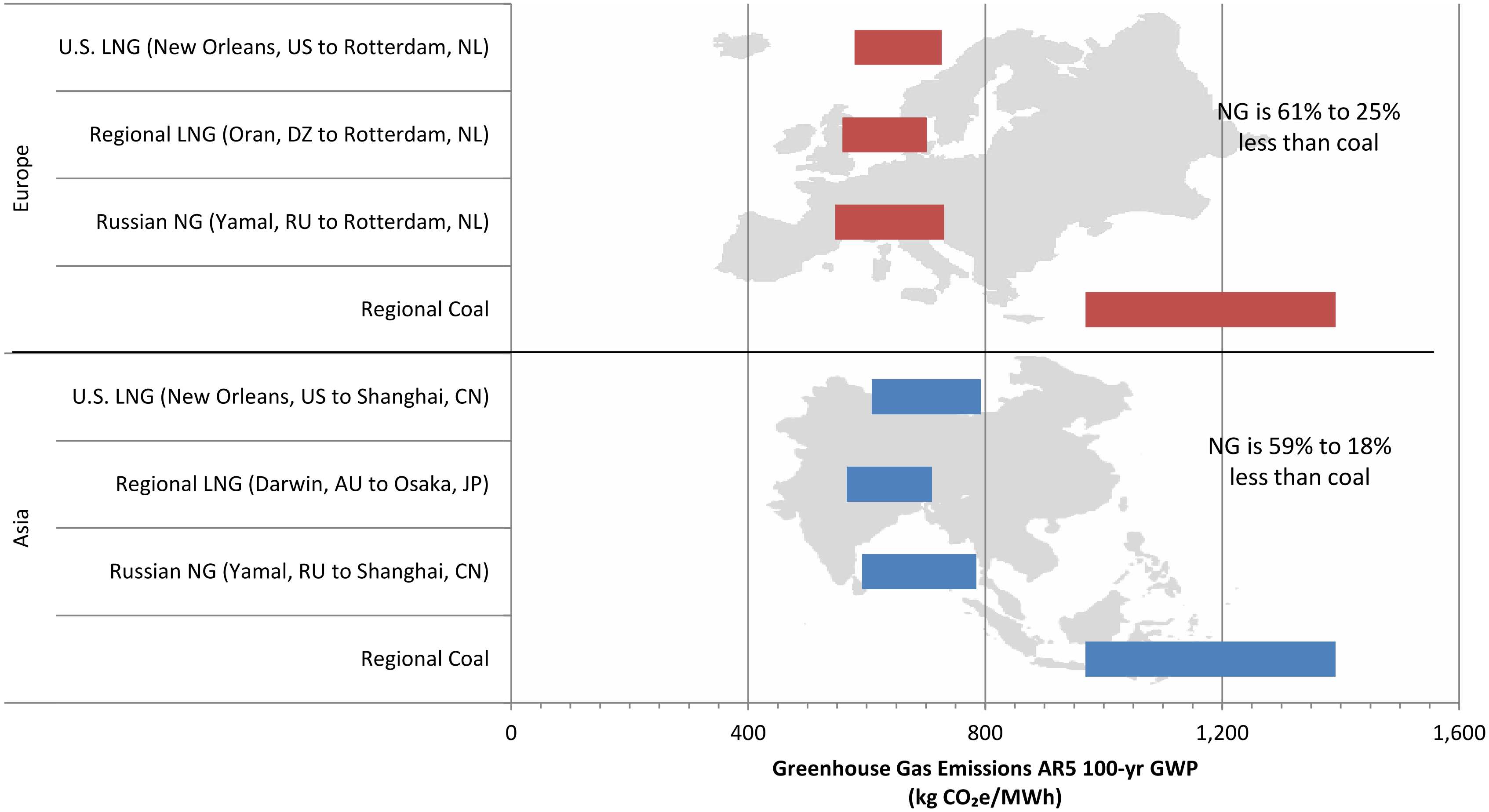
- Direct GHG emissions from liquefaction, tanker transport, tanker berthing/deberthing, and LNG regasification are 110 kg CO_2e/MWh
- Losses from LNG processes indirectly increase upstream GHGs by 17%, from 86 to 101 kg CO_2e/MWh (compared to a domestic production and consumption scenario)
- Methane emissions from upstream natural gas are a near-term opportunity for life cycle GHG reductions, and improved liquefaction efficiency will further reduce upstream emissions

Uncertainty is driven by power plant efficiency

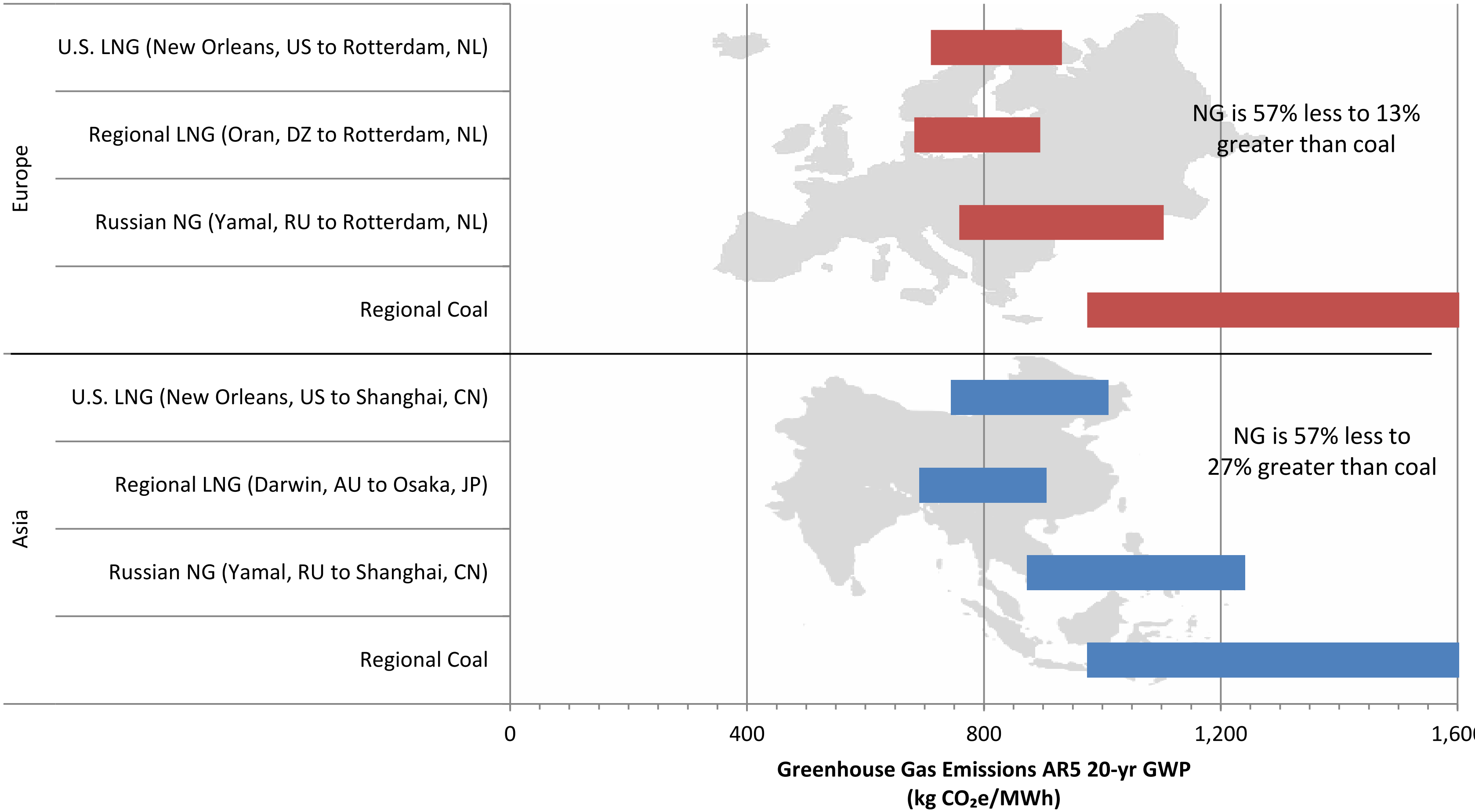


- Power plant efficiency is a data limitation
- Parameterization allows us to bound our results with likely scenarios
- Power plant operations in Europe or Asia may be beyond our control, but upstream methane reductions are within our control

Uncertainty does not overlap with 100-yr GWPs

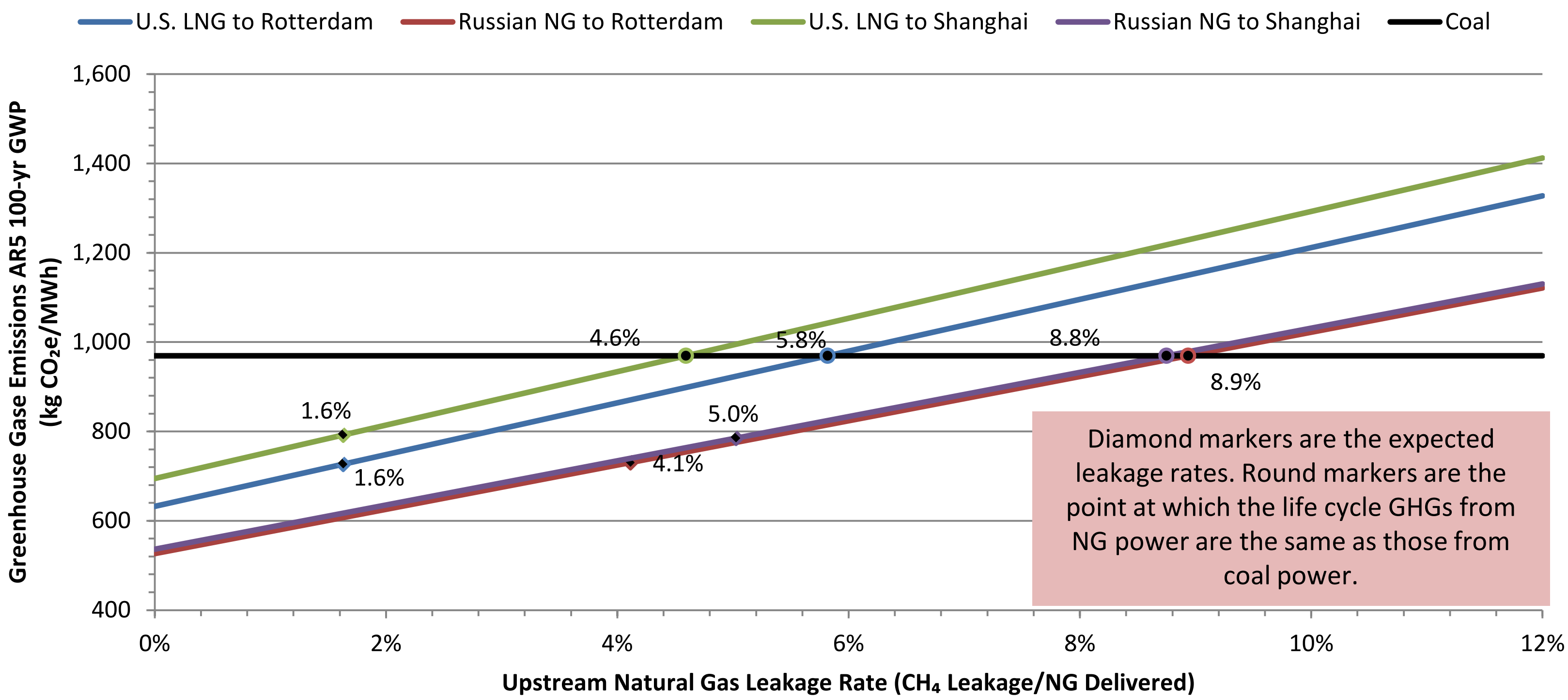


Uncertainty does overlap with 20-yr GWPs



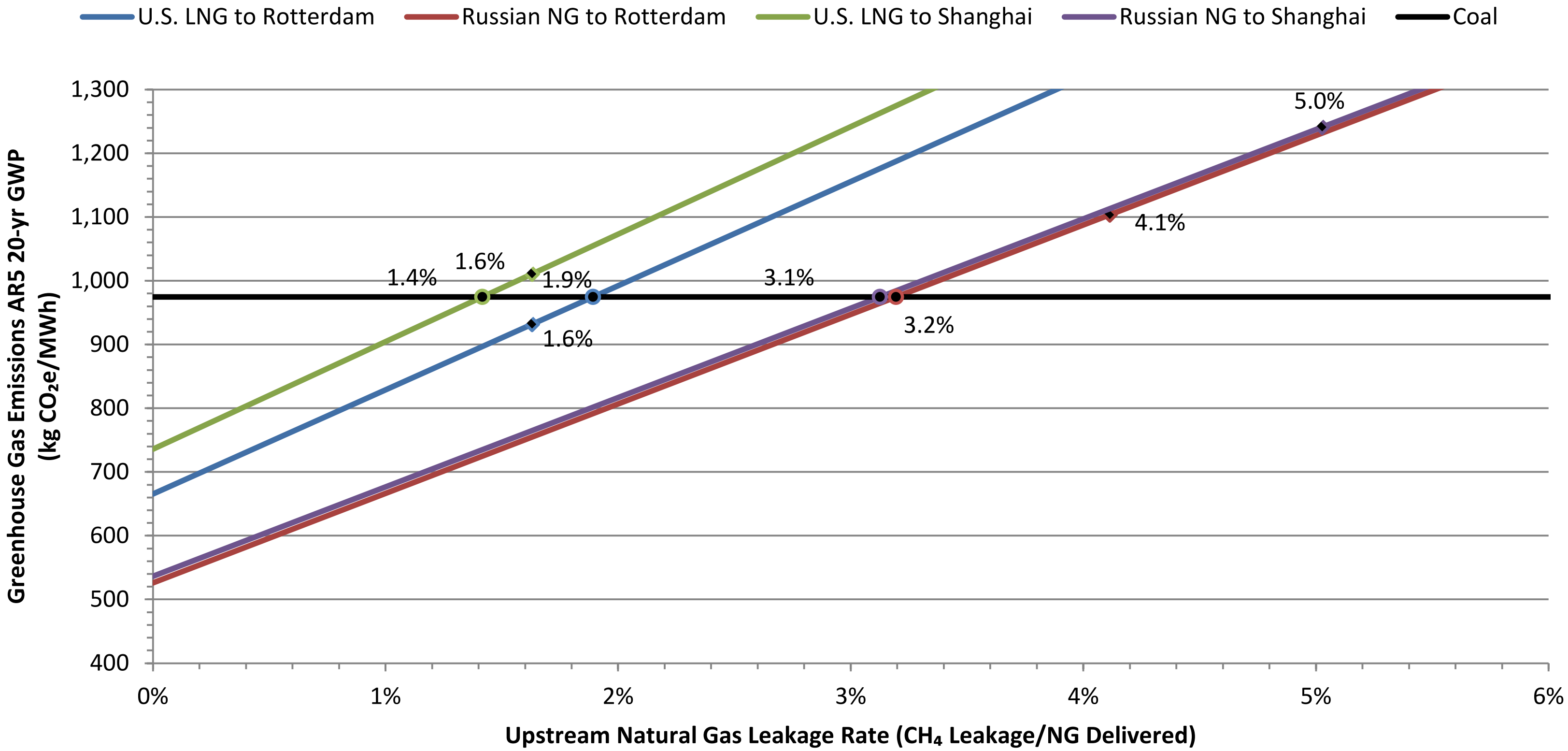
Overlaps represent the high GHG cases for NG and low GHG cases for coal (e.g., low NG power plant efficiency vs. high coal power plant efficiency).

At what point can upstream methane leakage offset the lower CO_2 intensity of NG power?



- Leakage rate is an *output* of our model, not an input
- Breakeven points are based on conservative parameters (e.g., lowest NG power plant efficiency vs. highest coal power plant efficiency)
- Using 100-year GWP, all natural gas scenarios have lower life cycle GHG emissions than coal scenario

Using 20-year GWP significantly lowers the breakeven CH_4 leakage rate



- On a 20-year GWP, only one NG scenario (U.S. LNG to Rotterdam) has lower life cycle GHG emissions than coal power
- Reductions in upstream methane leakage can ensure that NG has lower GHG emissions than coal in all power scenarios

Summary

- Use of U.S. LNG exports for power production in Europe and Asia will not increase life cycle GHG emissions when compared to regional coal scenarios
- Parameterized model allows us to account for data uncertainty in infrastructure and power plant characteristics
- Reducing upstream methane leakage is a near term opportunity for reducing life cycle GHG emissions from natural gas systems

Full report, supporting documentation, and public comments are available at
http://energy.gov/fe/life-cycle-greenhouse-gas-perspective-exporting-liquefied-natural-gas-united-states

DOE's responses to public comments are in the final authorization for the Cameron LNG terminal at
http://www.energy.gov/sites/prod/files/2014/09/f18/Cameron ORDER.pdf

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Supporting Information: Parameter Tables

Natural Gas

Property (Units)		Onshore Conventional	Marcellus Shale
Natural Gas Extraction			
Expected EUR (Bcf)		0.72 (0.50 - 0.94)	3.25 (2.19 - 4.92)
Flaring Rate of Potential NG Emissions (%)		51% (41 - 61%)	15% (12 - 18%)
Well Completion (Mcf natural gas/episode)		37	9,000
Well Workover (Mcf natural gas/episode)		2.44	9,000
Lifetime Well Workovers (Episodes/well)		1.1	0.3
Liquids Unloading (Mcf/episode)		3.57	N/A
Lifetime Liquid Unloadings (Episodes/well)		930	N/A
Valve Emissions, Fugitive (lb. CH_4/Mcf)		0.11	
Other Sources, Point Source (lb. CH_4/Mcf)		0.003	
Other Sources, Fugitive (lb. CH_4/Mcf)		0.043	
Natural Gas Processing			
Flaring Rate of Potential NG Emissions (%)		100%	
Acid Gas Removal: CH_4 Absorbed (lb. CH_4/Mcf)		0.04	
Acid Gas Removal: CO_2 Absorbed (lb. CO_2/Mcf)		0.56	
Acid Gas Removal: H_2S Absorbed (lb. H_2S/Mcf)		0.21	
Acid Gas Removal: NMVOC Absorbed (lb. NMVOC/Mcf)		6.59	
Dehydration: Water Removed (lb. H_2O/Mcf)		0.045	
Dehydration: CH_4 Emission Rate (lb. CH_4/Mcf)		0.0003	
Other Controllable Emissions (lb. CH_4/Mcf)		0.02	
Valve Fugitive Emissions (lb. CH_4/Mcf)		0.0003	
Other Fugitive Emissions (lb. CH_4/Mcf)		0.03	
Compressor Profile	Gas-powered Reciprocating	100%	100%
	Gas-powered Centrifugal	0%	0%
	Electrically-powered Centrifugal	0%	0%
Natural Gas Transmission Pipeline			
Pipeline Transport Distance (km)		971 (777 – 1,166)	
Distance Between Compressors (km)		121	
Compressor Profile	Gas-powered Reciprocating	78%	
	Gas-powered Centrifugal	19%	
	Electrically-powered Centrifugal	3%	
Power Plant Operation			
Power Plant Net Efficiency		46.4% (41.2 - 49.2%)	
Electricity Transmission and Distribution (T&D)			
T&D Loss		7%	

Coal

Property (Units)	Low	Expected	High
Coal Extraction			
Coal Mine Methane (scf/ton)	8	8	360
Coal Source	Powder River Basin (PRB)		Illinois No. 6 (I-6)
Coal Transport			
Rail Transport Distance (miles)	225	725	1,225
Power Plant Operation			
Power Plant Net Efficiency	28.3%	33.0%	36.7%
Electricity Transmission and Distribution (T&D)			
T&D Loss	7%		

Supporting Information: LC GHG for NG and Coal Power in Asia