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David J. Ramberg*, Y.H. Henry Chen†, Sergey Paltsev‡ and John E. Parsons§

Abstract

The paper examines conditions under which gas-to-liquids (GTL) technology penetration shifts the crude oil-natural gas price ratio. Technologies that enable direct substitution across fuels, as GTL does, may constrain the price ratio within certain bounds. We analyze the forecasted evolution of the crude oil-natural gas price ratio over the next several decades under alternative assumptions about the availability and cost of GTL and its natural gas feedstock. We do this using a computable general equilibrium model of the global economy with a focus on the refinery sector in the U.S. Absent GTL, a base case forecast of global economic growth over the next few decades produces dramatic increases in the oil-natural gas price ratio. This is because there is a more limited supply of low-cost crude oil resources than natural gas resources. The availability of GTL at conventional forecasts of cost and efficiency does not materially change the picture because it is too expensive to enhance direct competition between the two as fuels in the transportation sector. GTL only modulates the increasing oil-gas price ratio if both (i) natural gas is much cheaper to produce, and (ii) GTL is less costly and more efficient than conventional forecasts.

Contents

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1. INTRODUCTION

A tie between crude oil and natural gas prices has been documented by a number of researchers, including Serletis and Herbert (1999); Bachmeier and Griffin (2006); Asche *et al.* (2006); Villar and Joutz (2006); Brown and Yucel (2008); Hartley *et al.* (2008); Ramberg and Parsons (2012); Loungani and Matsumoto (2012); Brigida (2014).[1] Many of these researchers attribute the tie to explicit competition between the fuels in key sectors—for example, Serletis and Herbert (1999); Pyrdol and Baron (2003); Asche *et al.* (2006); Villar and Joutz (2006); Brown and Yucel (2008); Hartley *et al.* (2008); Ramberg and Parsons (2012); Loungani and Matsumoto (2012). However, the linkage could arise in a number of ways, including the following:

- Natural gas is discovered with crude oil in oil wells. This is a complementary linkage.
- Natural gas is a feedstock to petroleum refining. This is another complementary linkage.
- Natural gas and crude oil exploration compete for the same drilling rigs and labor. This is a competitive linkage.
- Natural gas and petroleum-derived fuels are interchangeable in some industrial processes (such as dual-fuel boilers). This is another competitive linkage.
- Natural gas and fuel oils compete for heating homes and buildings.
- In some regions (such as Pakistan and Argentina), compressed natural gas is a significant competitor to diesel or gasoline in transportation.
- An apparent linkage can also arise if global economic growth translates into correlated price trajectories through time even in the absence of direct fuel-to-fuel linkages.

Some have documented changes in the tie between the two price series and attributed that to changes in one or more of these linkages—see Serletis and Rangel-Ruiz (2004), among others. The empirical challenge in this literature is to filter out the influence of extremely short-term volatility in order to identify the longer-term relationship. The challenge is made harder when the underlying technological and economic factors shaping the relationship are also changing through time. This paper studies the tie between oil and natural gas prices from a different perspective, modeling the underlying linkages and the evolving economic variables driving the two price series. We use a computable general equilibrium (CGE) model of the global economy in which crude oil and natural gas resources are inputs to production in a number of different sectors feeding into a number of different end uses. We introduce a gas-to-liquids (GTL) technology that offers the potential for direct competition between the two fuels in the transportation sector. GTL converts a natural gas feedstock into liquid transportation fuels—generally diesel—and petrochemical feedstocks (such as naphtha), thus creating an explicit

[1] Formally, the tie is cointegration of the time series of crude oil and natural gas prices. Two or more non-stationary data series are considered cointegrated when the relationship between them can be characterized by a single stable equation. A non-stationary data series is one in which the mean changes substantially depending on the subset of the series chosen. This is a common feature of time series data, and especially of commodity price series, in which the average price tends to drift upward or downward over time.

competitive linkage between natural gas and petroleum products in any sector that initially uses petrochemical feedstocks or diesel fuels. At different cost and efficiency levels, GTL should deploy to varying degrees, and its influence on the usage (and thus prices) of crude oil and natural gas can be tracked. Using our model, we analyze scenarios for the future price paths for the two fuels over several decades, and the ratio of the two prices along those paths, and we document whether the GTL technology significantly impacts that ratio.

The structure of the remainder of this paper is as follows: Section 2 discusses the research design and the base case scenario, Section 3 details results when GTL is introduced, Section 4 reports results when factors affecting the feasibility of GTL are altered, and Section 5 concludes.

2. RESEARCH DESIGN AND BASE CASE

The set of indirect experiments utilizes the EPPA6-ROIL model developed at the MIT Joint Program on the Science and Policy of Global Change. EPPA6 is a CGE model that simulates the activities of 14 sectors (each producing a single commodity) and consumer demand over 18 global regions. Interregional trade of each commodity is explicitly modeled (Chen *et al.*, 2015). EPPA6-ROIL further breaks refined fuels into six different products. This allows for analysis of competition among distinct petroleum products, such as between gasoline and diesel fuels in transportation (Ramberg, 2015). It explicitly models changes in petroleum product fuel interactions in response to technological deployment.

The data are aggregated from the Global Trade Analysis Project (GTAP) version 8 (Global Trade Analysis Project). EPPA6-ROIL disaggregates the refined oil commodity into refinery gases (RGAS), distillate fuels such as diesel (DISL), gasolines (GSLN), residual heavy fuel oils (HFOL), lubricants/waxes/petrochemical feedstocks (OTHP), and petroleum coke (COKE). Disaggregation of the refined oil product is based on the International Energy Agency's (IEA's) *Energy Statistics and Balances* and *Energy Prices and Taxes* databases, the Energy Information Administration's (EIA's) *State Energy Data System (SEDS)* database, and on the calibration data for the International Council for Clean Transportation's (ICCT's) Roadmap model (International Energy Agency, 2010a, 2008; U.S. Energy Information Administration, 2014; International Council on Clean Transportation, 2012). The initial year for the model run is 2007. The full model is run from 2007 to 2010, then in 5-year intervals through 2100.

We examine the relative prices of crude oil and natural gas that evolve in the simulation. The crude oil price is set by global markets, which reflect global aggregate supply and demand. The ease with which oil can be transported by sea, truck, or pipeline provides significant opportunities for arbitrage across regional markets. The result is that the crude oil price tends toward a single global price. Unlike the crude oil price, natural gas prices vary widely across regions. Natural gas transport is limited to costly pipelines, and markets tend to develop around regional transport hubs. In part because the natural gas price is regional, this study focuses on U.S. natural gas prices and the global crude oil price. The global crude oil price is compared to the U.S. natural gas price through a ratio.[2]

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[2] Following industry conventions, the ratio is the crude oil price to the natural gas price, with the crude oil price measured in dollars per barrel ($/bbl) and the natural gas price measured in dollars per million British thermal units ($/mmBtu).

Petroleum products are nearly as easily transported as crude oil. However, region-specific fuel grades and emissions specifications make them less fungible than crude oil internationally. As a result, petroleum product prices are also regional, though with less variation than natural gas prices.

In the base case, GTL technology is not available for deployment. Subsequent simulations will set different cost and efficiency levels for GTL and different reserve levels and production costs for natural gas. We will then examine how differing levels of GTL penetration affect the crude oil-natural gas price relationship (if at all). In order to simplify the analysis, compressed natural gas (CNG), liquefied natural gas (LNG), and electric vehicle (EV) technologies are not included in the model. GTL is an easier drop-in technology than CNG, LNG, or EVs: the range of GTL-fueled vehicles is not limited and their acceleration is not inhibited, unlike CNG vehicles; EVs and LNG vehicles require complex infrastructure investments that complicate the modeling process. From a hedonic perspective, users will be indifferent about adopting GTL fuels because they are fungible with current diesel fuels and can be consumed in current diesel engines. GTL will thus be the only new route through which natural gas can compete with crude oil products in this simulation.

The base case model run provides the reference to which all other cases are compared. It reveals key dynamics in the simulated global economy over the course of the 21st century. Figure 1 shows the crude oil price path for this base case scenario, as well as other scenarios to be discussed later. In the Base case (solid black circles) the crude oil price increases from about \$71 per barrel (bbl) in 2007 to over \$240/bbl in 2007 dollars by 2100. **Figure 2** shows the U.S. natural gas price for all scenarios. In the Base case, the natural gas price increases from \$6.75 per million Btu (mmBtu) in 2007 to about \$7.75/mmBtu through 2035, then remains near that level for the remainder of the simulation.

Figure 3 shows the ratio of crude oil to natural gas prices over the simulation for all scenarios. The oil-gas price ratio rose from over 10-to-1 to over 31-to-1 over the span of the base case.

Crude oil prices steadily increased through 2100, ending over 240% above 2007 levels. U.S. natural gas prices rose until 2035, then stabilized at about 15% above 2007 levels through the end of the simulation. The quantities supplied of both fuels increased at similar rates through 2100, although the increase is larger for natural gas. By the end of the century, natural gas demand had increased about 256%, and crude oil demand had increased by 133%. Natural gas consumption increased from about 69% of crude oil consumption in 2007 (measured in mmBtu) to about 103% of crude oil consumption in 2100, putting the consumption of both fuels roughly at parity by the end of the simulation. To illustrate sensitivity of the price to increases in demand: the global crude oil price increased by 1.8% for each 1% increase in usage, while natural gas prices only increased by 0.06% for each 1% increase in usage between 2007 and 2100.

In the base case, the most rapid growth occurred in developing countries. As developing countries became wealthier, their demand for most goods and services increased. An exception was the growth in heating demand: most developing countries are in warmer regions, where heating demand (often served by natural gas) is weak. However, demand growth in other sectors followed increases in wealth. Demand for cooling and demand for private transportation both increased

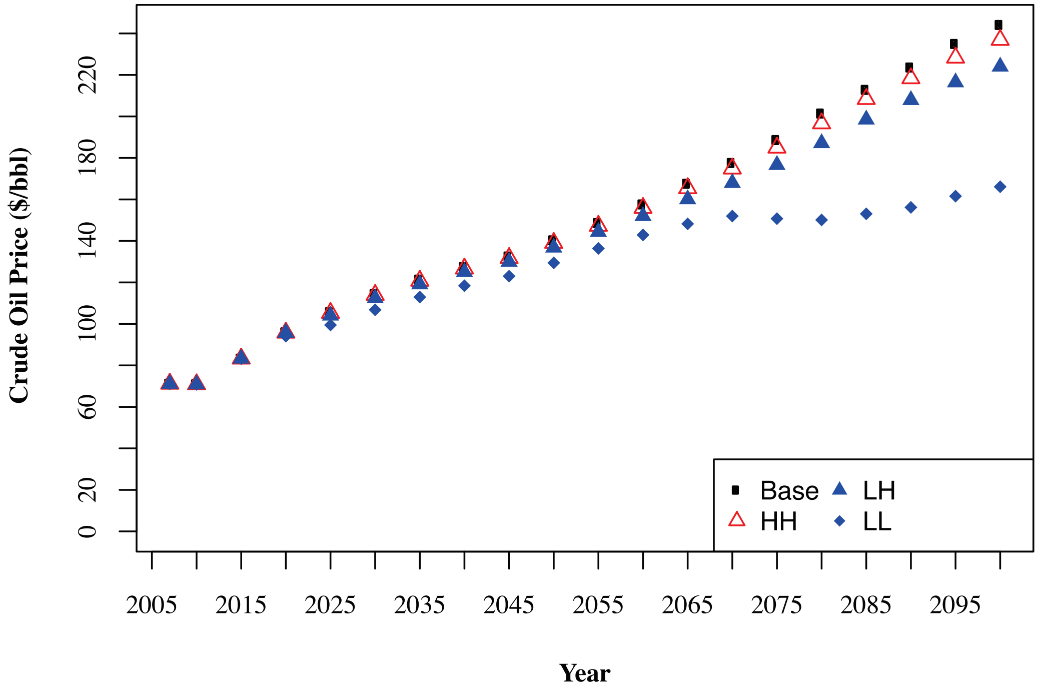

Figure 1. World crude oil price ($/bbl): Base case and 3 scenarios

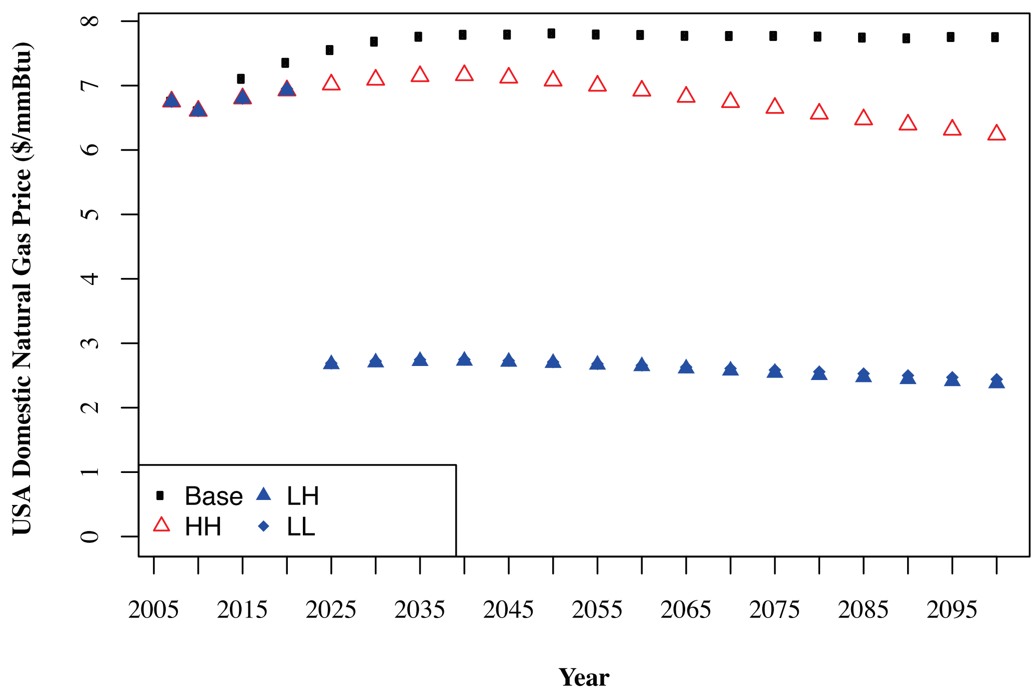

Figure 2. U.S. domestic natural gas price ($/mmBtu): Base case and 3 scenarios

GTL Share LL	0%	0%	3%	10%	12%	13%	14%	15%	16%	17%	19%	22%	26%	30%	33%	35%	36%	37%	38%
GTL Share LH	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	2%	2%	4%	5%	5%	6%	6%	6%	6%
GTL Share HH	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%

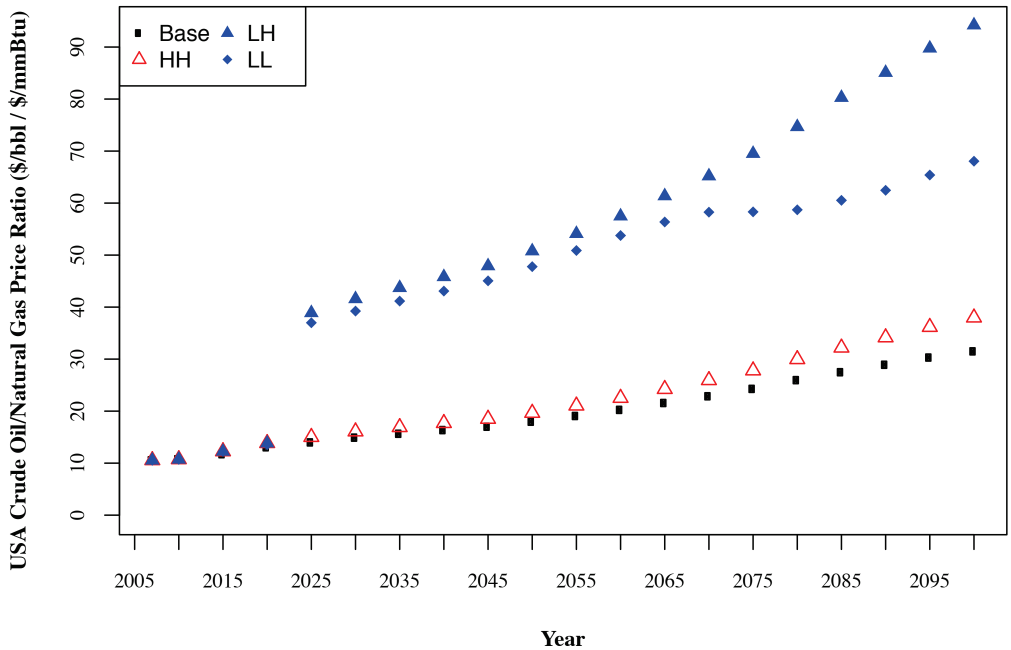

Figure 3. Crude oil / domestic natural gas price ratios ($/bbl / $/mmBtu) in the U.S.: Base case and 3 scenarios

substantially. These circumstances translated into rising demand for both crude oil and natural gas through time.

The cost curves for natural gas are parameterized based on the data used in the MIT Future of Natural Gas study (Moniz *et al.*, 2011). The cost curves for crude oil are based on the data in Chan *et al.* (2012). In 2007, crude oil production fell on a steeper part of the upward-sloping supply curve in comparison to natural gas. Over time, as crude oil production expanded, its cost of extraction—the resource cost—increased rapidly. In order to meet growing demand, more inputs of other factors of production (especially capital and labor) were required per unit of output. In 2007, cumulative production of natural gas put it on a relatively flat portion of its cost curve. Natural gas cost inputs remained fairly constant over the course of the simulation. In many regions, the production cost actually declined as the natural gas industry matured from its nascent stages into a well-established industry.

The equilibrium quantities consumed and the prices of the two commodities reflect the interaction between the evolving supply and demand as mediated by the available production technologies. The sectors using natural gas typically also have alternative inputs available—for example, coal and natural gas compete as fuels to produce electricity. The transportation sector, however, is fueled almost exclusively with petroleum products refined from crude oil. Thus, the increase in transportation fuel demand translated directly to an increase in crude oil demand, but only a portion of the increase in electricity demand translated to an increase in natural gas demand. In sum, the lack of low-cost crude oil reserves, and the relative abundance of lower-cost natural gas reserves, made production increases in crude oil more expensive than production increases in natural gas. However, crude oil use continued to increase because of the dominance of petroleum products in the transportation sector. The result is that crude oil prices rose more rapidly over time than natural gas prices, which moved very little. The oil-gas price ratio thus sloped dramatically upward.

Other notable dynamics revealed in the base case are that distillate fuels tended to gradually make inroads against gasoline in agriculture and household transportation, and diesel eventually completely displaced gasoline in commercial transportation by 2100. Energy-intensive industry gradually shifted toward electricity (and, to a lesser extent, coal) at the expense of refinery gases. Electricity generation fuels shifted toward natural gas at the expense of coal, making natural gas the dominant fuel in the latter half of the base case simulation. The natural gas share of energy inputs to global oil refining increased from about 6% in 2007 to nearly 15% by 2100, displacing some crude oil.

3. IMPACT OF GTL

The first indirect experiment makes the GTL technology available and measures the extent to which it is deployed. We then examine whether GTL deployment has an impact on the crude oil-natural gas price relationship. There are a number of GTL technology formats under development. Most make diesel or other distillate fuels, but some make gasoline (Greene, 1999; Robertson, 1999; Knott, 2002; Cohn and Bromberg, 2011). Only the diesel/petrochemical feedstock versions have been proven economic—at least on a large scale (Simbeck and Wilhelm, 2007; Hydrocarbons Technology, 2010b; Shell Global, 2011); the gasoline-producing version of the technology has not left the laboratory (Cohn and Bromberg, 2011). Since the gasoline-producing version of GTL has never been deployed, we model the less costly diesel-producing version. It is assumed to produce a perfect substitute for petroleum-based diesel fuels and petrochemical feedstocks, with some more favorable emissions characteristics (Perego *et al.*, 2009; Delucchi, 1997; Greene, 1999; Schaberg *et al.*, 1997; Martin *et al.*, 1997; Wang and Huang, 1999; Schaberg *et al.*, 2006). Under current technology, nearly 10 mmBtu of natural gas is required to produce an average barrel that is 70% diesel and 30% naphtha. This representative barrel contains about 5.5 mmBtu of energy, meaning that GTL is only 56% efficient.

The base case GTL cost and efficiency data were compiled in Ramberg (2015). Central figures for capital cost, fixed and variable operations and maintenance (O&M), labor costs, and natural gas inputs per barrel of output were drawn from an array of studies and reports: Pintz (1997); Choi (1998); Greene (1999); Robertson (1999); Wang and Huang (1999); Wallace *et al.* (2001); Halstead (2006); Gary *et al.* (2007); Simbeck and Wilhelm (2007); Slaughter *et al.* (2007); Taylor *et al.* (2008); Hydrocarbons Technology (2010a,2010b); International Energy Agency (2010b); Rapier (2010); Bala-Gbogbo (2011); Lefebvre (2011); Liu *et al.* (2011); Shell Global (2011); Shaw (2012); Salehi *et al.* (2013); Atuanya (2014). These GTL parameters reflect a plant of the scale of the Shell Pearl GTL plant in Qatar: 120,000 barrels per day of output, of which 70% are diesel fuels and 30% are petrochemical feedstocks. The key parameters are detailed in **Table 1**, along with the lowest and highest values encountered in the source literature.

Table 1. Key parameters of base case GTL plant

Parameter	Value	Low	High
Capital cost per b/d capacity:	$68,000	$13,000	$303,000
Fixed O&M cost per year:	4% CAPEX	4% CAPEX	4% CAPEX
Variable O&M cost per barrel produced:	$5.00	$3.13	$23.00
Gas input rate, mmBtu per barrel produced:	9.85	8.80	14.13
Plant capacity, b/d:	120,000	1,000	300,000
Capacity utilization:	93%	87%	96%
Project lifespan:	25 years	20 years	30 years
Construction lead time:	3 years	2 years	5 years
Tax rate (assumed):	35%	NA	NA
Debt financing (assumed):	0%	NA	NA
Discount rate (assumed):	10%	NA	NA

An analysis of these key parameters using a discounted cash flow model reveals that the base case GTL plant would face a levelized cost of $42.39 per barrel produced before natural gas feedstock costs are taken into consideration. With a feedstock requirement of 9.85 mmBtu per barrel and $5.00/mmBtu natural gas prices, the levelized cost per barrel would be $91.64. At a natural gas price of $2.00/mmBtu, the levelized cost per barrel would be $62.09, and at $8.00/mmBtu, the levelized cost per barrel would be $121.19. As the price of natural gas increases, the ex-feedstock cost becomes less significant than the cost of natural gas. At a $2.00/mmBtu natural gas price, the barrel of output needs to be over 30 times more valuable than the mmBtu of natural gas for the GTL plant to break even. At a $5.00/mmBtu gas price, this ratio drops to about 18-to-1, and at $8.00/mmBtu of natural gas, the ratio drops to 15-to-1.

In 2007, the natural gas price averaged $6.75/mmBtu. The diesel price averaged $49.89/bbl, and the petrochemical feedstock price averaged $102.60/bbl. The weighted price of a barrel of diesel/petrochemical feedstock output was thus $65.66. Under these conditions the base case GTL plant in the U.S. would have a levelized cost of $101.51/bbl—a loss of $35.85/bbl. The net present value (NPV) of the plant would have been -$9.96 billion if these prices were to hold over the 25-year lifetime of the plant. The internal rate of return (IRR) would have been 2%. Under the CGE calibration, output from a base case GTL plant operating in the U.S. costs about 72% more than producing the same products from a petroleum refinery.

In the indirect experiment examining GTL penetration in the CGE model, GTL is made available only in the United States. The U.S. was chosen both because its shale gas resources have made it a consistent candidate for proposed GTL projects and also to simplify the analysis of the effects of GTL penetration in a model with many interactions between and among regions and sectors. The focus on U.S.-based GTL deployment will permit examination of the rate at which the household transportation sector can shift from being predominantly gasoline-fueled to predominantly diesel-fueled.[3] Such a shift is plausible because the higher cetane rating of GTL diesel puts it on par with gasoline in terms of performance (Sasol, 2011; Eudy *et al.*, 2005;

[3] The United States is particularly well-suited for this analysis because it has a very well-developed household transportation sector and gasoline is firmly entrenched as its fuel of choice.

Greene, 1999). In addition, GTL diesel produces significantly less particulate matter, carbon monoxide, NO_x and volatile organic compounds than ultra-low sulfur diesel (Delucchi, 1997; Greene, 1999; Schaberg *et al.*, 1997; Martin *et al.*, 1997; Wang and Huang, 1999; Five Winds International; Schaberg *et al.*, 2006; Perego *et al.*, 2009), which alleviates concerns about diesel-based pollution. Taking these factors into account it is reasonable to assume that diesel could penetrate as quickly as consumers replace their vehicles if the diesel price is sufficiently below the gasoline price.

Initial calibration runs resulted in almost no GTL penetration. In order for GTL projects to be economic, three additional modifications were made to the base case model: first, restrictions on the rate of technological penetration were removed for GTL. This would allow the technology to immediately saturate the market to the extent that it is economic.[4] Second, the global natural gas resource base was increased 100-fold, ensuring that resource constraints do not impede potential GTL penetration should it be initially economic. Third, the elasticity of substitution between the natural gas resource and other inputs to natural gas production was increased 6-fold. This increases the elasticity of natural gas supply and makes substituting the natural gas resource for other inputs, such as capital or labor, less expensive. The case is labeled HH,[5] and it is plotted in red triangles in Figures 1, 2, and 3.

In the simulation, GTL achieved limited penetration in 2070, with about 7,000 barrels per day of output—essentially the size of a large demonstration plant. By 2080 output increased to 445,000 barrels per day, or the equivalent of less than 4 base case GTL plants. Subsequent capacity additions push total output to 2.6 million barrels per day (mmbd) by 2100. Total GTL output as a share of global refined fuel production did not exceed 1% until 2100. The impact on the trajectory of the oil-gas price ratio was negligible.

The oil-gas price ratio rose from 10-to-1 to 38-to-1 over the course of the simulation. The difference from the base case was driven by the increase in natural gas resource levels. Natural gas prices peaked in 2040 at $7.15/mmBtu, then declined slightly, ending the simulation 7.6% below 2007 levels in the U.S. instead of stabilizing as in the base case. Crude oil prices steadily increased through 2100, ending over 230% above 2007 levels. Natural gas was able to substitute for crude oil products in limited activities, slightly dampening the increase in crude oil prices, but without increasing natural gas prices. In all, global crude oil consumption was about 3% below base case levels by 2100, and natural gas consumption was twice as high.

These price shifts occurred despite the fact that natural gas never challenged crude oil in the transportation sector. Transportation sector demand growth expanded even more rapidly than under the base case, directly increasing crude oil demand with it. Natural gas displaced some electricity in the energy-intensive industry, other industry, services, food, dwellings, and final demand sectors. Natural gas accounted for over 50% of power generation in 2100, moving coal

[4] Essentially the "learning-by-doing" parameter limitation is being relaxed (Chen *et al*., 2015).

[5] The first "H" represents the base case natural gas production costs, which are the highest costs in the set of exercises. The second "H" represents the base case GTL costs, which are the highest costs and lowest efficiency settings modeled.

into second place. 25% of the crude oil feedstock inputs to oil refining were replaced by natural gas by 2100. In all, the growth in sectors that consumed natural gas caused the growth in natural gas demand to exceed the transportation sector-driven increase in crude oil demand. Part of this is because, with substantially expanded natural gas reserves, the HH case economy employed more natural gas in the activity of each sector, and part of it is because activity increased in sectors that use natural gas extensively. Overall, GDP and consumption were about 1% higher than in the base case by 2100 due to the insensitivity of natural gas prices to an increase in usage.

The quantities supplied of both crude oil and natural gas increased steadily through 2100, but the quantity of natural gas consumed increased much more rapidly than crude oil. By the end of the century, crude oil demand had increased by about 130%, but natural gas demand had increased by 645%. At the end of the simulation the world consumed 124% more natural gas than crude oil, reversing oil's dominant position in 2007, when 45% more crude oil than natural gas was consumed. The price sensitivities to growth in demand also shifted from the base case: the global crude oil price increased by 1.8% with each 1% increase in demand, while natural gas prices fell 0.01% for every 1% increase in demand between 2007 and 2100. Despite the weak penetration of GTL, the HH case demonstrates that if the natural gas resource base were much higher than currently envisioned,[6] natural gas usage could surpass crude oil usage within the century.

4. STRESS TEST: WHEN DOES GTL MATTER?

4.1 Low-cost natural gas production scenario ("LH")

GTL did not significantly penetrate in the HH case, which employed base case natural gas costs in conjunction with a massive increase in natural gas reserves. GTL penetration had an insignificant impact on the price paths of natural gas and crude oil products, and the crude oil-natural gas price ratio did not deviate from its prior trajectory. The two factors most relevant to GTL feasibility are the natural gas price and the amount of natural gas required to produce a barrel of output. This scenario will examine how a technology that reduces the cost of producing natural gas affects GTL deployment, and whether under these circumstances GTL technology deployment can impact the relative prices of crude oil and natural gas. This case is labeled LH,[7] and is represented by blue triangles in Figures 1, 2, and 3.

The global deployment of a gas production technology (akin to hydraulic fracturing) cut natural gas production costs to 1/3 of the baseline in 2025, which lowered natural gas prices by over 60% after accounting for the corresponding increase in natural gas demand. The gas production technology deployment represented a downward shift in the natural gas supply curve; costs decreased for each level of quantity supplied. GTL was marginally profitable in the LH

[6] For example, if shale gas resources or ocean-floor methane hydrates were to be economically exploitable, natural gas reserves would no longer be a binding limitation to expansions of natural gas usage.

[7] In this case, the "L" refers to the low cost of natural gas production, and the "H" represents the base case (high) cost of GTL and its currently-estimated efficiency.

case, and initial deployment began in 2025 at 340,000 barrels per day, or about 0.3% of global refined oil production. GTL capacity expanded by 20-50% each period, but GTL capacity did not exceed 1% of global refined fuel production until 2055. That year GTL capacity was 2.2 mmbd—the equivalent of just over 18 base case GTL plants. By 2100, GTL capacity had expanded to 16.3 mmbd, which was about 6.4% of global refining capacity.

The low-cost natural gas production technology had an immediate impact on the crude oil-natural gas price ratio, but the penetration of GTL did not. The lower natural gas price pushed the crude oil-natural gas price ratio from 14-to-1 in 2020 to 39-to-1 in 2025. The low cost and high reserve levels dampened the increases in natural gas prices over time that were driven by global growth. Crude oil prices continued to rise. The result was a steeper price ratio curve, terminating in a 94-to-1 oil-gas price ratio by 2100. The gas production technology made natural gas comparatively less expensive. However, cheaper natural gas did not significantly increase competition between natural gas and crude oil.

In the LH case, lower natural gas prices made gas more attractive in the sectors in which it competed. Global natural gas consumption doubled between 2020 and 2025. In the year the gas production technology deployed, global natural gas consumption was more than twice the base case level and was 80-90% higher than in the HH case. The trend increased over time as natural gas became more dominant in its competitive sectors.

The shift toward natural gas usage occurred in industry, electric generation, food production, oil refining, services, dwellings and final demand. The shift was most pronounced in the latter two sectors. The effects of the low-cost gas technology deployment on the mix of fuel consumption in the final demand sector is depicted in **Figure 4**. The change in final demand is stark because final

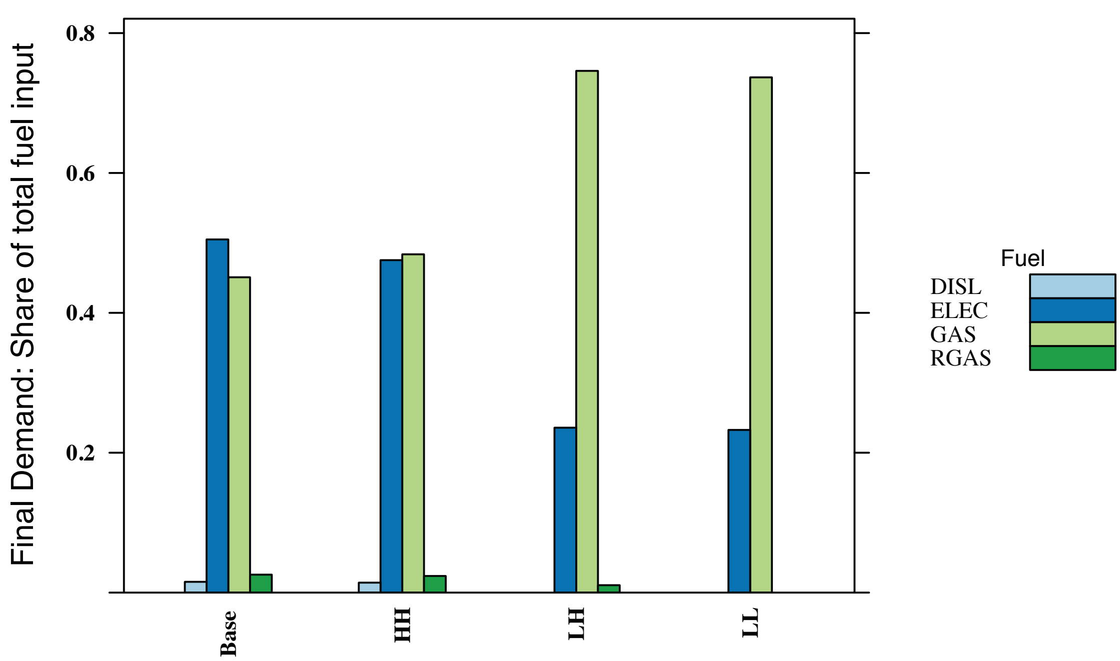

Figure 4. U.S. energy usage shares for final consumption at deployment of low-cost gas production technology in 2025: Base case and 3 scenarios

consumers used a narrow range of fuels and because natural gas competed directly with electricity for cooking, home, and water heating, and with fuel oil for home heating. A significant portion of stoves and home and water heaters could be replaced over a 5-year period at lower cost than, for example, the re-tooling of an industrial facility. The base case featured baseline natural gas costs and resource levels. The HH case featured baseline natural gas costs but greatly expanded natural gas reserves. Deployment of the low-cost natural gas production technology in the LH case cut natural gas prices by shifting down the natural gas supply curve.

In the base and HH cases, final demand consumption shares were fairly equally divided between natural gas and electricity. In the LH case, over three quarters of final energy consumption was natural gas in 2025, when the natural gas production technology deployed. Final demand became increasingly dependent on natural gas over time. The rapid shift reflects the high level of substitutability in final consumption between natural gas and electricity. The shift over time reflected the drive to replace energy-consuming technologies from electricity to lower-cost natural gas, where possible (such as for heating and cooking).

The electric generation sector shifted more gradually toward natural gas and away from coal because a large number of coal-fired power plants had not yet depreciated, coal plants are less expensive than gas plants to operate, and coal remained an inexpensive feedstock. However, even though natural gas displaced significant amounts of electricity in key sectors, the low cost of natural gas feedstocks nonetheless reduced the cost of electricity as well, and its use expanded by 10% beyond base case levels in 2025, rising to 35% above base case levels by 2100. The low cost of natural gas even caused a shift toward natural gas inputs at the expense of crude oil in the refined oil sector, with natural gas comprising 40% of total refinery inputs by 2100, versus crude oil inputs to refining of about 43%.[8]

Despite this shift toward natural gas within oil refining, low-cost gas could not significantly displace crude oil products beyond the shifts that occurred in the HH case with the expanded resource base. Even with access to low-cost natural gas feedstocks, GTL technology in the LH case was not sufficiently competitive with oil refineries to significantly displace oil-based transportation fuels, so the crude oil price continued to rise with transportation demand. Despite considerable increases in natural gas usage, there was not enough opportunity for substitution between oil products and natural gas for interfuel competition to increase after a relative shift in prices.

To affect the oil-gas price ratio, GTL penetration would have had to either increase natural gas prices or dampen price increases in crude oil by displacing its products. The penetration of GTL was not sufficient to pull natural gas prices up (see the blue triangles in Figure 2), nor did it displace enough petroleum products to significantly affect crude oil demand (or its price), as depicted in Figure 1. GTL deployment capped the U.S. distillate fuel price, but not enough distillate (diesel) fuels were available at a low enough price for significant substitution away

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[8] This result is not surprising, either, since crude oil resources were much more costly than natural gas resources, prompting substitution away from crude oil wherever possible.

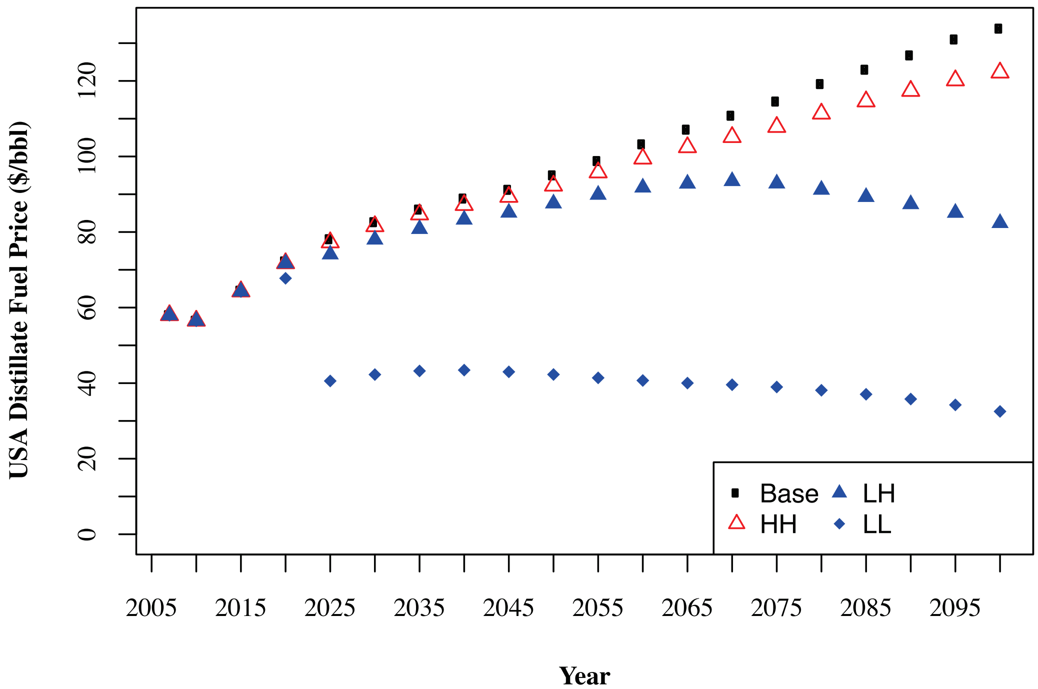

Figure 5. U.S. distillate fuel price ($/bbl): Base case and 3 scenarios

from gasoline to occur in the household transportation sector. **Figure 5** depicts the path of distillate fuel prices in every scenario.

Because petroleum-sourced diesel remained dominant, crude oil consumption remained robust, and prices continued to steadily increase over the course of the simulation. It was only after 2070 that crude oil prices even deviated downward by 5% from the base case trend line, and oil prices were only 8% below base case levels in 2100. Global crude oil consumption was only about 9% below base case levels in 2100. This is because the substitution of crude oil with natural gas in refining was offset by overall increases in the demand for transportation fuels. The price sensitivity of crude oil was about +1.7% per 1% increase in quantity demanded from 2007 to 2100. LH case natural gas consumption in 2100 was nearly 3.5 times the base case consumption. The natural gas price fell by 0.04% for every 1% increase in quantity demanded from 2007 to 2100 because of the low-cost gas production technology coming online in 2025.

4.2 Low-cost natural gas production/low cost and highly efficient GTL scenario ("LL")

The HH scenario modeled base case GTL costs and efficiencies under greatly expanded natural gas reserves. The LH scenario modeled base case GTL costs and efficiencies in an environment of extremely low natural gas production costs and expanded natural gas reserves. Both cases showed an expansion of natural gas usage and incremental decreases in crude oil consumption where natural gas was able to displace crude oil or petroleum products. However, GTL was not sufficiently economic to allow natural gas to significantly compete with crude oil-derived fuels in the transportation sector in either case. The final scenario, labeled LL,[9] maintains the expanded

[9] The first "L" denotes low-cost natural gas, and the second "L" denotes low-cost/high-efficiency GTL.

natural gas resource base and deploys the low-cost natural gas production technology as in the LH case, but also cuts the non-fuel input costs of GTL to a third of the baseline value and increases GTL efficiency to 100%: 5.5 mmBtu of feedstock produce the 5.5 mmBtu barrel of output. This is thermodynamically impossible, but it serves to define the upper bound at which GTL may compete with crude oil under the economic assumptions and mechanisms embedded in the CGE model. The LL case is represented by blue diamonds in all time-series figures.

Natural gas usage in the LL case responds almost identically to the 2025 deployment of the low-cost natural gas production technology as in the LH case in the sectors in which natural gas is initially competitive. This is evident in Figure 4 for final demand. The response in dwellings, energy-intensive industry, electricity, food production, services, and oil refining is similar: natural gas initially makes inroads against the previously-dominant fuel in much the same manner as in the LH case. In sectors where petroleum products are not widely used, the trend in proportional fuel usage in the LL case is a close match to the LH case—these are final demand, dwellings, and services (where natural gas competes primarily with electricity), electricity (where natural gas competes primarily with coal), or energy-intensive industry (where natural gas competes with both coal and electricity). Where the LL case outcomes diverge from the LH case outcomes is in the sectors that use petroleum-based distillate fuels or petrochemical feedstocks—these are the outputs of GTL plants.

The low-cost, high-efficiency GTL technology enables a more robust deployment when it first becomes available in 2020. Initial capacity is 3.3 mmbd, or about 2.9% of 2020 global refining capacity. When the low-cost natural gas technology deploys in 2025, GTL capacity nearly triples to 12.8 mmbd, or about 9.5% of global refined fuel capacity. This is the equivalent of building over 100 base-case GTL plants within the first decade. Capacity additions thereafter decline from about 37% in 2030 to settle in a 20% per-year average capacity increase through 2085. It is in 2065 that GTL production first surpasses 20% of total refined fuel production. In Figure 3, 2065 is also the date at which the crude oil-natural gas price ratio begins to flatten and deviate from the LH trend line. How the deployment of GTL eventually provokes a shift in the oil-gas price ratio is a combination of an initial shift in the supply curve, followed by movements along the crude oil and natural gas supply curves as demand adapts to the changing relative cost of fuel inputs to economic activity.

At initial deployment, the LL case version of GTL produced distillate fuels at a cost slightly below that of oil refineries, as depicted in Figure 5 in 2020. However, the 2025 deployment of the low-cost natural gas production technology made distillate production through GTL particularly inexpensive. The combination of a low-cost, high-efficiency GTL technology and the low-cost natural gas production technology capped the cost of producing distillate (e.g., diesel) fuels 40% below the 2020 value, which is well below the oil refiners' costs for distillate production. Furthermore, the cost remained flat in the LL case in contrast to the trend of rising prices in all other scenarios. There are thus two major differences in fuel prices from the base case: both the distillate fuel price and the natural gas price are much lower after 2025.

Non-transportation sectors that initially use transportation fuels or petrochemical feedstocks see substantial shifts toward GTL distillates and GTL petrochemical feedstocks beginning in 2025. For example, the crop and livestock sectors initially shift toward GTL distillates from petroleum based fuels beginning in 2025. Over time, there are shifts from gasoline and refinery gases to GTL distillates as well, culminating in GTL distillate fuel dominance by 2100. The food production sector gradually displaces some of the natural gas inputs that initially displaced electricity with low-cost GTL distillate fuels as well. GTL petrochemical feedstocks displace substantial amounts of coal, petroleum-based petrochemical feedstocks, and heavy fuel oils in the forestry sector by 2100.

The transportation sectors were affected by the penetration of cost-competitive GTL plants in the LL case. GTL was able to produce distillate fuels at costs far below oil refineries throughout the simulation; U.S. distillate prices were 40–70% below the global diesel price from 2025 through 2100. Oil refinery operations did not initially change dramatically, because the bulk of oil refinery profits are from sales of distillate fuels and gasolines. Although refineries would no longer find distillate fuel production profitable, gasoline demand remained high, so refineries continued processing crude oil into refined fuels.

Relatively inexpensive distillate fuels made diesel an attractive alternative to gasoline in the transportation sectors. This was especially true in household transportation, which was initially dominated by gasoline consumption. **Figure 6** depicts the evolution of energy usage in U.S. household transportation as GTL distillate fuel production increased in the LL case.

Initially, U.S. household transportation demand was met almost entirely by gasoline (see "Initial", which was 2007). When the low-cost natural gas production technology deployed

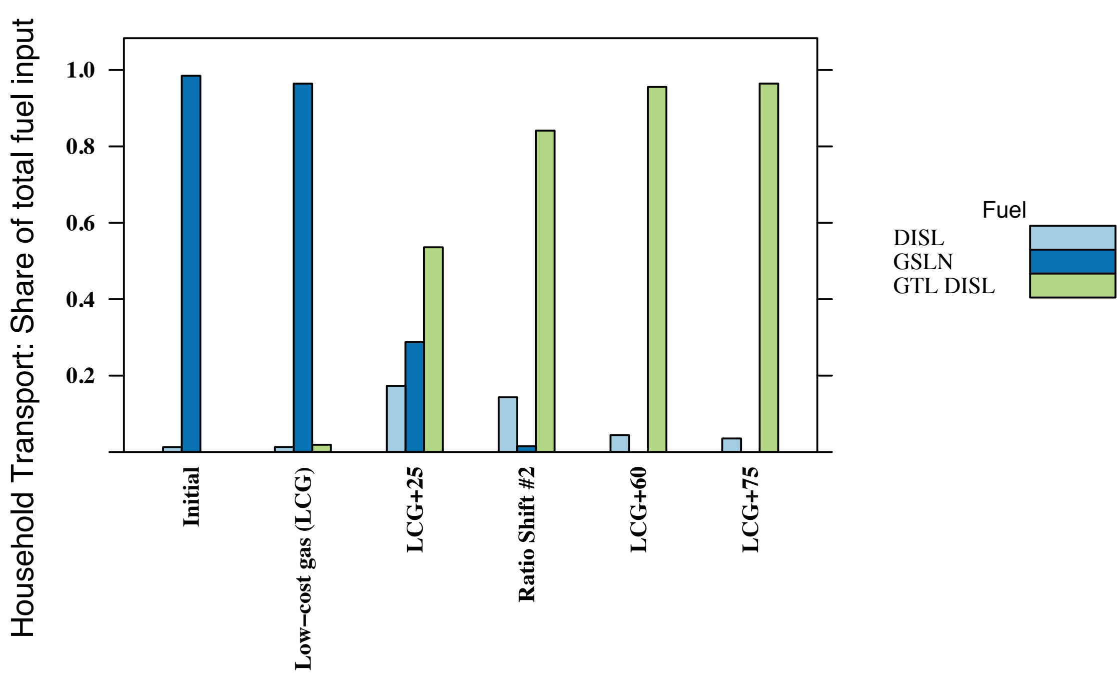

Figure 6. U.S. household transportation energy consumption shares in 2007, 2025, 2050, 2065, 2085, and 2100: LL case

(Low-cost gas (LCG)) in 2025, there had been only a slight shift toward GTL diesels. By the time the first wave of GTL plants had fully depreciated (LCG+25, in 2050), the gasoline share of energy consumption had fallen below 40%. By the start of the second shift in the oil-gas price ratio (Ratio Shift #2, in 2065), gasoline had been nearly completely displaced by petroleum and GTL distillate fuels. GTL diesel made up over 80% of energy consumption in household transportation. GTL diesel increasingly displaced petroleum diesel in household transport through 2100.

The U.S. commercial transportation sector followed a similar pattern. Commercial transportation fuel consumption was about 75% diesel in the base year, with gasoline making up the bulk of the remainder. **Figure 7** shows that by the time of the second price ratio shift in 2065, GTL diesels had replaced gasoline, and had nearly displaced petroleum-based diesel, in the LL case.

Diesel gradually replaced gasoline in commercial transportation in all four cases. Even in the base case, diesel accounted for nearly 90% of commercial transportation fuel consumption by 2065. However, the LL case is a clear outlier in its displacement of petroleum-based fuels, and in its effect on the oil refining sector: the low cost of GTL diesel made it increasingly attractive, and distillate production from oil refineries was uneconomic after 2025. However, oil refineries were not able to eliminate distillate fuel production because, depending on the grade of crude oil and the refinery configuration, fuels are produced in largely fixed proportions. By the second shift in the oil-gas price ratio, U.S. distillate prices were the lowest in the world—about 44% of the global average. The low costs of both distillate fuels and natural gas provoked strong rebound effects in the sectors that use those fuels. This is one reason that normal oil refinery production continued for so long in the LL case despite the superior economics of GTL plants: the additional

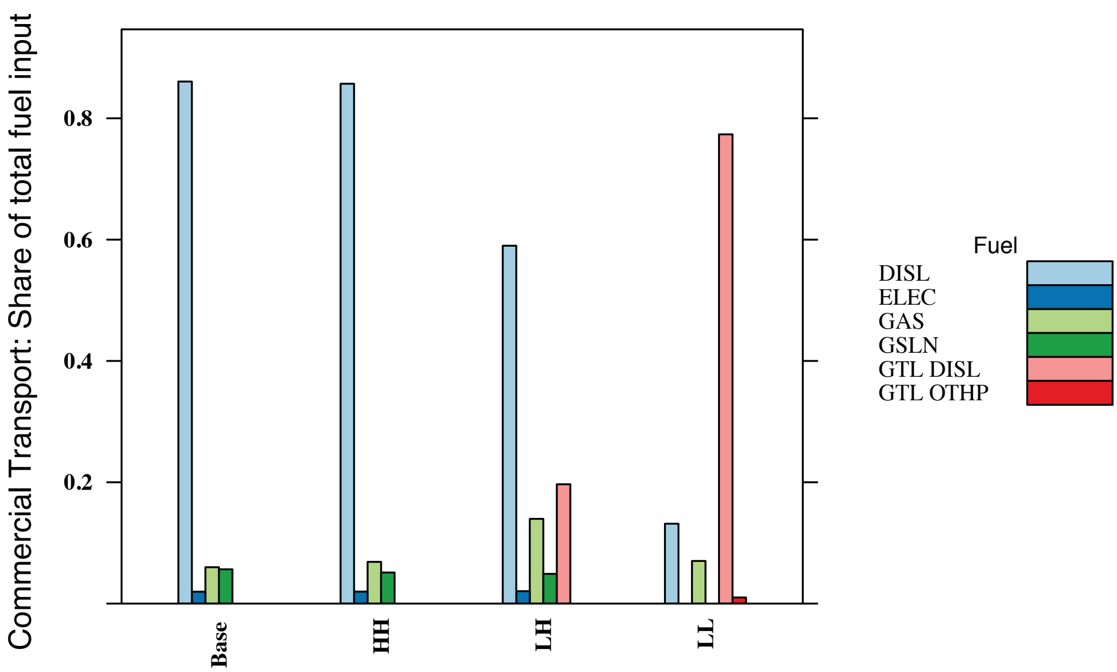

Figure 7. U.S. commercial transportation energy consumption shares at the second major price ratio shift in 2065: Base case and 3 scenarios

demand was met almost entirely by expanding GTL production capacity. Global refinery production in the LL case tracked to within 1% (either above or below) the base case levels up until the second oil-gas price ratio shift in 2065. **Figure 8** shows that U.S. refinery output tracked below base case levels, but never by more than 15% until 2065. This changed dramatically at the start of the second oil-gas price ratio shift.

Demand for distillate fuels had exploded in the U.S. due to the rebound effect. However, the price of distillate fuels remained flat at any GTL-supplied quantity while crude oil prices continued to rise. For oil refineries, the rising cost of crude oil and the falling price of distillates made distillate fuel production unprofitable. Furthermore, by 2065 both gasoline and heavy fuel oils had also been displaced by the low-cost distillates or natural gas in most sectors. Faced with this loss of profitability, U.S. refiners sharply cut back on fuel production. By the time the trend in the oil-gas price ratio flattened, U.S. refinery output in the LL case was 65% below the base case, and 43% below 2007 output levels. Crude oil inputs to refinery operations were half of what they were in 2060, just before the second oil-gas price ratio shift. The decrease in U.S. crude oil inputs weakened global crude oil demand. Figure 1 shows how these events affected the crude oil price.

The stabilization of crude oil prices flattened the crude oil-natural gas price ratio at the end of the LL case time series in Figure 3. This was partially because the stagnation of crude oil consumption halted the advance of oil production up its marginal cost curve. Under the circumstances examined in the LL case, about 10% less crude oil is consumed in 2100 than under the base case. Movement along crude oil's supply curve is arrested, and prices end up nearly 32% below base case levels in 2100. The price sensitivity between 2007 and 2100 is also lower, with crude oil prices increasing by just 1.2% for every 1% increase in quantity supplied. There is more than 16 times more natural gas consumed in 2100 than in 2007 in the LL case, and nearly 80% more natural gas is consumed in 2100 than in the base case. However, the low-cost

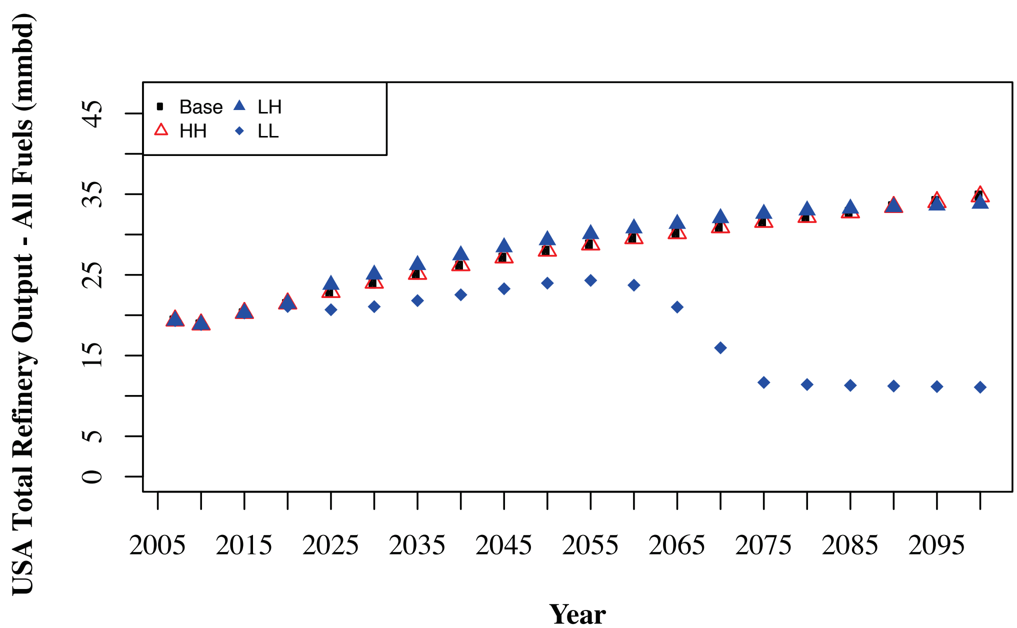

Figure 8. U.S. refined oil sector output in million barrels per day (mmbd): Base case and 3 scenarios

gas production technology and expanded natural gas reserves prevent prices from rising after the 2025 cut in production costs. The 2007–2100 price sensitivity is low: prices decrease by 0.04% for each 1% increase in quantity supplied. It is thus possible for GTL to compete with oil refineries to the extent that crude oil demand weakens and the crude oil-natural gas price ratio shifts downward. However, it can only do so under below-baseline natural gas costs, above normal assumptions about natural gas reserves, and lower-cost/higher-efficiency GTL configurations.

4.2.1 Differences between the shifts in the oil-gas price ratios

The first shift in the price ratio developed more rapidly than the second. This is not solely because the development of the GTL industry depended on lower-cost natural gas. The low-cost gas production technology operates at the wellhead. Decreasing the cost of natural gas production represents a downward shift in the supply curve. This translates into a fall in the natural gas price at each quantity supplied. Cutting the natural gas price directly results in an increase in the oil-gas price ratio. The technology does not create any additional linkages between sectors, but it does make natural gas more attractive in the sectors that already use natural gas.

The market integration of GTL is more complex. GTL's highest-value output is sold into the transportation fuels market, where oil refining is a dominant technology. GTL competes only if it can make transportation fuels at or below the cost of oil refineries. At the date of availability, oil refineries already have all of the capacity needed to cover all of the demand for transportation fuels. GTL enters the market by deploying to meet the incremental increases in transportation fuel demand. Investors must prefer to build a new GTL plant rather than a new oil refinery to meet increases in transportation fuel demand. Second, GTL makes diesel, which is only one of the major transportation fuels. Diesel is the dominant fuel in commercial transportation, but gasoline is the dominant fuel in private transportation. GTL must make diesel at a low enough cost that private consumers switch from gasoline to diesel when they make their next vehicle purchase. This process takes time. Eventually, enough consumption shifts away from gasoline and toward diesel that oil refiners lose their two most profitable products, and must cut production. This dampens global crude oil demand, and flattens its price. Once crude oil prices stop rising, the oil-gas price ratio stabilizes at the second shift. The GTL technology thus involves movements along the crude oil and natural gas supply curves as demand increases for distillate fuels in a shift away from gasoline over time.

The effect of each technology on inter-fuel competition is distinct. The first shift in the oil-gas price ratio was the result of a technology that did not increase competition between crude oil and natural gas. It muted natural gas price increases, but did nothing to affect the unabated growth in crude oil prices. The result was a widening rift between crude oil and natural gas prices. The second shift was the result of GTL technology penetration, which increased competition between crude oil and natural gas through transportation fuel production. Eventually, GTL won enough market share to depress the increase in crude oil demand, which dampened its price increases. This stabilized the oil-gas price ratio over time.

5. CONCLUSION

We use a computable general equilibrium model to examine conditions under which GTL technology penetration shifts the future crude oil-natural gas price ratio. Our results suggest that GTL penetration has an impact only under very extreme assumptions. Using conventional estimates of costs and efficiencies, the GTL technology is too expensive to enhance direct competition between the crude oil products and natural gas as fuels in the transportation sector, which is the critical sector for crude oil use and pricing. In addition to needing GTL to be less costly and more efficient in order to have an impact, it is also necessary for natural gas to be still cheaper to produce than the current shale revolution in the U.S. has realized. Our model results do not factor in any increasingly stringent global carbon limits, which would decrease further the prospects for GTL.

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