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Joint Program Co-Directors

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The economic viability of gas-to-liquids technology and the crude oil–natural gas price relationship

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ABSTRACT

This paper explores the viability of a gas-to-liquids (GTL) technology and examines how GTL penetration could shape the evolution of the crude oil–natural gas price ratio. Much research has established the cointegrated relationship between crude oil and natural gas prices in the U.S. The persistently low U.S. natural gas prices in recent years seem to mark a shift in this relationship, and have led some in industry to begin considering investments in GTL capacity in the US. In order to look forward over decades when the underlying economic drivers may be outside of historical experience, we use a computable general equilibrium model of the global economy to evaluate the economic viability of GTL and its impact on the evolution of the crude oil–natural gas price ratio. Our results are negative for the potential role of GTL. In order to produce any meaningful penetration of GTL, we find it necessary to evaluate scenarios that seem extreme. With any carbon cap GTL is not viable. Moreover, even without a carbon cap of any kind, extremely optimistic assumptions about (i) the cost and efficiency of GTL technology and about (ii) the available resource base of natural gas and the cost of extraction, before the technology penetrates and it impacts the evolution of the crude oil–natural gas price ratio.

1. Introduction

Gas-to-liquids (GTL) is an old technology dating back to the start of the 20th century. It is an alternative to the production of liquids from crude, and therefore its economic viability has depended on the relative cost of crude oil and natural gas. The wide availability of inexpensive crude oil throughout the 20th century undercut commercial interest in GTL outside of a few special situations. In the 1990s, the discovery of numerous stranded gas fields sparked a push to commercialize GTL plants: stranded gas is, by definition, relatively cheap because it does not have the means to move to the places of the high-price demand. Two of the most important plants currently in operation, the Oryx and Pearl plants in Ras Laffan, Qatar were built to utilize gas from Qatar's massive North field. A number of other plants proposed for stranded gas fields were ultimately either shelved or delayed, but Shell now operates a plant in Bintulu, Malaysia, a partnership led by SASOL operates one in Uzbekistan, and Chevron operates one in Escravos, Nigeria. Interest in the U.S. has arisen recently in the wake of the expanded availability of very inexpensive natural gas. A number of proposed plants have been announced in press releases, although none are yet actually under construction.

Looking past the enormous short-term volatility in crude oil and natural gas prices, industry professionals and econometricians have identified a long-term tie between the two prices: see for example, the cointegration analysis of 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), and Brigida (2014). Industry professionals express this tie with a number of different rules-of-thumb or benchmarks. The simplest among them is the 10-to-1 rule: the crude oil price in the U.S. (expressed in dollars per barrel) should roughly equal 10 times the natural gas price in the U.S. (expressed in dollars per MMBtu). Since 2005, the actual ratio has been above this benchmark more often than not, and since late 2008 it has persistently been well above it. This represents a real shift in the tie as documented in Ramberg and Parsons (2012), Loungani and Matsumoto (2012) and Brigida (2014), and it is this shift in the long-term price relationship that lies behind the increased interest in GTL in the U.S.

All of these statistical analyses are backward looking by their nature. New capital investments in GTL need to demonstrate their profitability on a forward looking basis. Can an investor expect that the ratio of crude oil and natural gas price will continue to be as high as it has been recently? Or, should she expect it to revert to its old level? Many factors help to

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determine the relationship between the two price series, and these factors change over time. Indeed, some of the statistical work on the cointegration relationship have documented the role of technology change in moving the benchmark—for example, Hartley et al. (2008) document that the introduction of combined cycle natural gas power plants increased the demand for natural gas and therefore shifted the benchmark ratio down. See also Serletis and Rangel-Ruiz (2004). How will the evolving equilibrium in supply and demand for each fuel change as the global economy develops, and how will this move the equilibrium price ratio and the profitability of GTL? How will constraints on carbon emissions shape this equilibrium price ratio and the profitability of GTL?

To address these questions, we use a computable general equilibrium (CGE) model of the global economy to analyze the penetration of the GTL technology under different scenarios for several underlying economic drivers. We also use the model to analyze the impact of the GTL technology on the price ratio by contrasting how the ratio evolves differently depending upon the efficiency of GTL and therefore its ability to penetrate as prices shift. Of course, the CGE model is not a crystal ball telling us what the future will bring. But it is a useful tool for analyzing in a rigorous fashion different constellations of assumptions about key drivers—scenarios—and how each shapes and constrains the total economic picture in equilibrium. The exercise can help us to think through the scenarios that might be consistent with economically rational expansion of GTL and the scenarios that are not consistent with it. And the exercise can help us understand how the crude oil and natural gas price ratio evolves in each scenario, shaped in part by the availability of GTL, but also by other drivers.

The structure of the remainder of this paper is as follows: Section 2 presents our parameterization of a GTL technology and the CGE model in which we embed it. Section 3 discusses our choice of scenarios and analyzes the penetration of GTL under each scenario. Section 4 concludes.

2. A CGE model with a GTL technology

2.1. The GTL technology

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). Accordingly, we model the less costly diesel-producing version.

GTL efficiency and cost data were compiled in Ramberg (2015) from an array of studies and reports. We assume GTL produces a perfect substitute for petroleum-based diesel fuels and petrochemical feedstocks. Indeed, the higher cetane rating of GTL diesel puts it on par with gasoline in terms of performance (Sasol, 2011; Eudy et al., 2005; Greene, 1999). In addition, GTL diesel produces significantly less particulate matter, carbon monoxide, NOx and volatile organic compounds than ultra-low sulfur diesel (Delucchi, 1997; Greene, 1999; Schaberg et al., 1997, 2006; Martin et al., 1997; Wang and Huang, 1999; Five Winds International, 2004; Perego et al., 2009). However, GTL produces significantly greater CO_2 emissions than crude oil refining. In part, this is due to the relatively low thermal efficiency of GTL. 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. In contrast, crude oil refining can reach a thermal efficiency near 90%.

Table 1 shows the lowest and highest values encountered in the source literature for key parameters such as capital cost, fixed and variable operations and maintenance (O&M) costs, labor costs, and natural gas inputs per barrel of output reflecting 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—see 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), IEA (2010b), Rapier (2010), Bala-Gbogbo (2011), Lefebvre (2011), Liu et al. (2011), Shell Global (2011), Shaw (2012), Salehi et al. (2013), and Atuanya (2014).

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 per barrel produced	$5.00	$3.13	$23.00
Gas input rate, MMBtu per barrel produced	9.85	8.8	14.13
Plant capacity, b/d	120,000	1000	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

There is a wide range between the high and low estimates, which reflect various assumptions and technological specifications. Table 1 also shows the central figures chosen as the base case assumptions for our modeling which reflect the cost of GTL as currently deployed in the handful of commercial scale plants in operation.

It is useful to translate these assumptions into some simple cost benchmarks using a discounted cash flow calculation. Construction and operation of the base case GTL plant incurs a levelized cost of $42.39/bbl of output before natural gas feedstock costs are taken into consideration. The feedstock cost obviously varies with the price of natural gas. With a feedstock requirement of 9.85 MMBtu per barrel of output, and applying a natural gas price varying from $2.00/MMBtu to $5.00/MMBtu to $8.00/MMBtu, the levelized feedstock cost ranges, respectively, from $19.70/bbl of output to $49.25/bbl to $78.80/bbl. The total levelized cost therefore ranges from $62.09/bbl of output to $91.64/bbl to $121.19/bbl.

These figures show how challenging it is for GTL to be a profitable choice. Consider, for example, the situation in 2007, when the price of natural gas in the U.S. averaged $6.75/MMBtu, the price of diesel averaged $49.89/bbl, and the price of petrochemical feedstock averaged $102.60/bbl, yielding a weighted price of a barrel of diesel/petrochemical feedstock of $65.66 (EIA, 2014). The corresponding levelized cost of the GTL output would have been $101.51/bbl, so that the process would have made a loss of $35.85/bbl or $9.96 billion if these prices were to hold over the 25-year lifetime of the plant. Or consider, for example, the more favorable situation in 2015 when the price of natural gas in the U.S. averaged a much lower $2.62/MMBtu (EIA, 2016a), the price of diesel averaged $68.46/bbl (EIA, 2016b), and the price of petrochemical feedstock averaged $80.78/bbl (EIA, 2014, 2016b), yielding a weighted price of a barrel of diesel/petrochemical feedstock of $72.16. The corresponding levelized cost of the GTL output would have been $77.06/bbl, so that the process would have made a smaller loss of $4.90/bbl or $1.36 billion if these prices were to hold over the 25-year lifetime of the plant. Therefore, for our base case cost numbers, in order for an investor to confidently invest in GTL, she would need to anticipate either a reliably lower price of feedstock or a reliably greater product price than in the recent period. Alternatively, she would need to anticipate GTL costs that are lower than our base case.

2.2. Embedding GTL in a CGE model

We embed this technology into the computable general equilibrium (CGE) model EPPA6-ROIL, developed at the MIT Joint Program on the

Science and Policy of Global Change (Ramberg, 2015). It is an extension of the EPPA6 model of production and consumption across 14 sectors (each producing a single commodity) and over 18 global regions, including interregional trade of each commodity (Chen et al., 2015). EPPA6-ROIL further breaks refined fuels into six different products: refinery gases, distillate fuels such as diesel, gasolines, residual heavy fuel oils, lubricants/waxes/petrochemical feedstocks, and petroleum coke. This allows for analysis of competition among distinct petroleum products, such as between gasoline and diesel fuels in transportation. It explicitly models changes in petroleum product fuel interactions in response to technological deployment. The model is calibrated using the Global Trade Analysis Project (GTAP) dataset for 2007 (Global Trade Analysis Project, 2010). 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 (IEA, 2010a, 2008, 2014; International Council on Clean Transportation, 2012). Under the CGE calibration, output from a base case GTL plant operating in the U.S. initially costs about 72% more than producing the same products from a petroleum refinery.

In the model, there is a single, global market for crude oil with one crude oil price reflecting global aggregate supply and demand. For our purposes, this is a good approximation to the actual, global market where the ease with which oil can be transported by sea, truck, or pipeline provides significant opportunities for arbitrage across regional markets that produce small regional cost differentials. In contrast, the transport of natural gas—whether by sea in the form of LNG or by pipeline—is much more expensive per unit of energy, with the result that markets tend to develop around regional transport hubs and the prices at these hubs often diverge widely. Therefore, the model allows for different prices of natural gas in different regional markets. For reasons discussed later, our focus will be on the ratio of the model's global crude oil price to the model's U.S. natural gas price.[1] Petroleum products are nearly as easily transported as crude oil. However, region-specific fuel grades and emission specifications make them less fungible than crude oil internationally. Therefore, the model allows for regional petroleum product prices, though the resulting regional variation is less than the regional variation in natural gas prices.

We make GTL 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.[2] 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. The rapid shift to diesel vehicles would thus resemble the experience of Europe in recent decades. Although the model accommodates some expansion of global trade in LNG, including increased exports from the US, it is probably less flexible in this regard than it should be given the long time frame covered by the analysis, the sizable expansion of global economic activity contemplated in the results, and the dramatic reduction in extraction costs used in certain scenarios. However, as we shall see, our results already point to the very limited GTL penetration in the U.S., where natural gas resource costs are lower than in the other regions. Restructuring the model to accommodate an even greater expansion of U.S. LNG exports to a broader set of destinations would only strengthen our results that the role of GTL is limited.

Following the usual convention of CGE models, the solution focuses on the long-term trends and abstracts from details such as inter-firm competition or explicit dynamics across different types of consumers, and from short-term market shocks and adjustments: there are no boom-and-bust cycles and no bubbles. Prices and the availability of goods are driven purely by the cost of alternative technologies and the cost of accessing various resources. Therefore, in any given scenario, crude oil and natural gas prices, like the prices for all goods, evolve smoothly over time and will not exhibit the sharp up- or downward spikes we see in the actual time series.

The model is run every 5 years from 2010 to 2100, so the prices should be treated as 5-year averages. Important underlying drivers of economic growth through time are rates of population growth, productivity growth and autonomous energy efficiency improvement (AEEI), each of which is specified exogenously. Global population increases 1.6 fold, to 10.8 billion persons in 2100, with the rates of growth varying by region. Productivity growth is roughly 4% per year at the beginning of the model, falling to less than 2% at the end. AEEI growth is 1% per year for each sector in each region, except for oil refining, for which it is 0%, and except for energy-intensive industry where it is 0.3%. Other important assumptions shaping the equilibrium through time are the available resource bases for natural gas and crude oil, or more accurately put, the cost curves for extraction. The cost curves for crude oil are based on the data in Chan et al. (2012). The cost curves for natural gas are parameterized based on the data used in the MIT Future of Natural Gas study (MIT, 2011). These cost curves will be discussed in more detail below. As the global economy consumes a natural resource, it moves along the supply curve for each resource at the rate of consumption of that resource. The rate at which the prices for crude oil and natural gas change, and their ratio, depends upon the different rate at which global demand for each product presses against the available supply at then prevailing extraction costs.

3. Analysis of scenarios

We analyzed the model under many different scenarios, each using different parameterizations of key inputs to the model or the application of different constraints. Anticipating one of our main results, initial calibration runs with our base case assumptions on the cost of GTL and on other parameters yield virtually no penetration of GTL as far out as 2100, even with no restrictions on CO_2 emissions. Since work by Paltsev (2012) has shown that stringent greenhouse gas (GHG) mitigation scenarios reduce oil prices by a greater amount than they do natural gas prices,[3] making GTL even more unprofitable, our negative results on GTL penetration without any restrictions on carbon emissions are a strong demonstration that GTL is not economically viable if CO_2 emissions are restricted. Indeed, in order to coax out a meaningful penetration of GTL, our analysis shows that it is not only necessary to have no restrictions on CO_2 emissions, but also that it is necessary to make extremely favorable assumptions on (i) the cost and efficiency of GTL technology, and (ii) the supply curve of natural gas. Therefore, to economize on our presentation, we focus on four selected scenarios around the boundary where GTL begins to penetrate and therefore where GTL begins to impact the evolution of the crude oil-to-natural gas price ratio. We first discuss some key features common to all four, and then we describe the assumptions that vary across the four.

In all four scenarios, we (i) relax the model's standard assumption modulating the rate at which a new technology penetrates the market

[1] 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).

[2] 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.

[3] This result is mostly driven by availability of substitutes (where oil is substituted away by biofuels and electric cars, but natural gas demand is positively affected by switching from coal in power sector), higher carbon content of oil in comparison to natural gas, and profit margins in production of oil and natural gas.

(Morris et al., 2014), allowing GTL to immediately capture any market share that the assumed costs warrant, (ii) expand the natural gas resource base 100-fold[4]—which is equivalent to stretching the cumulative supply curve rightward—ensuring that resource constraints do not impede potential GTL penetration, and (iii) increase the natural gas well productivity. The last change we modeled as a 6-fold increase in elasticity of substitution between the natural gas resource and other inputs to natural gas production. This last change 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 idea is that very low-cost natural gas would prod industry to devise new uses for it in much the same way that oil refiners have incrementally increased their recycling of refining by-products. For the same amount of capital, labor and other inputs, natural gas wells will be more productive and produce more natural gas.

Also, all four scenarios assume no constraints on CO_2 emissions (as discussed above, carbon policy would likely make natural gas relatively more expensive than oil). Correspondingly, we leave the electric vehicle out of our model: while electric vehicles have an important benefit when CO_2 emissions are restricted (Heywood and MacKenzie, 2015), they would not play a major role were this constraint missing. We also leave out of our model certain competing technologies such as compressed natural gas (CNG) vehicles and liquefied natural gas (LNG) vehicles. Natural gas-based vehicles reduce greenhouse gas emissions, but increase demand and price for natural gas (Kragha, 2010), thereby further undermining the economic case for the GTL technology. As our results are already negative for GTL even without CNG or LNG vehicles, their availability would only reinforce our argument.[5]

The four scenarios capture variations in two parameters: (i) the cost of GTL, and (ii) the cost of extracting natural gas, and are shown in Table 2. Scenario HH uses the base case cost of GTL and the natural gas cost curves as originally parameterized (but with the expanded resource base common to all scenarios). Scenario HL assumes a cost of GTL in 2020 that is 1/3 the existing cost together with a dramatic increase in thermal efficiency. Since we are pushing limits here, we set the thermal efficiency at 100%. Scenario LH assumes a natural gas extraction cost in 2025 that is 1/3 of the current extraction costs. Scenario LL combines these two changes, assuming lower cost and improved efficiency for GTL as well as lower extraction costs for natural gas.

Scenario HH, while the most conservative of the four, nevertheless benefits from the earlier optimistic assumptions about the natural gas resource base and increased well productivity, and even then there is almost no penetration of GTL. Therefore, this case gives us a starting point to understand how the model functions almost as if there were no GTL.

3.1. Scenario HH: base case GTL and gas extraction costs

Fig. 1 shows GTL penetration, measured as a share of global refined fuel production.[6] As with most of the figures, it shows results for each scenario, but here we focus on the results for scenario HH. GTL achieves limited penetration in 2070, with about 7000 barrels per day of output—essentially the size of a large demonstration plant. By 2080 output increases 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 does not exceed 1% until 2100.

This limited penetration is striking since the use of both crude oil and natural gas increased through 2100, with natural gas use increases about twice as fast as oil use, ultimately overtaking crude oil use measured in MMBtu. By the end of the century, natural gas use had increased about 451%, and crude oil by 127%. Natural gas use started out at about 67% of crude oil consumption in 2010 and increased to about 134% by 2100. This dramatic shift is made possible, in part, by our assumption of significantly expanding the available supply of natural gas at every cost level, an assumption that applies across all four scenarios. Although natural gas use increases significantly, it is not being used for GTL. Instead, natural gas is increasingly being used in other sectors where it is already employed. For example, in electricity generation natural gas becomes the dominant fuel globally, displacing coal. Because we have assumed the resource available at current cost is so large, as global GDP expands, it is cheaper in these sectors to shift the share of output to natural gas. GTL remains too costly, despite the low cost feedstock.

Figs. 2, 3 and 4 show, respectively, the global price of oil through the simulation, the U.S. price of natural gas, and the ratio of the two. In scenario HH, the crude oil price increases from about $44.20 per barrel (bbl) in 2010 to over $147/bbl by 2100 (all measured in 2007 dollars). The natural gas price, in contrast, increases from $4.12 per million Btu (MMBtu) in 2010 to a peak of $4.46/MMBtu in 2040, then declined slightly, ending the simulation 5.6% below the 2010 level. Consequently, over the course of the century the ratio of crude oil to natural gas prices rises significantly from 10-to-1 all the way up to 38-to-1. Nevertheless, in this scenario there is only limited penetration of GTL.

Together, these results on quantities and prices can be summarized with the statement that in 2010, 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 contrast, in 2010, cumulative production of natural gas put it on a relatively flat portion of its cost curve—in part an artifact of our assumption that stretched the supply curve rightward. 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.

3.2. Scenario LH: low gas extraction costs

In the LH case, starting in 2025, the extraction cost of natural gas is lowered to 1/3 of the base case level assumed in scenario HH, while retaining the base case cost and efficiency of GTL as in scenario HH. Naturally, this leads to a massive increase in the use of natural gas: global use doubles between 2020 and 2025 and is 80–112% higher than in the HH case over the 2010–2100 time window 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 low cost of natural gas feedstocks reduced the cost of electricity as well, and in 2025 its use expanded by 10% beyond base case levels in 2025, rising to 34% above base case levels by 2100. The dramatic decrease in natural gas extraction costs in 2025 also enables initial deployment of GTL in 2025 at 340,000 barrels per day, or about 0.3% of global refined oil production, as can be seen in Fig. 1. The break-even 70/30 diesel/petrochemical feedstock weighted barrel cost was below $65 (including the cost of natural gas). 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

[4] This is an extreme assumption designed to illustrate an inclusion of methane hydrates, which are unlikely to be a commercially viable source anytime soon, but with deposits exceeding 100,000 Tcf, mostly in ocean sediments (MIT, 2011).

[5] However, other drop-in fuel technologies that compete with GTL are included: biofuels (both crop-based and waste biomass-based), coal-based synthetic crude, oilsands and oilsand upgrading, synthetic natural gas (from coal, coke, and heavy fuel oils), and heavy fuel oil upgrading in the refinery sector are all on the palette of technologies available in every scenario. Due to their expense and complexity, none of them except for the refinery upgrading technology ever evolves beyond marginal deployment, and their effect on crude oil and petroleum product prices is modest to negligible.

[6] Although GTL only deploys in the US, diesel is a globally-traded product which, like crude oil, is priced as an internationally homogenous good.

Table 2
Parameterization of the four scenarios.

Base case: current gas reserve estimates, GTL not available	Natural gas resource base expanded × 100	Gas resource base × 100, gas production cost 1/3 in 2025
GTL available in US at existing cost and 56% efficiency in 2020	HH	LH
GTL available in US at 1/3 existing cost, 100% efficiency in 2020	HL	LL

16.3 mmbd, which was about 6.4% of global refining capacity. Consequently, crude oil use continued to rise with transportation demand.

Because petroleum-sourced diesel remained dominant, crude oil consumption remained robust, and the crude oil price steadily increases over the course of the simulation as shown in Fig. 2. It was only after 2090 that crude oil prices even deviated downward by only 5.5% below the HH scenario levels in 2100. Global crude oil consumption actually rose to 11% above HH scenario 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, and the substitution away from crude oil products in sectors where gas became competitive freed up crude oil supplies at a lower price than under the HH case. This caused a modest crude oil rebound effect. The lower cost of extracting natural gas in 2025 immediately lowers the price of natural gas dramatically, as shown in Fig. 3. This translates into a much higher crude oil–natural gas price ratio as shown in Fig. 4 where the ratio jumps from 14-to-1 in 2020 to 39-to-1 in 2025. As crude oil prices continue to rise and natural gas prices stay flat or gradually decline at the lower level, the crude oil–natural gas price ratio climbs to 94-to-1 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. 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, but penetration was not significant enough to do either of these things. However, GTL does cap the U.S. distillate fuel price. Fig. 5 depicts the path of distillate fuel prices in every scenario.

3.3. Scenario HL: low cost and highly efficient GTL

For this scenario, we cut the non-fuel input costs of GTL to 1/3 of the base case value and increase GTL efficiency to 100%: 5.5 MMBtu of feedstock produce the 5.5 MMBtu barrel of output. Although this efficiency level is thermodynamically impossible, it identifies the absolute upper bound to which GTL could possibly penetrate against crude oil under the economic assumptions and mechanisms embedded in the CGE model. For this scenario, we keep the base case assumptions about the extraction costs for natural gas, just as they are in scenario HH. The lower cost and more efficient GTL enables penetration to reach nearly ¼ of total global transportation fuels by 2100, reflecting a highly successful industry. Nevertheless, the impact on the oil and natural gas prices is minimal as shown in Figs. 2 and 3. GTL only modestly bounds the increasing oil-gas price ratio at the end of the century, as shown in Fig. 4. The GTL technology dampened price increases in distillate fuels, which accelerated the transition from gasoline to distillate fuels in the US transportation sectors. However, since natural gas costs remained high, the HL case did not exhibit substitution away from crude oil products and toward natural gas in non-transportation sectors. This helped delay the loss of profitability in the refinery sectors until near the end of the simulation.

3.4. Scenario LL: low cost and highly efficient GTL combined with low cost natural gas production

The final scenario, labeled LL, combines the two assumptions from scenarios LH and HL: it cuts the non-fuel input costs of GTL to 1/3 of the baseline value and increases GTL efficiency to 100%, as in the HL case, and deploys the low-cost natural gas production technology as in the LH case. As in the LH case, natural gas usage expands dramatically, and GTL penetration increases significantly over the HL case. 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. The rate of capacity additions thereafter decline from about 37% in 2030 to settle in a 20% per-year average capacity increase through 2085. Availability of the low cost feedstock enables GTL deployment rates that are roughly double those of the HL.

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; US distillate prices were 40–70% below the global diesel price from 2025 to 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, demand for gasoline and refinery gases remained high, so refineries continued processing crude oil into refined fuels.

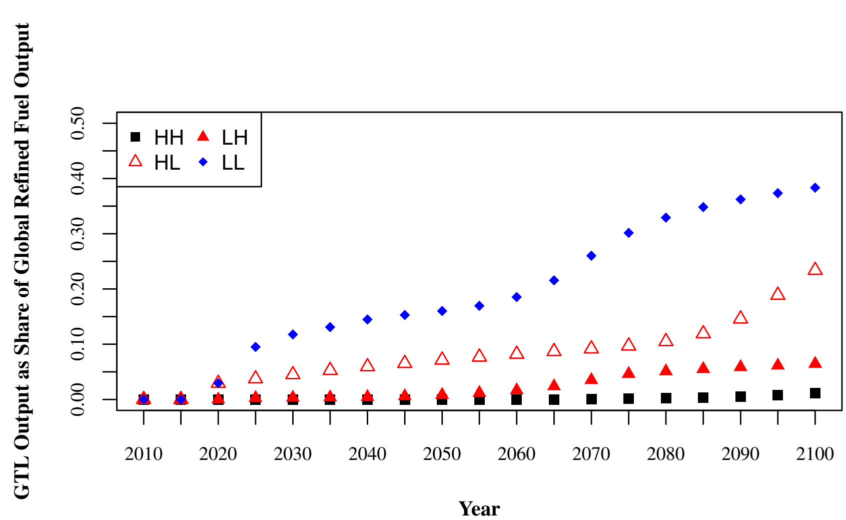

Fig. 1. GTL share of global refined fuel production.

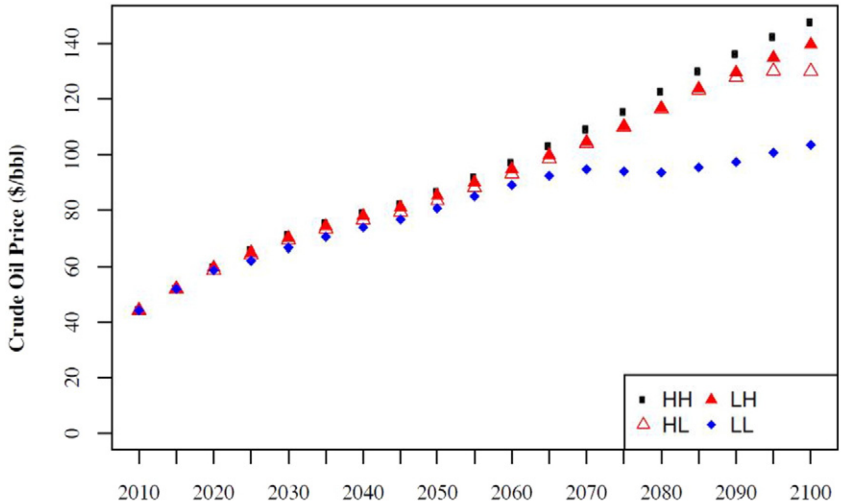

Fig. 2. World crude oil price ($/bbl).

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. Fig. 6 depicts the evolution of energy usage in US household transportation as GTL distillate fuel production increased in the LL case.

Initially, in 2010, US household transportation demand was met almost entirely by gasoline. In 2025, when the low-cost natural gas production technology is deployed, there is only a slight shift toward GTL diesels. In 2050, when the first wave of GTL plants is fully depreciated, the gasoline share of energy consumption has fallen below 40%. By 2065, gasoline has been nearly completely displaced by petroleum and GTL distillate fuels. GTL diesel makes up over 80% of energy consumption in household transportation. GTL diesel increasingly displaced petroleum diesel in household transport through 2100.

The US commercial transportation sector followed a similar pattern. Commercial transportation fuel consumption was about 3/4 diesel in the base year, with gasoline making up the bulk of the remainder. Fig. 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. In the HL case, petroleum distillate fuels still control a significant share of transportation fuels.

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.

This penetration is significant enough to have a large impact on the oil price. As shown in Fig. 2, the price stops its dramatic increase around 2065 when GTL production first surpasses 20% of refined fuel production. As shown in Fig. 4, this also translates into a flattening of the oil-natural gas price ratio as compared to the trend line in the comparable LH scenario.

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. For example, the HL case simply arrested the price increase in distillate fuels at 2020 levels. 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.

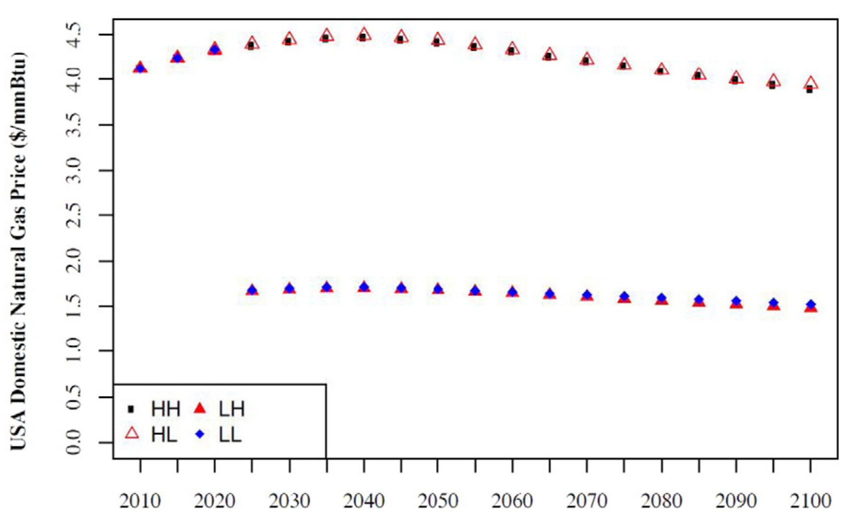

Fig. 3. U.S. domestic natural gas price ($/MMBtu).

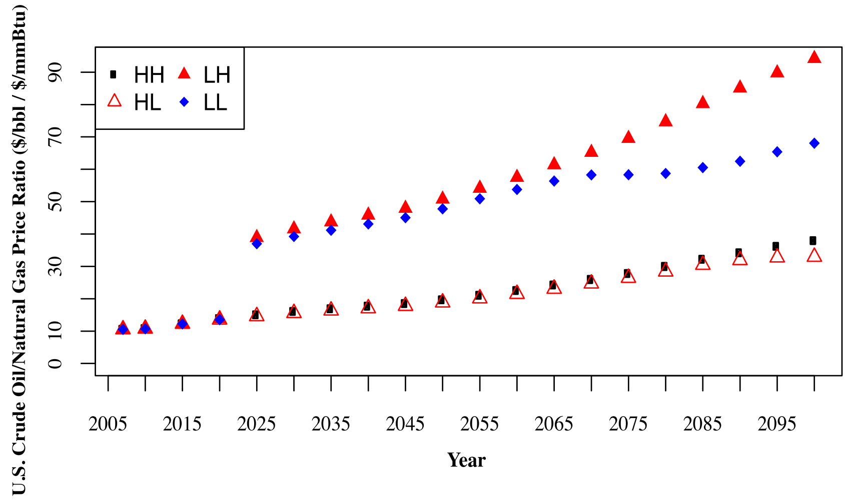

Fig. 4. Crude oil/domestic natural gas price ratios ($/bbl/$/MMBtu) in the USA.

It is worth reemphasizing at this point that this scenario is purposefully an extreme one, with unwarrantedly low costs for GTL and for natural gas extraction, as well as a plentiful supply of natural gas resources. More importantly, this scenario, like the others considered here, has no cap on carbon or other GHG emissions. The point of the scenario is to demonstrate the extreme assumptions required to elicit deep penetration of GTL technologies. Indeed, the emissions under this scenario are frightening. The LL case results in a 500% increase in global carbon emissions over the HH case, which itself has emissions that increase significantly over current levels. The success of GTL in the LL case results in a massive increase in fuel usage due to a rebound effect. The very low price of distillate fuels increases their usage and the consumption of natural gas required to produce those fuels causes global carbon emissions to rise significantly. In the LL case, global economic activity releases 567 billion ton of CO_2 in 2100, compared to just 95 billion ton in the HH case. Methane, which is even more effective at trapping heat than CO_2, is emitted at a 240% higher rate in the LL case than in the HH case, with 739 million ton emitted in 2100. Considering that even the HH case emissions are much too high to avoid the dangerous impacts of global warming–or even come close to meeting the requirements of the Paris Climate Accords–it is clear that technological pathways that make using fossil fuels easier or less expensive are not conducive to ensuring the achievement of any climate stabilization goals.

4. Conclusion

We use a computable general equilibrium model to examine conditions under which GTL technology penetrates to capture a meaningful share of the market and 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. GTL must be less costly and more efficient in order to develop as an industry, and to have any impact on the crude oil–natural gas price ratio, it is also necessary for natural gas to be still cheaper to produce than the current shale revolution in the US has realized. These very negative results obtain assuming no restrictions on carbon emissions, which is another generous assumption that favors the profitability of GTL. Our results make clear that with limits on carbon, GTL is a fortiori not economical.

Given that GTL is not likely to be a major part of global industry in the future, U.S. transportation fuel production is likely to continue to be dominated by petroleum. Carbon limits will encourage the expanded use of electric vehicles and biofuels, and in certain locations to CNG or LNG vehicles. The crude oil–natural gas price ratio is likely to be

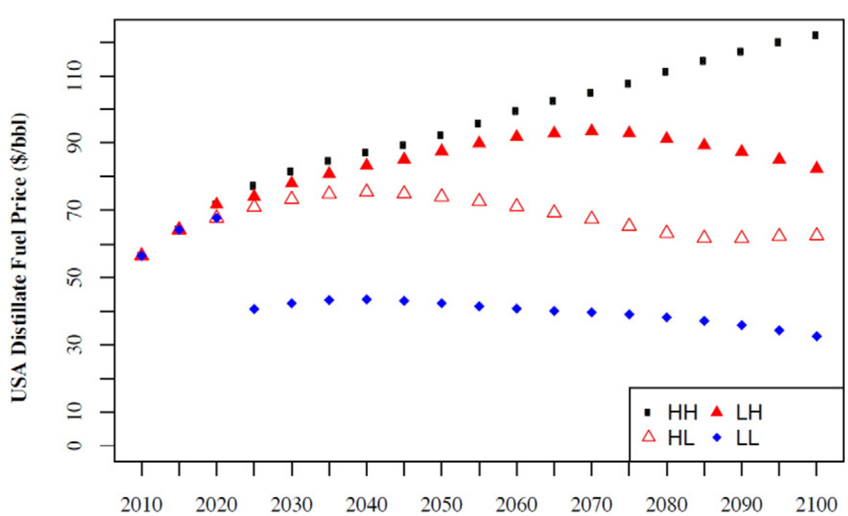

Fig. 5. U.S. distillate fuel price ($/bbl).

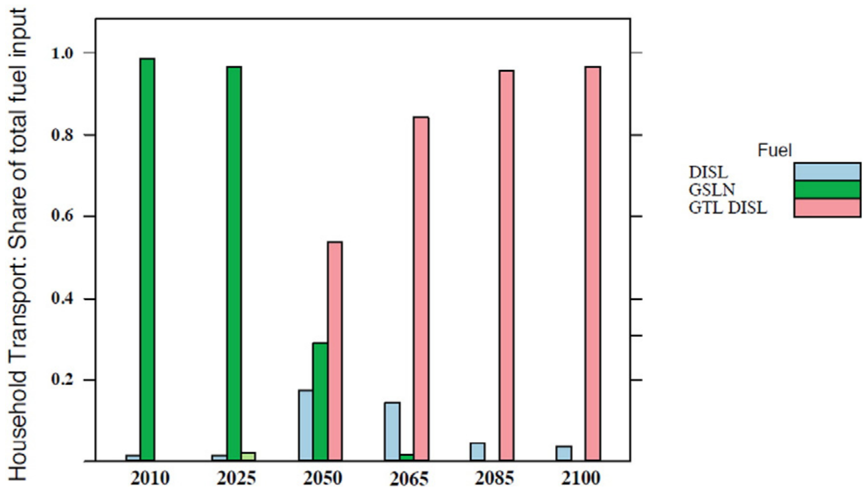

Fig. 6. USA household transportation energy consumption shares in 2010, 2025, 2050, 2065, 2085, and 2100: LL case.

impacted more by the changing stringency of a carbon limit and its interplay with the evolution of these other competing technologies than by GTL.

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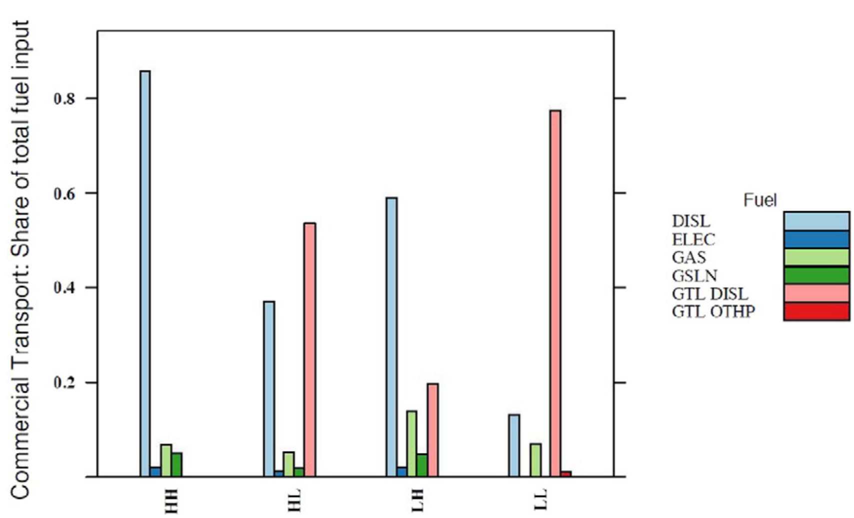

Fig. 7. U.S. commercial transportation energy consumption shares at the second major price ratio shift in 2065.

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