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Research Report – UCD-ITS-RR-13-28

Exploring Options for Natural Gas in Transportation

May 2013

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SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

An Institute of Transportation Studies Program

Preliminary Report:
NextSTEPS Natural Gas Scenarios Workshop - February 2013
"Exploring Options for Natural Gas in Transportation"

May 20, 2013

Executive summary of presentations

Rapid growth of oil and natural gas production from unconventional shale resources in the United States and Canada is radically changing the dynamics of the energy industry. Shale gas will have transformational impact on energy supply, pricing, energy trade patterns and geopolitics, and to existing oil and gas industry business models and transportation fuel pathways, speakers concluded at special scenarios workshop examining the potential pathways for natural gas to emerge as a transportation fuel. The two day workshop, organized by The Next Steps program of the Institute for Transportation Studies UC Davis, was held on February 4-5, 2013, and included representatives from vehicle manufacturers, financial institutions, energy companies, natural gas market analysts, policy makers, fuels infrastructure companies, trucking firms, fuels engineers/scientists, academic researchers, and students. The workshop covered wide ranging discussions of scenarios for natural gas market supply and pricing as well as for technological breakthroughs in vehicle and conversion technologies, fuel switching and policy adoption and influence. Both direct use in vehicles as well as indirect applications such as natural gas as a feedstock for hydrogen fuels or for electricity generation as part of the electrification of the transportation sector was discussed as part of the proceedings. This report summarizes the background presentations made at the workshop which was aimed to investigate the potential pathways for natural gas to emerge as a transportation fuel. A second expanded report is planned that will include major scenarios for natural gas in transportation.

In introducing the workshop, Amy Myers Jaffe, executive director for Energy and Sustainability at ITS Davis and lead for the Next Steps natural gas research track, explained that the so-called "shale revolution" has already unleashed an enormous amount of oil and gas activity in the United States, altering the landscape for how natural gas' role may evolve in the US transportation sector. Shale gas production in the United States has increased from virtually nothing in 2000 to 2.5 tcf this past summer, a record high. Shale gas production could more than quadruple by 2040, accounting for well over 50 percent of total U.S. natural gas production over the next two decades versus 37% today.[1] There is also plentiful conventional gas and other carbonate sources of rock (e.g., tight gas, gas hydrates) that can also be extracted, thus further expanding the potential for

[1] See Kenneth B. Medlock III, Amy Myers Jaffe, and Peter R. Hartley, "Shale Gas and U.S. National Security" (working paper, James A. Baker III Institute for Public Policy, Rice University, Houston, TX, July 2011) and Energy 2020 North America, the New Middle East? Citi GPS: Global Perspectives & Solutions, March 20, 2012.

natural gas supply. *Tight oil,* that is unconventional oil from shale structures, is also developing at an extraordinarily rapid rate in the US as well, reaching more than 1.5 million b/d and end 2012, or 1.6% of global production.

One of the most interesting aspects of the shale revolution is that it reverses an expected pattern of global energy trade. Generally speaking, shale resources are located in or very near to major energy consuming regions. This is in contrast to supply patterns that were developing in the 1990s and early 2000s when the world's largest oil and gas companies were investing in multi-billion dollar mega-projects to link the vast distant resources in the Middle East, former Soviet Union and North American Arctic to Western consuming centers and China. With the development of massive shale resources in the lower-48 United States and the possibility of similar exploitation of shale gas in places near developed markets such as Australia, the UK, Eastern Europe, Mexico, Argentina, China and South Africa, the need for long, expensive supply chains and massive infrastructure such as cross border pipelines and long haul LNG tankers is waning. Shale gas is ushering in a changed paradigm where consuming countries will increasingly be able to source their supply at home, lowering geopolitical risks and enhancing economic benefits.

The geopolitical repercussions of expanding shale gas production will be substantial, according to Jaffe. Already, rising shale oil and gas production is improving the US balance of trade and enhancing energy security for both the US and Europe. US shale gas has already played a key role in weakening Russia's ability to wield an energy weapon over its European customers by displacement. By significantly reducing US requirements for imported liquefied natural gas (LNG), rising US shale gas production has increased alternative LNG supplies to Europe in the form of LNG displaced from the US market. The geopolitical role of US natural gas surpluses in constraining Russia's ability to use its energy supplier role as a wedge between the US and its European allies[2] could further weaken over time, to the extent that the current Administration stays the course with approvals of US LNG export terminals. US Asian allies Japan and South Korea also are seeking flexible US Gulf coast LNG contracts for reasons of economic and geopolitical leverage.

Current US natural gas self-sufficiency will also mean that heavy global reliance on natural gas exports from the Middle East will likely be delayed for two decades or more. By reducing US and Chinese dependence on Middle East natural gas supplies, it lowers the incentives for geopolitical and commercial competition between these two largest consuming countries in energy while at the same time, reducing Iran's ability to use energy as a diplomatic tool to strengthen its regional power or buttress its nuclear

[2] Edward L. Morse and Adam J. Robinson argue in their article, "Growing Pains: Russia's New Muscle" *Aspenia* 32-4, February 2007, p. 110-119, that Moscow has used energy as a means to pull European states away from close alliance with the United States by brief demonstrations that reliability of supply could be subject to geopolitical considerations. Russian energy "diplomacy" is mentioned in EU discussions as a factor in slowing the eastward expansion of NATO to Ukraine and elsewhere.

aspirations. Industry speakers also noted that since the geography of shale is highly diversified, the resource offers better security of supply and resilience. Shale drilling requires only one-twentieth of the land use of comparable wind power and on a Btu basis water use per lifetime for a gas well is significantly smaller than coal or nuclear energy production.

The high promise of shale is changing both where the oil industry invests as well as who invests, Jaffe went on to explain. The proportion of oil and gas investment capital flowing to North America and Australia has jumped significantly in the last two years. Oil and gas total upstream investment hit a record high in 2012 at $550 billion. Investment in North America was over 30 % of this total, and will represent bulk of future investment growth. Investment in *tight oil* prospects in North America has quadrupled since 2010, with consultants Wood Mackenzie forecasting it will reach $80 billion by 2015. Australia stands as the highest growing investment region for oil and gas exploration after United States, reflecting the massive shale potential there as well.

Another likely consequence of the shale play is that it will also divert capital away from prolific conventional oil producing regions with high geopolitical risk. For example, the pace of withdrawals of oil explorers from Iraq and the former Soviet Union is gaining pace, and Russia is even having difficulty finding partners for its resource-rich Arctic developments. This trend may accelerate over time as instability spreads in the Middle East in light of the Arab Spring. So far, the exploitation of global shale resources outside of North America has been slow, given technical, logistical and regulatory barriers. But the global potential is high, at over 6,600 trillion cubic feet (tcf), according to US Energy Information Administration estimates, and international companies are actively pursuing shale resource development in South Africa, Australia and China, among other locations.

Citibank puts *tight oil* break-evens in the $50 to $70 a barrel range, putting a hole in the theory of those who argue that the marginal costs of incremental oil supply is above $75. Even the thesis that US natural gas production remains a low price island is somewhat incorrect as US coal exports to Europe and Asia transmits the competitive impact of US cheap natural gas prices into those markets.

Beyond its pricing impact, the shale revolution is also transforming the structure of the oil industry, according to ITS-Davis Graduate School of Management joint research. Smaller US independents and new firms created through financial backing via arrangements called master limited partnerships over the last decade have outspent the large oil majors (IOCs) to dominate shale play. There were over 35 companies that spent over $4 billion in capex in 2011, up from 10 in 2001. New entrants including financing from private equity capital and institutional investors, leading to creation of new companies which are staffed with technical personnel laid-off or given early retirement in downsizing of majors during mega merger phase of 1998 to 2002. Since 2008, however, the deep pocketed majors and national oil companies began to buy into important shale

plays, bringing new expertise and in some cases lowering costs.[3] Overall, a six-fold increase in capex spending worldwide is contributing to a giant rise in oil and gas reserves, leading some analysts to lower oil and gas price expectations for the 2020s.

The US Energy Information Administration reports that foreign companies accounted for 20% of joint ventures making the $134 billion in investments in US shale plays between 2008 and 2012, including China's CNOOC, Australian BHP Billiton (with its outright purchase of PetroHawk), and Statoil, often providing upfront cash infusions with a commitment to cover a portion of drilling costs.[4] In early 2013, Sinochem made a $1.7 billion acquisition of a share in the Wolfcamp shale in Texas with Pioneer Resources. The IOCs, ExxonMobil, Shell, BP, Chevron and ConocoPhillips have also all made major acquisitions of shale acreage in recent years and are expected to pick up additional acreage as declining US natural gas prices knock out the more poorly financed players, allowing natural gas to keep flowing even at lower prices. Jaffe noted that many shale plays, including those with dry gas, are seeing breakeven costs as low as $2.00 to $3.00 per mcf. Moreover, as operators have shifted focus onto known *wet* gas discoveries and *tight oil*, the associated natural gas has become less of an investment target itself but more of a by-product that is subsidized by profitable liquids production and sales. As a by-product from the operator's point of view, the natural gas output stream is rendered insensitive to falling market value, in some cases leading to outright flaring and in others, to innovative efforts to create new demand. [5]

It is precisely this desire to create new demand that is opening up the possibility that natural gas will increasingly enter into transportation sector in the United States. In the past several months, several US energy companies, including Shell, BP, Apache, Pioneer Resources, and ConocoPhillips have announced businesses to utilize their natural gas in transportation, either in their own fleets or through sales into existing or future expansion in fueling infrastructure. Major commercial investments in liquefied natural gas (LNG) fueling infrastructure now coming on line in United States for heavy-duty trucks and pilot projects are under way in for rail locomotives. The economics of compressed natural gas

[3] http://www.eia.gov/todayinenergy/detail.cfm?id=10711
[4] Ibid
[5] For further discussion of the shale liquids industry and its implications, see Alan Troner, Natural Gas Liquids in the Shale Revolution. Companies have been seeking to optimize revenue by shifting to shale basins with associated liquids, with the top target being black oil, that as *tight oil*; or alternatively, shale gas high in natural gas liquids (NGLs) content – known as *wet gas*, to reap the highest possible earnings. In the case of this strategy, the liquids content from a producing shale formation becomes the primary target, with natural gas relegated to an associated stream, if not a waste product to be flared. The high value of liquids production essentially compensates for any softening in natural gas prices from increasingly abundant supply. NGLs are liquid hydrocarbons suspended in gas in subsurface hydrocarbon reservoirs, at underground pressure and temperature. They sit in the zone between natural gas, also known as methane (C1 consisting of a single carbon molecule) and black oil, also known as oil or crude oil. NGLs are made up of ethane (C2 or two carbon molecules), propane (C3 or three carbon molecules) and butane (C4 or four carbon molecules), the latter two together are called Liquefied Petroleum Gas (LPG). Condensate (C5 +) is the heaviest NGL and the only one that does not require specialized containment. Once condensate becomes a liquid, it remains a liquid, and is similar to, but not exactly the same as, crude oil.

(CNG) light and medium duty fleets is also increasingly commercial, renewing interest among state, local and municipal governments as well as among private sector fleets.

Technological improvement of natural gas vehicles will play a role in defining how and to what extent natural gas enters the transportation sector, academic researchers and industry participants agreed. Already, LNG truck manufacturers are introducing larger 12-liter engines that will reduce the frequency of refueling and higher demand for LNG trucks is bringing down costs of manufacturing. Honda is marketing a new CNGV with city driving efficiency of 27 miles per gallon, a sizable improvement over historical efficiency ratings for CNG vehicles, However, questions remain about the longevity of the wide oil-gas price differential that is now propelling sales of natural gas vehicles and about the life cycle environmental benefits of natural gas as a fuel for transportation compared to gasoline and diesel fuel.

Citibank projects that US natural gas production may continue to grow in the coming years as efficiency and productivity improvements drive higher output, even in the face of a decline in rig counts. Citibank forecasts that over 1,000 drilled-but-not-producing wells could add a significant amount of natural gas between end 2012 and early 2014, keeping the US on an upward producing path, even in the face of naturally declining output at more mature wells. Associated gas production will also remain strong as the US ramps up production from tight oil plays. Learning by doing is the name of the game in the shale industry and improvements in reservoir management techniques and well productivity are meaning that initial production rates are not only coming in higher but production rates at the later sustained plateau is also higher than earlier declines seen in the Barnett and Marcellus plays. In fact, Citibank analysis of actual production curves of various companies now operating in the Marcellus show that average initial and subsequent production is nearly two times the level of a typical 2009 Marcellus well.

As a tech play, shale drilling is likely to follow the same principles as the semi-conductor industry. There will be a lot of room for lowering costs and improving productivity through both incremental improvements and in applying various technologies in different combinations, such as computing and signal processing, to maximize different kinds of capabilities. In fracture modeling and reservoir simulation, increases in computing power, particularly for detailed 3D geological modeling and analysis, are leading to improved simulations to enhance drilling design and fracturing operations. Improvements in geo-steering to better fit wellbore placement to individualized shale layers, logging-while-drilling techniques that could improve fracturing productiveness, remote control systems for sliding sleeves and channel fracturing are among some of the technologies expected to fuel productivity gains and drive down costs.

Industry participants from gas producing companies agreed that improvements in resource identification methods will allow companies to better tap production sweet spots and that continued technological improvements will also likely mean that the industry will be able to sustain high production even in the face of low prices, even as production

shifts from those sweet spots to fringe prospects. Although the industry players say that the US power sector and LNG exports could turn out to be among the biggest absorbers of rising shale production, they anticipate a long, large supply curve that can fill this demand without raising US domestic natural gas prices.

Despite low natural gas prices around $3/MMBTU and the lowest natural gas drilling rig count in years, U.S. natural gas production has not declined materially. Horizontal drilling and other technologies like "pad drilling" are dramatically lowering the amount of drilling days required to get the same volume of hydrocarbons. Moreover, shale gas produced in association with tight oil and liquids plays will come to market (it is currently flared in some cases, as in North Dakota where 30% of natural gas production is flared) even if gas prices are low since profits from liquids production covers any losses on the gas sales and production. Thus, industry players expect US natural gas prices to remain below a $4 to $6 /MMBTU level out to 2020 and possibly beyond. With oil prices remaining high due to political unrest in the Middle East, the current broad spread between oil and gas prices is expected to continue, improving the commercial case for fleet managers to consider natural gas vehicles.

The current wide gap between diesel fuel prices and liquefied natural gas (LNG) fuel currently provides commercial incentives for fuel switching. The largest gains from fuel switching will be seen for heavy trucks because of the intensity of their vehicle miles traveled (VMT). Given the current fuel price spread of $1.00 to $2.00 of oil equivalent between diesel and LNG, for vehicles that travel over 90,000 miles a year or more, costs per mile payback can accrue in less than 3 years. Payback times for a standard CNG automobile are considerably longer (perhaps as much as 8 years), given lower average VMT.

Although these commercial incentives are substantial, the degree to which natural gas can penetrate into the transportation sector will depend largely on the durability of the currently wide price differential between spot crude oil and natural gas prices. Concerns that natural gas' present discount won't be sustained remains a barrier discouraging fuel switching. As a result, many OEMs, vehicle fleet owners and individual consumers focus on fuel efficiency instead of alternative fuels. But as the Henry Hub spot and futures prices for natural gas have fallen and supplies have continued to mount, a new push has surfaced in the United States for both LNG exports and natural gas in trucking.

Natural Gas in US Transportation

The size of the US diesel fuel market is approximately 41 billion gallons a year (excluding military). Heavy duty vehicles represent about 62% of this market, with roughly 23-25 billion gal/yr demand coming from line haul class 8 trucks. Given the $20 MMBTU differential between natural gas and diesel fuel prices, there is a significant opportunity for natural gas penetration in the transportation sector. So far, fuel switching

has mostly affected trucking and marine markets, but opportunities may also come for fuel switching by railroads as well, industry participants predicted. New enabling fueling infrastructure technologies include GE's new modular CNG in a box mobile fueling unit, which is being installed in convenience store stations for use by fleet owners. Three micro-LNG production plants are also under construction, two by GE with a 250,000 gallon per day capacity, and one by ConocoPhillips. GE is also announcing LNG In a Box, a modular, portable plug-and-play system, capable to deliver 10,000 to 50,000 LNG gallons daily, with the first commercial applications being deployed in Europe in collaboration with Gasfin, a European operator. The modular approach is believed to be able to bring market up to scale in a manner that dramatically reduces the costs and risks involved in launching fueling stations. GE is currently working on CNG home fueling equipment, which could cost as low as $500, and a modular CNG in a box for commercial compressed natural gas fueling stations.

While natural gas vehicles sales will continue to grow in urban markets, the single largest market opportunity to displace conventional gasoline or diesel fuel may well come from the heavy duty market, industry participants said. The Class 8 truck market offers strong opportunities for both LNG and CNG sales given their focused, tight fueling network. Currently, there are only 9,500 truck stations in the United States that serve 1.5M Class 8 trucks. They use 40 billion gal/yr diesel consumption, the equivalent to 3.3 TCF/year natural gas or 14% of current U.S. natural gas consumption. Nearly half of garbage trucks sold in the United States last year run on natural gas.

Currently, there are 16.5 million natural gas vehicles worldwide. In the United States, there are 250,000 natural gas vehicles, the majority of which are heavy-duty vehicles, where fuels savings can more quickly offset cost differential of vehicle. Heavy-duty vehicles importance by classes from NRC is Class 8B (67%), Class 6 (14%), Class 8A (8%), Class 7 (5%), class 3(1%).

Clean Energy is the largest natural gas fuel provider in North America with over 330 CNG fueling stations, mostly public access, serving 660 fleets and 25,000 vehicles. The company currently averages 200 million gallons a year in sales of CNG. CNG prices in most areas of the country are between $2 and $3/gge but in Oklahoma CNG is currently available at a low price of around $1/gge, driving a more rapid adoption of natural gas vehicles.

While city buses and garbage truck fleets have been shifting over to natural gas for the past several years, the move to natural gas for long haul trucking is a relatively recent phenomenon. To convince a larger number of truckers to make the shift, natural gas fueling providers are selecting key, heavily traveled highway routes in major markets such as California to build out LNG fueling stations. The projected America's Natural Gas Highway (ANGH) by Clean Energy includes 150 LNG gas stations spread out every 200-300 miles. ANGH added 70 stations in 2012 and will see an additional 80 but in place in 2013. All of the ANGH stations currently provide LNG fuel but it is eventually

planned to provide CNG produced from LNG (LCNG) at the stations. Clean Energy says it is able to achieve a return to capital for fueling station investment and still pass on between $1.00 to $1.50 a gallon in fuel savings to customers. The company's business model is to line up with return to base segment shipping that is enabling a shift to LNG fuel. A typical LNG fueling facility costs about $1.5 million and it takes as few as 20 trucks/day, equivalent to a throughput of 400,000 gallons/station to achieve a break-even on the upfront capital investment.

Other examples of investment on LNG fueling stations include a partnership effort between Shell and Travel Center of America. This co-venture has current plans to install LNG fueling stations for long-distance trucking in an additional 100 locations. Another venture between ENN of China and CH4 energy Corp. will also be introducing 50 LNG stations starting in Utah, with ultimate plans for a network of 500 stations in the United States. ENN, led by energy investor Wang Yusuo, has already been successful building natural gas stations in China. ENN and CH4's venture, Transfuels LLC, say they have plans to build LNG plants.

One consideration for fleet truck owners is that vehicle turnover typically takes place within 5 years, at which time trucks are then sold to secondary and tertiary markets in the US and Mexico. The economics of conversion to natural gas or an outright purchase of a newly manufactured natural gas vehicle must therefore take into account resale value of the vehicle as well as lower operating costs but current rapid paybacks and the gradual emergence of buyers in the secondary market is driving more companies to consider natural gas fuel. Several national fleets are deploying natural gas trucks; including Cisco, Pepsi, Walmart, Fritolay, HEB, Trimac Transportation, Truck Tire Service Corporation (TTS), Verizon, UPS, ATt&T, Food Lion, and Ryder.

Despite the relatively quick payback period, fleet managers have been reluctant to fully embrace natural gas for a variety of reasons including concerns about the reliability of continued cheap supply. In California, the push to zero emissions vehicles has meant that other renewables-based fuels are considered preferable to natural gas, especially until the the controversy over how to calculate greenhouse gas emissions leakage from natural gas production and transmission is resolved. In addition, fleet owners worry that supply chains for natural gas vehicles are not yet sufficiently high to avoid higher maintenance costs than traditional diesel vehicles and knowledge of the vehicle among trained maintenance workers is also lower, again potentially leading to higher fixed operating costs. The lower energy density of the fuel compared to oil affects vehicle range and the frequency required for refueling.

The dynamics of inter-modal competitive between trucking and rail means that railroads may want to capture the savings offered by LNG fuel in an effort to remain competitive. Several major natural gas producers are also focusing efforts on promoting natural gas in rail. While locomotives represent only 8% of annual diesel use, the market is centralized and transparent with only 5 major companies, creating a marketing advantage for natural

gas sellers. A single locomotive company uses roughly 1.4 billion gal diesel/year.

Consumer behavior

In the light-duty sector, consumers have not gravitated widely to natural gas vehicles (NGVs). CNG is perceived as an old 1950s Soviet technology, in contrast with EVs which are viewed as innovative, forward looking technology. The primary reason costumers buy NGV is because cheaper fuel costs and access to HOV as opposed to fleet owners who originally gravitated to NGVs to comply with clean air standards. The range of the vehicle and initial cost remain barriers. The Honda Civic NG, with improved fuel economy and acceleration, can go 248 miles without fueling, about 10% more than the previous Honda Civic GX and has roughly a seven year payback period. Other models, like the Honda Ridge Line (pickup truck) have lower payback periods due to higher fuel use.

On a 2006 US National New Car Buyers survey, non-NGV drivers did not rate natural gas well, compared to alternatives and ranked NGVs fifth after other options including "Electric", "all biofuels", "hydrogen", and "I have no idea." A 1995 survey among 455 California new car buyers resulted in NGVs positioned between PEVs and reformulated gasoline.

NPC Forecast

The National Petroleum Council (NPC) study "Natural Gas Insights" describes the potential commercially viable fuel/vehicle portfolio mixes projected to meet 2050 demand. In its study, NPC modelers assume that commercial factors are the main driver of fuel shifting, and transition hurdles such as infrastructure development are assumed to be overcome in the long term. The study suggests that market opportunities for both LD and HD vehicles exist with only a few technical barriers to NGV expansion. The current price advantage of natural gas compared to diesel fuel will have to continue for a prolonged period in order to sustain the required effort on infrastructure and OEM product offering expansion, the NPC study suggests, but adds that there will be a strong economic incentive if natural gas prices remain low. Fuel savings are significant for vehicles with high VMT, and the economics are compelling especially given that technologies exist that can increase new vehicle fuel economy by up to 100% from the current 8.5 mpg of Class 3-6, and 6.2 mpg of Class 7 and 8 fleets. Experts believe that cost reductions and increasingly accessible dispensing infrastructure are critical for growth, but economic incentives are currently strong and momentum is growing, the NPC report suggests. The investment requirement in infrastructure is lowest for urban fleets and gradually increases for HD fleets, private LD fleets and is the highest for personal consumers, according to the NPC. The study projects that LNG could possibly capture as much as 40% of the Class 7 & 8 fleets by 2050 in the reference oil price scenario ($156.20 a barrel by 2025 and $223.88 by 2035), and 50% in the high oil price

scenario ($263.01 a barrel by 2025). For class 3-6 the percentage market share of NGV could be 20% in 2050 in the reference oil case, and 30% in the high oil price case. NGV could represent 18-50 of the LDV market. The European state of the art for NGVs demonstrates near term potential for gains in fuel efficiency. NGVs have powertrain architecture similar to traditional gasoline vehicles; enabling common technology advances for NGVs such as downsizing, highly boosted engines, direct injection, hybridization and light-weighting and aerodynamic design but the infrastructure challenges for consumer NGV use are greater than in for commercial sector fleets. Spark Ignition engines could be a promising technology for natural gas use while CNG is also bolstered by cost avoidance of increasingly complex diesel after treatment, replaced by TWC (three way catalyst) and EGR (exhaust gas recirculation). Hybrid options exist and could find traction in specific applications.

Effects of Policy

Policy can be a major driver to fuel and vehicle choices and manufacturers have been confused by competing priorities that have come to the fore in recent years, including air quality, greenhouse gas emissions and fuel economy goals. NGV sales are highly influenced by these trends, industry participants agree.

There are basically two sets of policies that might influence the competitiveness of natural gas vehicles: tax/subsidy policies and performance standards. Current tax policies penalize natural gas by about 20 cents a gallon by basing fuel taxes on volumetric measure (gallons) vs energy content.

At present, the California Low Carbon Fuel Standard (LCSF) gives NGVs a credit compared to oil-powered vehicles. A push to promote renewable natural gas (biogas)[6] could also provide support for natural gas fueling infrastructure and vehicles. But environmental groups have raised concerns about methane leakage that takes place throughout the natural gas supply chain. Industry participants said that green completions are enabling companies to limit upstream emissions to 2 percent or lower in most instances but initial studies are showing that some 10 to 15% of drillers are not using the most advanced procedures to limit venting of carbon from shale operations. Studies to determine the leakage rates in urban distribution and delivery systems are being undertaken in several locations including Boston and New York City and preliminary

[6] The California Biomass Collaborative, a University of California Davis led public-private partnership for the promotion of California biomass industries, estimates that 32.5 million BDT of in-state biomass feedstocks could be available for conversion to useful energy. In particular, estimates for methane production from landfill gas are 55 BCF/year, 4.8 BCF/yr for waste water biogas, and 14.6 BCF/yr for biogas from manure sources. Similar biomass resources are located in states that border California or along routes for the transmission of natural gas to the state from major producing states. We estimate that the methane potential from landfill gas in the Western states outside of California is 105 BCF/yr based on existing and candidate landfills identified by the U.S. Environmental Protection Agency.

data shows a highly variable range of ambient methane concentrations, requiring further analysis to determine the sources.

Black swans and other uncertainties

Optimistic estimates for the penetration of natural gas into transportation suggest that the US could see demand growth of 1 bcf/d to 3 bcf/d in the coming decade but many risks and uncertainties remain. Should oil production from shale formations and other new sources rise faster than expected, oil prices could decline, narrowing the price differential to natural gas, which might be supported over time by substitution effects with coal and oil.

Workshop participants developed scenario storylines for natural gas in transportation based on four parameter conditions. A brief outline of these scenarios follows. A future publication will lay out these scenarios in greater detail.

Scenario One High Supply/High Tech

2015-2020 Continued oil supply disruptions out of the Middle East keep oil prices high and US shale boom gains momentum, driving high demand for LNG fuel for Heavy trucks in the US and China

Major breakthroughs in CNG and hydrogen on board and on site storage tankage improve driving range and decrease costs of natural gas vehicles and fueling stations, accelerating the adoption of natural gas vehicles. At least two of the 13 projects funded under the $30 million budget of ARPA-E's Methane Opportunities for Vehicular Energy (MOVE) program have yielded success. The first is a low-pressure metal-organic material-based natural gas fuel system developed by Ford Motor Company. The on-board adsorbed natural gas tank system material increases the energy density of compressed natural gas. By enabling the storage of natural gas at low pressures, this technology induces huge materials and energy savings, as well as safety improvements. In the light duty sector, natural gas vehicle costs will be dramatically reduced with the adoption of low pressure conformable modular storage design that can fit into tight undercarriage space of vehicles. The new technologies reduce costs of natural gas fueling systems from $15 to $6/KWh, close to the DO target of $4/KWh, and issues with handling and off-site regeneration are solved.

2020-2030 Acceleration in climate severe weather events creates political will in the United States and California's Low Carbon Fuel Standard and Cap and Trade system are expanded across the country as national policy. Major cost breakthroughs seen in home refueling for CNG and for low cost steam methane reforming. Natural gas and hydrogen from natural gas start to penetrate the market more broadly and biofuels industry fades in importance.

2030-2040 Continued high oil prices mean that natural gas takes larger share in transportation in the US, reaching 40% of heavy truck market. Fuel cell vehicles rise to 30% of market but overall demand is falling through the rising use of zip and driverless cars in major cities and improved mass transit. Carbon policy drivers increase the amount of natural gas coming from waste and companies are forced to use more carbon capture technologies to reduce the GHG emissions upstream.

Scenario Two Low Supply/Low Tech

2015-2020 The large gap between oil and natural gas prices slowly closes as rising tight oil supplies and a collapse in China's economic miracle bring down oil prices while natural gas substitution effects have created rising demand for natural gas in US manufacturing and power generation in addition to sporadic US LNG exports. Tighter regulations on methane releases dampen enthusiasm for LNG trucking and vehicle manufacturers see only slow progress on lowering vehicle costs. No breakthroughs come in on board storage, batteries or CNG systems, leaving these technologies still not cost effective compared to hybrid and conventional gasoline engines.

2020-2030 Incentives to overcome technical barriers for natural gas vehicles have faded and LNG in heavy duty trucks shrinks to a small niche business. Automotive companies begin to focus more on vehicle efficiency and driverless cars and less on alternative fuels. Electric vehicles gain more of the fleets market, as a result of the imposition of a new CO2 tax that favors renewable energy and coal with carbon capture and storage. The CO2 tax helps bring more waste to energy businesses to the fore and biogas, along with EVs start to take off after 2030.

Scenario Three Low Supply/High Tech

2015-2020 An acceleration of climate severe weather events leads to threats to food supply and large losses of property and human life and propels the adoption of binding global and national climate policy through a major deal between China and the US. The new agreement leads to a more serious effort to establish cap and trade markets for carbon and the carbon price begins to creep higher. The United States also creates a major R & D push in carbon capture and storage technologies that contributes to a major commercial breakthrough.
2020-2030 By 2020, CCS demonstration projects are begun and by 2030 deployment starts to become widespread. Oil prices ease over time as carbon policy takes hold, reducing the incentives to bring natural gas into transportation and coal with CCS even starts to edge out natural gas in the power sector due to spread of bans on fracking in certain US states. Natural gas' role in power sector vastly outweighs any possibility that it could be economical to use in transportation and fleet managers look increasingly to lower carbon alternatives such as solar to electric vehicles and hydrogen fuel cells.

Breakthroughs in spark ignition and waste to energy also support alternative fuel vehicles that do not utilize fossil natural gas.

Scenario Four Low Tech/High Natural Gas Supply

2015-2020 The US recession lingers and vehicle manufacturers stick with existing lines, focusing on evolutionary improvements in efficiency, scaling, and performance of existing technologies. Several major energy companies enter the natural gas fueling station business and investment in infrastructure gains momentum. As a result, LNG fuels reach a penetration of 10-20% of the heavy duty truck market.

2020-2040 Few breakthroughs come in the clean tech industry and battery technology makes only slow incremental progress, reducing the momentum to switch to still expensive EVs. Natural gas prices remain low, and its market share as a fuel continues to expand. More states begin to implement programs to provide incentives for natural gas vehicles as cost savings continue to mount. Oil prices remain high due to instability in the Middle East while US natural gas supply remains ample. Low natural gas prices in the US contribute to a rise in new manufacturing plants, adding US jobs and US GDP growth tops 4%. The economic progress stimulates more purchasing of cars and fleet managers turn increasingly to natural gas vehicles. Shell and other US major oil companies invest large sums in the LNG trucking business, enabling more and more fueling stations to the point where a larger number of fueling stations in the US are hooked up to natural gas pipelines. LNG rises to 40% market penetration in heavy trucking by 2040. More individual consumers in oil and gas states like Oklahoma, Texas, Louisiana, Ohio and Pennsylvania also switch to natural gas CNG light duty vehicles to grab cost savings. Abundant cheap natural gas also knocks more coal out of the power sector in many parts of the US, keeping the US onto a falling greenhouse gas path and reducing the political incentives for a stricter climate policy. As natural gas production rises substantially in states that were previously coal states, the politics of energy policy starts to see substantial changes. The natural gas lobby becomes increasingly powerful because of the high number of jobs being created in and around cheap natural gas and policy makers focus mostly on carbon regulations that restrict emissions from coal in power sector. Many coal plants need to be retired because carbon capture and storage technologies remain too costly to allow coal fired plants to remain open. Displaced coal is exported abroad and natural gas becomes more dominant in manufacturing and power generation in the US.

Closing remarks

The shale revolution in the United States is driving significant penetration of natural gas in transportation, especially in fleets and the heavy duty sector. This effect is driven by improved economics based on low natural gas fuel costs and short paybacks periods for high mileage vehicles. The shift to natural gas in transportation has generally taken place

without any type of regulation or incentive. Some states, such as Oklahoma, have hastened the shift through government purchasing and fueling subsidies but in other parts of the United States, the rapid adoption of natural gas fuel has been driven by commercial economics. To the extent that shale production keeps natural gas prices low compared to oil prices, the positive trend in natural gas fuel is likely to be sustained or even gain momentum without government intervention. However, potential regulatory prohibitions arising from currently unresolved environmental concerns related to methane leakage from natural gas production and transmission infrastructure could cast a shadow over the market in California and other markets with stricter climate regulations.

The Natural Gas Pathway at NextSTEPS is conducting a comprehensive analysis of the economics, engineering, and environmental issues associated with natural gas production and use in transportation. The aim of the study is to determine the impact of the "Shale Revolution" will play in the US transportation sector, including the development of alternative low carbon fuel pathways. Specifically, we are conducting 4 levels of economic modeling to be able to forecast natural gas and oil prices and price differential under different circumstances. The NextSTEPS Natural Gas Pathway program is also evaluating the environmental risks to water and air resources associated with fracking of shale gas, estimating LCA GHG emissions and analyzing the implications to the California LCFS, of both fossil natural gas as well as biogas for use in transportation in California. Overall society costs of natural gas fuel will be estimated and compared to those of other transportation pathways. A white paper on natural gas in US transportation will be released on April 2014.

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