## Alternative Natural Gas Applications Workshop:

# Creating a Prosperous Demand Market

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This workshop was made possible thanks to a generous grant from the United Engineering Foundation.
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# Alternative Natural Gas Applications Workshop: Creating a Prosperous Demand Market

## 1. Executive Summary

The American Institute of Chemical Engineering (AIChE) Center for Energy Initiatives, along with Savannah River National Laboratory (SRNL) and the National Energy Technology Laboratory (NETL), organized a workshop entitled "Alternative Natural Gas Applications Workshop: Creating a Prosperous Demand Market," conducted on October 8 and 9, 2014, at the Hilton Hotel in Alexandria, Virginia. The objective of the workshop was to identify both high impact applications for increased utilization of natural gas (NG) and related technology gaps. Participants included 71 key representatives from industry, academia, national labs, and the Department of Energy (DOE). Invited speakers and panelists included representatives from Shell, Dow, Honeywell-UOP, Air Products, Gas Turbine Association, Fuel Cell Energy, Sasol, Chrysler, Toyota, Ford, Bayer, Braskem, Ashland Inc., University of South Carolina, Exxon, Global CCS Institute, Trillium CNG, and DOE. This report provides a summary of the workshop results for each of the three market sectors.

This workshop was the first to focus comprehensively on creating a prosperous demand for natural gas utilization. The workshop covered the three market sectors - Transportation, Chemical Synthesis, and Stationary Energy Generation - that could potentially provide significant energy efficiency gains and reductions in greenhouse gas (GHG) emissions with increased NG utilization. The workshop addressed this scope by involving industry, academia, and national labs who are engaged in each of the three market sectors. The workshop involved both cross cutting sessions and market sector focused sessions, seeking to

- Identify the current and highest impact alternative uses of natural gas
- Identify the technology gaps associated with each major NG alternative application
- Determine the roles for the government as well as the private sector for the RD&D
- Begin the development an integrated RD&D roadmap for advanced NG applications

The overall goal was to provide important input to decision makers and stakeholders in advancing NG utilization in an economically and environmentally sustainable way.

### Transportation

Even though NG accounts for 26 percent of total U.S. energy consumption, only about three percent of the NG consumed annually in the U.S. is used for transportation. The fastest growing market is fueling for heavy duty (HD) and medium duty (MD) trucks, buses, and commercial fleets. This market is expected to grow from 30 billion cubic feet (bcf) of gas consumed in 2012 to 850 bcf by 2040. Other areas of anticipated expansion are the marine, rail, and mining industries.

Major difficulties in the use of NG for transportation include a combination of regulatory and technical issues. Some of the regulatory obstacles include inconsistent taxes and credits for NG use at the local, state, and national levels, as well as inconsistent regional refueling and infrastructure standards. The availability of NG refueling stations continues to be an impediment with only 750 compressed natural gas (CNG) and 65 liquefied natural gas (LNG) stations currently operating in the U.S., compared to over 150,000 gasoline stations.

Key technical challenges involve storage, engine technology, and infrastructure. Storage needs include development of lower cost composite tanks and tank materials, and the pursuit of conformal tanks, with low-pressure/adsorbent technology. Engine technology needs include development of higher temperature materials and lubricants as well as new internal combustion engine technologies such as lean burn, compression ignition, methane oxidation catalyst, Reactivity Controlled Compression Ignitionand adaptive controls, along with dual and tri-fuel engines. Infrastructure needs include lower cost, higher efficiency compressors; faster full fill capability including heat of compression dissipation designs; and home refueling options.

The major roles of government are to (1) develop consistent federal and state policies for using NG as a transportation fuel; (2) use the national laboratories to help provide data to support good market driven decisions; and (3) coordinate individual stakeholders, both for the short- and long-term, to address and overcome the technical gaps.

The National Energy Goals and Presidential Climate Action Plan call for a 50 percent reduction in oil imports and 17 percent reduction in GHG emissions by 2020. Natural gas, as a transitional fuel, can play a major role in helping to achieve these targets, either by direct use or by aiding the transformation to hydrogen, electricity, or higher energy liquid fuels.

## Chemical Synthesis

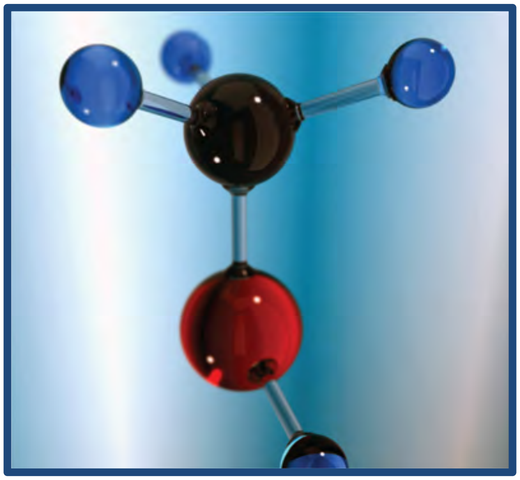
With current domestic NG prices low, U.S. producers have turned towards “wet” gas reserves in an effort to capitalize on an emerging energy and feedstock source and maximize profit. The trends in NG production have resulted in a surplus of ethane, while petrochemical refining trends have resulted in shortages of propylene, butadiene, aromatics and pentanes.

The fastest growing NG chemical synthesis and utilization market is the downstream derivatives sector. Areas of consideration for technological expansion that would further the chemical synthesis and utilization sector are new chemical processes focused on direct conversion to the desire products and new separation technologies circumventing conventional, energy intensive distillation methods (i.e. membranes).

The major obstacles affecting the use of NG as a source for chemical feedstocks include a combination of regulatory and technical concerns. The regulatory barriers include streamlining the regulatory process and developing a rationalized regulatory framework, including a comprehensive energy policy.

The largest technical road blocks were identified with associated time frames. For short term implementation, R&D should address selective C-H bond deviation, capital cost reduction for syngas production, selective building of C-C bonds, and membrane-based separations. For the long term, R&D should address direct catalytic conversion of C1-C2 (non-syngas routes), selective methane activation (C-H bond), and development of cost effective high temperature materials (>1300° C) enabling $CH_4$ pyrolysis.

The suggested role of government is to develop technical roadmaps and to steward a sustained long-term effort to enable Industry, academia, and national lab partnerships. The government should also provide basic R&D funding, promote workforce development, and rationalize the regulatory framework.



## Stationary Energy Generation

The current system for generating and delivering electricity consists primarily of a fuel-to-electricity model where coal, natural gas combined cycle (NGCC) and nuclear plants are used as the energy sources, followed by transport across the U.S. grid via transmission and distribution (T&D) networks, and finally to the end-user. The baseload generation is complemented by spin reserves such as simple-cycle natural gas turbines that provide additional capacity during peak hours, as well as, ancillary services such as voltage regulation, load following and system protection, etc. The primary benefit of the chemical fuel-to-electricity centralized approach is the cost and efficient improvements at scale. For example, a state-of-the-art 510 MW NGCC plant can have electrical efficiencies on the order of 51-55% on a higher heating value (HHV) basis[1]. In contrast, smaller simple cycle gas turbines with a capacity of 1-10 MW have electricity generation efficiencies of roughly 21-29% HHV[2].

While the current approach for stationary energy generation provides some key cost and efficiency benefits at scale, there are some significant disadvantages related to emissions and energy security that arise from the continued use of these technologies without further advances in the technology. Currently, 7% of all electricity generated in the U.S. is lost during T&D which results in 218 million tons of $CO_2$ emissions and $25 billion in lost revenue[3,4]. Also, using a centralized approach increases the vulnerability of those resources to natural disasters and terrorist attacks including cyber attacks, as indicated in the 2013 Congressional report, "Electric Grid Vulnerability: Industry Responses Reveal Security Gaps"[5]. Finally, the centralized approach does not lend itself to allowing an increase in the integration of renewable energy technologies that will be required to meet future emission reductions.

The challenges associated with the centralized power generation approach from 'prime movers' indicate the potential for

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1 http://www.netl.doe.gov/kmd/cds/disk50/NGCC%20Technology_051507.pdf; Accessed on March 20, 2015.

2 "Catalog of CHP Technologies," U.S. Environmental Protection Agency Combined Heat and Power Partnership (2008).

3 http://www.eia.gov/tools/faqs/faq.cfm?id=77&t=11; Accessed on March 20, 2015.

4 Calculation assuming 1.67 lbs. of $CO_2$/kWh (average of coal and NG) and retail electricity price of $0.10/kWh.

5 "Electric Grid Vulnerability: Industry Responses Reveal Security Gaps," http://democrats.energycommerce.house.gov/sites/default/files/documents/report-electric-grid-vulnerability-2013-5-21.pdf (2013); Accessed on March 20, 2015.

significant benefits when shifting to distributed generation (DG) approaches. Currently, there are over 12 million DG units in the United States with a capacity totaling greater than 200 GW[6]; however, the majority exist as backup generators that are infrequently operated. Yet, increased DG in the U.S, would have multiple benefits, including peak load reduction, reactive power and voltage support, reduced T&D congestion, improved power quality and reduce grid vulnerability. Another key benefit of DG is the ability to utilize waste heat generated in the process of converting chemical energy to electricity, a.k.a., combined heat and power (CHP). Combined heat and power has the potential to increase efficiency of these generation systems to greater than 80% percent at residential homes, commercial businesses and industrial facilities[7].

Current DG technologies that could show significant benefits from increased NG utilization include micro-turbines, gas turbines and fuel cells. Each of these technologies has specific technical barriers that could prohibit the expansion in stationary power generation. However, there are common challenges such as the need for high temperature ceramics that would suggest a national initiative into these material types. Additionally, there are ancillary benefits such as CHP and Polygen that would make considerable contributions in overall system efficiency and economic value.

The increased supply of domestic natural gas has led to increased sales of land-based gas turbines for power generation as both prime movers and DG. A substantial investment in associated R&D is needed for the U.S. to build on these gains. For NG-fueled turbines, major technical areas requiring attention are combustion, heat transfer, high temperature materials, and thermal barrier coatings.

For fuel cells, reliable, resilient, distributed power generation is an emerging market where NG has a demonstrated advantage for use as clean fuel. Solid oxide fuel cell (SOFC) technologies can efficiently utilize NG in CHP (combined heat and power) and electricity generation at scales ranging from small commercial to large, distributed generation. The technical gaps for fuel cells include deployment of a clean and efficient energy conversion system such as SOFC and development and deployment of oxygen transport membranes (OTMs). Technology development areas include functional ceramics and membranes, catalysts, and robust filtration processes. Viable means of extending the lifetimes and reducing the materials and manufacturing costs of fuel cells are needed. Greenhouse gas (GHG) emissions mitigation is an uncertain factor. Current proposed regulations exempt NG generation from counting towards emission reduction goals, but if GHG mitigation goals are to be reached, eventually, regulations will require mitigation from DG sources, especially NG-fired sources.

If NG gas turbine or fuel cell technologies are to reach their potential for near-zero GHG emissions, carbon capture and sequestration (CCS) will be required. CCS requires an R&D program to develop capture technologies specific to natural gas-fired

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[6] "The Potential Benefits of Distributed Generation and Rate-Related Issues that May Impede their Expansion," U.S. Department of Energy (2007).

[7] "Combined Heat and Power: A Clean Energy Solution," U.S. DOE and EPA (2012).

systems. DOE is actively funding coal-focused R&D for CCS, but it should also consider funding natural gas-focused CCS R&D to overcome the differences in flue gas content.

Cross-cutting R&D should focus on integrated basic science programs designed to help us understand thermal barrier coatings and high-temperature materials. These technologies are complimentary in nature, so integrated research is required.

Cross-cutting areas of expansion, including CHP and Polygen (in which value added products, in addition to electric power are produced), were also identified. Polygen includes production of oxygen plus power, production of $CO_2$ for enhanced oil recovery plus power, and production of hydrogen plus power and $CO_2$.

Current state regulations and policies make it difficult to connect CHP to the utility grid and should encourage and/or incentivize utilities to invest in or support CHP. State-wide energy efficiency goals or air emissions regulations coupled with monetizing the CHP benefit could drive the adoption of CHP while reducing the costs for the customer.

Government funding for NG-fueled turbines R&D is needed in order to maintain the current U.S. competitive advantage. For SOFCs, the government should support development of programs to attack the key technical problems associated with implementing the fuel cell technology in next generation systems. Overall, the federal government should fund R&D beyond the near-term five-year vision, along with demonstration projects that validate efficient and cost-effective technologies. Stationary power programs for natural gas should develop and demonstrate cost-effective GHG reduction strategies related to NG stationary power generation (all technologies - gas turbines, fuel cells, and CCS) with parallel targets for reduction over time.

## 2. Workshop

The Savannah River National Laboratory and NETL teamed together with the United Engineering Federation and the American Institute of Chemical Engineering-Center for Energy Initiatives to organize a workshop entitled “Alternative Natural Gas Applications Workshop: Creating a Prosperous Demand Market”, conducted on October 8 and 9, 2014 at the Hilton Hotel in Alexandria, Virginia. The objective of the workshop was to identify both high impact applications for increased utilization of natural gas and related technology gaps. Participants included 71 key representatives of industry, academia, national laboratories, and the U.S. DOE.

Invited speakers and panelists included representatives from: Shell, Dow, Honeywell-UOP, Air Products, Gas Turbine Association, Fuel Cell Energy, Sasol, Chrysler, Toyota, Ford, Bayer, Braskem, Ashland Inc., University of South Carolina, Exxon, Global CCS Institute, Trillium CNG, and DOE. The workshop focused on three market sectors: Transportation, Chemical Synthesis, and Stationary Energy Generation. The first day of the workshop comprised keynote presentations and panel discussions with invited speakers who provided answers to questions concerning technical gaps impeding future deployment of natural gas. The agenda on the following day was comprised of three break-out sessions, one for each technical topic, in which the experts and interested participants discussed the previous day’s talks and addressed specific questions developed to identify the remaining technical gaps and the role of government in helping industry close them. This report provides a summary of the workshop and the break-out session results for each of the three market sectors. This document is provides input for a technical roadmap to more effectively utilize the abundant natural gas currently available in the U.S. market.

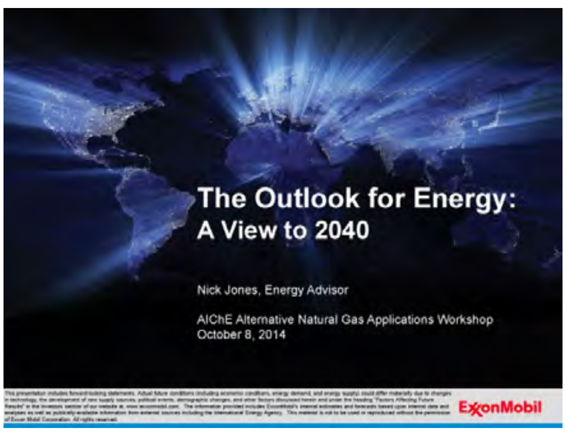
The workshop program book, including the agenda, is in the Appendix A.3. The workshop began with a welcome and presentation of meeting objectives (Appendix

A.4.1) by workshop chairmen Don Anton of Savannah River National Laboratory and Bryan Morreale of NETL. Keynote presentations were provided by Nick Jones (Exxon), Monty Alger (Penn State), and Frank O'Sullivan (MIT). Workshop participants are listed in Appendix A.1.

## 2.1 Keynote Presentations

### 2.1.1 Nick Jones

Nick Jones, an Exxon Energy Advisor, presented "The Outlook for Energy – a View to 2040" (Appendix A.4.2.1), discussing how much energy will be needed, where it will be needed, and the related sources. He stated that efficiency is key to meeting future energy demand and projected that most U.S. growth in natural gas utilization will be in electricity generation.



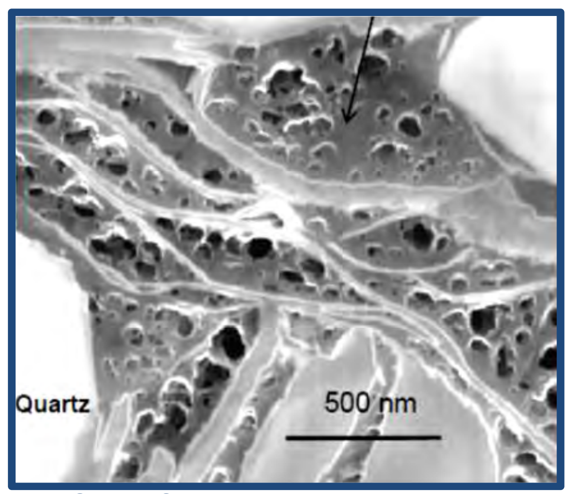

Dr. Jones pointed out that NG fuel cost savings for transportation are exceeded by increased vehicle costs, but are nearly equal to that of heavy transportation, and the key issue for transportation is the fueling infrastructure. Because of high investment, NG is expected to be sold under long-term contracts versus highly variable spot markets.

### 2.1.2 Monty Alger

Monty Alger, director of the Institute for Natural Gas Research at Penn State University, presented (Appendix A.4.2.2) a perspective on market data, technology, and policy related to the increased availability of natural gas. He encouraged investment in projects with direct financial return including power generation, novel supply chain investments, and residential and industrial conversion. Dr. Alger also pointed out risks associated with the unknown, including the long-term price of natural gas, regulation of emissions and water usage, and high capital risk. He identified needs for coordinated supply chains; transportation fuel infrastructure; and technologies to produce gas to liquid fuels, hydrogen, compressed natural gas, liquid natural gas, and dimethyl ether.

### 2.1.3 Frank O'Sullivan

Frank O'Sullivan of MIT presented "U.S. Natural Gas – A Decade of Change and the Emergence of the Gas-Centric Future" (Appendix A.4.2.3). Dr. O'Sullivan stated that unconventional natural gas and oil have fundamentally altered our perspective on supply and price. (Natural gas produced from shale now represents 50 percent of U.S. NG production). He also said that we do not fully understand the physics of shale gas production and projected that NG will dominate the building of fossil units going forward due to carbon limits.




Pore Size in Shale

## 2.2 Panel Discussions

Panel discussions were conducted for each of the three workshop focus areas. Industry experts provided related perspectives then discussed specific questions of interest.

### 2.2.1 Stationary Energy Generation

The stationary energy panel leader was Professor Kevin Huang from the University of South Carolina. Panelists were Michael F. Carolan (Air Products), Bill Day (Gas Turbine Association), Ron Munson (Global CCS Institute) and Pinakin Patel (FuelCell Energy). Related presentations are provided in Appendix A.4.3.1.

### 2.2.2 Transportation Energy Generation

Dr. Donald Anton of Savannah River National Laboratory led the Transportation discussion which opened with a featured speaker, Ruben Sarkar from the Department of Energy. Panelists included Allen Aradi (Shell), Dan Bowerson (Chrysler), William Chernicoff (Toyota), Jim Coleman (Ford), Joseph Rende (Trillium CNG), and Ned Stetson and Kevin Stork (U.S. DOE). Presentations given during this discussion are presented in Appendix A.4.3.2.

### 2.2.3 Chemical Synthesis

Dr. Bryan Morreale of the National Energy Technology Laboratory led the Chemical Synthesis panel discussion. A featured speaker presentation was provided by Billy Bardin (Dow Chemical Company). Panelists were Paul Barger (UOP-Honeywell), Jan Boshoff (Sasol), Peter Dias (Braskem), Joe Fox (Ashland), Mike Gallagher (Bayer), Jonathan McConnachie (Exxon), and Brien Stears (Dow Chemical Company).

# 3. Round Table Discussions

The second day of the workshop consisted of roundtable discussions in each of the three focus areas. Prior to the workshop, participants were provided with questionnaires (see Appendix A.2) covering topics of interest. These questionnaires were also used to guide the round table discussions.

## 3.1 Stationary Energy Generation

The focus of the Stationary Energy Generation workshop session was to identify opportunities to better utilize natural gas feedstock to decrease dependence on conventional centralized power generation technologies that could also potentially reduce grid vulnerabilities, increase renewables integration while significantly lowering GHG emissions. Summary slides presented by the Stationary Energy Generation Round Table group are in Appendix A.4.4.1.

### 3.1.1 Areas for Expansion

Areas for expansion in stationary power include gas turbines and fuel cells which are complementary versus competing technologies. These two sectors are advancing on different time scales. The gas turbine industry is established, and will grow from a large base, while the stationary fuel cell industry is not as established and will grow slowly given appropriate economic conditions. The capital invested in gas turbine infrastructure precludes easy replacement of gas turbines with fuel cells. The size of installation makes a great difference as well in terms of how gas turbines compete with fuel cells (smaller applications) because fuel cells are very efficient at small sizes and right sized for DG applications.

The increased supply of domestic natural gas has greatly advanced the U.S. manufacture of gas turbines. However, maintaining or increasing these gains will require a substantial investment in associated R&D. The major variable is U.S. government support of increased R&D funding. If it does not happen, the share of the Natural Gas Combined Cycle market filled by US-based manufacturers is projected to drop from the current 84 percent to 42 percent by 2037 with 36,000 fewer U.S. jobs by 2035. One area of recommended research is improved efficiency for combined cycles.

Reliable and resilient distributed power generation is an emerging market where NG has a demonstrated advantage for use as clean fuel. Technologies such as SOFC can efficiently utilize NG in CHP and electricity generation at scales ranging from small commercial to large distributed generation.


**Siemens/Westinghouse 220 kWe Pressurized SOFC/GAS Turbine Hybrid System**

Cross-cutting areas of expansion, including CHP and Polygen (where products, in addition to electric power, are produced), were also identified. Polygen includes production of oxygen plus power, production of $CO_2$ for enhanced oil recovery plus power, and production of hydrogen plus power and $CO_2$.

### 3.1.2 Major Players

The major commercial players in this section are not meant to be a comprehensive listing, but only a general characterization of the current market. More comprehensive and current listings of vehicle manufacturers and users can be found at industrial organizations such as Gas Turbine Association, American Gas Association, or the Fuel Cell and Hydrogen Energy Association.

**For NG Turbines:**

- The major players in NGCCs are US-based manufacturers GE, Siemens and Alstom; and Japanese supplier Mitsubishi Heavy Industries (MHI). For smaller gas turbines (< 5-10 $MW_{th}$) which are often used in simple cycle or combined heat & power applications the major players are GE, Rolls-Royce, Solar Turbines (part of Caterpillar) and PW Power Systems (part of MHI).

**For Fuel Cells:**

- Bloom Energy, FuelCell Energy, LG Fuel Cell and GE Fuel Cells

**CCS:**

- Mitsubishi and Cansolv

**Polygen Suppliers:**

- Air Products; Praxair

### 3.1.3 Regulatory and Policy Barriers

Greenhouse gas mitigation is an important factor in the future growth of the NG for stationary energy generation. Current proposed regulations do not recognize the advantages NG generation, but if GHG mitigation goals are to be reached, eventually, regulations will require mitigation through NG-fired sources. The interim period where NG is not subject to GHG regulations provides an ideal time for R&D targeted at reducing costs for carbon capture, utilization, and storage so that industry will be ready to comply once regulations are introduced. This is a persistent problem and the cost of solving it will only increase over time.

Current state regulations and policies make it difficult to connect CHP to the utility grid and should encourage and/or incentivize utilities to invest in or support CHP. State-wide energy efficiency goals or air emissions regulations coupled with monetizing the CHP benefit could drive the adoption of CHP while reducing the costs for the customer.

### 3.1.4 Technical Barriers

Major technical barriers related to NG turbines are combustion, heat transfer, and materials for thermal coatings. The overall efficiency goal requires addressing all three barriers.

Technical gaps for fuel cells include (1) deployment of clean and efficient energy conversion systems such as SOFCs, (2) development and deployment of OTM, and (3) reclamation of water used during NG extraction. Technology development areas include functional ceramics and membranes, catalysts, and robust filtration processes.

Another barrier is the lack of low cost carbon capture. DOE is actively funding coal-focused CCS R&D but should consider funding natural gas-focused CCS R&D to overcome differences in flue gas content. Demonstration would alleviate some of the risks associated with the technology.

Primary technical gaps in terms of GHG mitigation involve development of cost-effective capture technologies that have been demonstrated at scale. (Cost and energy penalty associated with carbon capture). Cost targets for 2025 $40/tonne. (Cost is based on the use of the $CO_2$ being enhanced oil recovery but not really understanding the market value).

Demonstration would alleviate some of the risks associated with the technology. Fuel cells can produce quality $CO_2$ streams but that needs to be proven so demonstration could benefit technology. DOE goal is 90% $CO_2$ with no increase in COE greater than 30%. Current technology requires 1/3 of energy for $CO_2$ extraction/separation with greater than 80% increase in COE.

The top three technical priorities were considered to be:

1. Develop more efficient NG systems for gas turbines and fuel cells with a 20 percent advantage (capital expense and operating expense) over competing technologies
2. Develop cost-effective strategies for greenhouse gas reduction specific to NG utilization with parallel regulatory targets
3. Emphasize parallel and complementary technologies such as thermal barrier coatings and membranes

### 3.1.5 Needed Science or Engineering Research and Development

The workshop also identified programs that should be expanded to address the technical gaps. The Gas Turbine Association pointed out that the Tonko Bill would provide funding sufficient to enable 64 percent of U.S.-based NGCCs to go on line by 2022 and 67 percent by 2027. This House bill was introduced in November 2013 and will be reintroduced with the next congress requesting $50MM/yr. for 7 years ($350MM total), which would support major component testing.

Viable solutions are needed to extend the lifetime and reduce the materials and manufacturing costs of fuel cells; for example, a SECA Core Program – basic research to understand ceramic membrane structural changes.

Commercialization of the technology is currently in sync with the national emphasis on enhancing manufacturing ability and increasing employment.

Cross-cutting R&D should focus on integrated basic science programs developed to understand thermal barrier coatings and high-temperature materials. These technologies are complimentary in nature, so integrated research is required.

A CCS R&D program is needed to develop capture technologies specific to natural gas-fired systems. This program should be focused on accelerating the development of technologies tailored to the unique characteristics of natural gas derived flue gases such as lower $CO_2$ concentrations and lower contaminant concentrations.

The need to extend life-cycle analyses for NG utilization technologies is critical. For example, studies on the energy-water nexus need to show how NG utilization for stationary power generation affects water utilization.

### 3.1.6 Suggested Role of Government

DOE Fossil Energy Program and NETL would be the government facilitating office in the proposed Tonko Bill which would address the R&D needs of the gas turbine technologies.

The government should continue to support development of programs to attack the key technical problems associated with implementing fuel cell technology in next-generation systems. These programs should fund R&D beyond the near-term vision (i.e., 5 year horizon) along with demonstration projects for efficient and cost- effective NG utilization for stationary applications. An example for Polygen is to gain market confidence and acceptance and de-carbonized fuel demonstration projects.

Public–private partnerships under the guidance of federal/ state government, university research and industrial participation at the R&D and demonstration level should be examined. National laboratories will play key roles in developing big science and engineered systems for accelerating deployment.

**Fuel Cells and Hydrogen for Greater Sustainability Using Natural Gas**

### 3.1.7 Metrics

Stationary power programs for natural gas should develop and demonstrate cost-effective GHG reduction strategies related to NG Stationary Power Generation for all technologies with parallel targets for reduction over time. A goal could be to demonstrate a 20 percent improvement (CAPEX and OPEX) over current state of the art, which will enable further capital investment.

## 3.2 Transportation

Even though Natural Gas (NG) accounts for 26% of the total U.S. energy consumption, only about 3% of the NG consumed annually in the U.S. is used for transportation, whereas petroleum accounts for 92% of the energy consumed each year in transportation. By taking advantage of our increased domestic supplies of NG as a transportation fuel, the US could drastically reduce its dependence on imported petroleum. This course of action would not only have the potential economic benefit of creating more U.S. jobs, but also help reduce the trade deficit and enhance overall national energy security. Summary slides presented by the Transportation round table group are in Appendix A.4.4.2.


### 3.2.1 Current Uses

Natural gas fueled vehicles today are primarily heavy duty trucks where the current low cost of fuel justifies the investment to modify the engine to efficiently utilize natural gas. Refueling can be accomplished either at a fleet refueling site or at strategically located interstate refueling sites which form transportation corridors.

### 3.2.2 Potential Areas of Expansion

The fastest growing NG Transportation market is direct fueling for Heavy Duty (HD) and Medium Duty (MD) Trucks, Buses, and commercial fleets. Below are projections for the near-term NG vehicle market:

- HD Class 8 – largest use (10% of HD sales by 2020)
- Refuse Haulers = 40-50% of new sales

- Transit (Buses) = 30-40% of new sales
- Light Duty (LD) Commercial: no current market (5 to 10+ yrs.)
- LD Fleets/Taxis: have good potential for continued growth.

Even though Light-Duty (LD) vehicles make up approximately 60% of the total vehicle market, natural gas penetration will be slow except in certain fleet vehicle applications. This is due primarily to a lack of refueling infrastructure and the volume of CNG storage in smaller vehicles. Automotive OEMs mostly rely on 2nd tier manufacturers and qualified vehicle modifiers (QVM) to provide small quantities of NG vehicles, mostly to fleet operators.

The market for HD/MD vehicles, which represent 22% of the vehicle market, is different. This is the fastest growing sector for NG use and is expected to grow from 30 bcf on gas consumed in 2012 to 850 bcf by 2040.

Other areas of future expansion are in Marine, Rail and Mining Operations. Diesel exhaust regulations, especially near metro area has allowed several NG niche applications such as fishing and tug boat fuels to gain some traction along with shipping terminal cargo moving vehicles.

The pathways identified in this workshop for enhancing the use of NG as a transportation fuel include development of the following technologies:

- Direct Fuel (CNG, LNG)
- NG to Electricity (Battery Electric Vehicles – BEV)
- NG to Hydrogen (H2 Fuel Cell Vehicles – H2 FCV)
- NG to Liquid Fuels (ICE and Hybrids).

### 3.2.3 Major Players

The major commercial players in this section are not meant to be a comprehensive listing, but only a general characterization of the current market. More comprehensive and current listings of vehicle manufacturers and users can be found at such industrial organizations such as Natural Gas Vehicles America, NGVA.

- Commercial Heavy Duty Vehicle markets include: OEMs like PACAR, Daimler, International, and Volvo; qualified vehicle modifiers (QVM) including BAF, IMPCO, Westport and Landi; and commercial customers as well as shippers such as Swift, UPS, Frito Lay, P&G, and J.B. Hunt.
- The Mid Duty Vehicle market includes automotive OEMs such as Ford and GM who market primarily through QVMs. Customers for Mid Duty are composed mostly of fleet vehicles such as refuse companies (*e.g.* Waste Management) and municipal transit markets in areas in New York; Washington, DC; Richmond, VA(?); and Cleveland, OH(?).
- Light Duty Vehicles, also run through fleet operations, are supplied by Honda, Chrysler with GM, and Ford through QVMs.
- NG Suppliers include: Shell, Exxon, Chevron, BP, and NG Utilities such as Atlanta Gas Light and Southern California Gas Company.
- NG Fueling Station Investors include: Trillium CNG, TruStar Energy, Clean Energy, and ANGI International

### 3.2.4 Technical and Regulatory Barriers (Regulatory and Externalities)

The major difficulties affecting the use of NG in transportation include a combination of regulatory and technical issues. Some of the regulatory issues involve inconsistent taxes and credits for NG use at the local, state, and national levels, while others involve inconsistent regional refueling and infrastructure standards. The unavailability of NG refueling stations continues to be an obstacle, with only about 750 CNG and 65 LNG stations currently in the U.S., compared to over 150,000 gasoline stations. The cost discrepancy between LNG and CNG is another issue. LNG not only has higher associated processing and delivery costs but also is often taxed at higher rate based on being a liquid fuel. In addition, NG's lower combustion efficiency and the much lower volumetric energy density (compared to gasoline) are major issues for LD vehicles.

### 3.2.5 Magnitude of Technical Gaps

The top technical gaps for NG utilization in vehicles revolve around:

- Compact, lower cost, and more efficient on-board storage
- Improved fuel economy and engine efficiencies
- Lower cost and higher rate refueling stations

### 3.2.6 Level of Technical Gap Impact

The near-term impact of the technical gaps is believed to be small compared to the impact of inconsistent state and federal regulatory policies. However, in the long-term improving both the storage and engine efficiency of NG HD and MD vehicles will be critical if NG will eventually supplant today's diesel fleets. Technology improvements to improve the delivery rate and cost of NG refueling stations to match the current expectations from diesel stations will also be needed.

### 3.2.7 Role of Government

The major roles by the government in transportation include: 1) developing consistent federal and state policies for NG as a transportation fuel, 2) using the National Labs (NLs) to help provide data to support good market driven decisions, and 3) using the NLs, Universities, and Industry to help address and overcome the technical gaps, both for the short- and long-term.

### 3.2.8 Priority of Technical Gaps

Some of the goals and challenges related to the technical gaps involve the following:

- NG Storage
  - Develop lower cost composite tanks and tank materials
  - Pursue conformable tanks, with absorbent/low-pressure technology
- Engine Technology
  - Develop higher temperature materials/lubricants
  - Examine new ignition technologies (lean burn technologies, methane oxidation catalyst, RCCI, adaptive controls, dual and tri-fuel engines)
- Infrastructure
  - Pursue lower cost, higher efficiency compressors
  - Examine faster fill options, including heat of compression dissipation designs
  - Evaluate home refueling options

### 3.2.9 Metrics

The National Energy Goals and Climate Action Plan call for a 50% reduction in oil imports and 17% reduction in GHG emissions by 2020. Natural gas as a transitional fuel can play a major role in helping to achieve these targets either by direct use or by transformation to hydrogen, electricity or a higher energy liquid fuel.

## 3.3 Chemical Synthesis

The focus of the Chemical Synthesis and Utilization workshop session was to identify opportunities to better utilize natural gas feedstock to decrease dependence on conventional petrochemical routes toward the development of a variety of beneficial end use products. Summary slides presented by the Chemical Synthesis Roundtable group are in Appendix A.4.4.3.

### 3.3.1 Current Uses

Low domestic natural gas (NG) prices have prompted U.S. producers to consider “wet” gas reserves in an effort to capitalize on an emerging energy and feedstock sources and maximize profits. During this time, crude oil refining has been relatively flat while natural gas processing plants have accounted for an increase in nearly 75 percent of NGL production from 2008 to 2014. NG production trends have resulted in a surplus of ethane, while petrochemical refining trends have resulted in shortages of propylene, butadiene, aromatics, and pentanes.

***The current pathways for NG use in chemical synthesis and utilization include:***

- Continued dominance of ethane cracking.
- Maturation of technologies focused on the production of propylene, butadiene, and aromatics through affordable NG.

***What will success look like three years from now?***

- Successfully scaled pilots of one-to-three economically viable processes.
- A prioritized research agenda for federal resources in which research efforts could have the greatest impact. Also, development of a timeline and identification of steps to accomplish the plan.
- Concrete DOE policies for supporting R&D to enable further/broader utilization of NG in the chemical industry.

### 3.3.2 Potential Areas of Expansion

The fastest growing NG chemical synthesis and utilization market is the downstream derivatives sector. Global demand for ethylene and propylene is expected to increase at five percent per year. Market segments for “on purpose” manufacturing of C3+ hydrocarbons are projected to fill the gaps developed from steam cracking of ethane. Areas of consideration for technological expansion that would further the chemical synthesis and utilization sector are as follows:

- New chemical routes/processes focused on direct conversion to desired products (i.e., direct conversion of methane to methanol).
- New separation technologies circumventing conventional, energy intensive distillation processes (i.e., membranes).

***What is the value proposition in capitalizing on NG?***

- Profound economic development with renewed U.S. manufacturing of durable goods, packaging, pipes, nonwoven fibers, etc., based on polymers derived from NGLs.
- U.S. energy security with geopolitical benefits.
- Economic security for future generations.
- A return to a manufacturing-based economy that provides good paying jobs and a strong service sector that provides services to manufacturers.

### 3.3.3 Major Players

The entire value chain, from resource production through final product sales, can benefit from a robust downstream market capable of consuming NG at rates consistent with production.

- Producers (ExxonMobil, Chesapeake Energy, Anadarko)
- U.S. gas processors (Spectra Energy Corporation, Enterprise Products Partners LP, ExxonMobil, Targa Resources Partners, and Williams Partners LP) operate over 530 processing units.
- Transportation, storage, and fractioners (Kinder Morgan, Dow, Formosa, Shell, Chevron)
- Petrochemical derivatives sector (MarkWest, Braskem, Dow, Chevron,

Oneok, Bayer, Ashland, and multiple others)

- Catalysts and alternative methods (UOP/Honeywell, BASF, JM, INEOS, Sasol, Siluria)

**Megawatt-class Distributed power Generation Solutions**

### 3.3.4 Technical and Regulatory Barriers (Regulatory and Externalities)

The major obstacles affecting the use of NG as a source for chemical feedstocks include a combination of regulatory and technical concerns.

***The regulatory barriers***

- Streamlining the regulatory process
- Developing a rationalized regulatory framework including a comprehensive energy policy

***What are the largest technical roadblocks?***

- 5 Years
    - Selective C-H bond deviation
    - Capital cost reduction for syngas production
    - Selective building of C-C bonds
    - Membrane-based separations
- 20 Years
    - (Direct) catalytic conversion of C1-C2 (non-syngas routes)
    - Selective methane activation (C-H bond)
    - Development of cost-effective high-temperature materials (>1300°C) enabling CH4 pyrolysis.

### 3.3.5 Magnitude of Technical Gaps

Successful development of a robust downstream NG market is hindered by several technical gaps. Some of the most significant technical gaps for NG chemical synthesis identified by industry leaders revolve around:

- Efficient separation technologies for intensive distillation processes.
- Direct, selective conversion of NG.
- Process intensification.
- The challenges of building small chemical production facilities due to the lack of market demand for stable end products.
- The potential of biological, electrochemical, and several other processes to disrupt this environment.
- A need for better project economics – capital costs to build NG chemical synthesis facilities are too high (typically a 30 to 50 year investment). For example, $10B is needed to convert an existing facility, and between $20B and $25B is needed to build a new plant. Financing these projects is very difficult.
- Completion of a (cradle to grave) life-cycle assessment when developing a project.
- NG chemical facilities require a larger footprint than conventional crude oil facilities.

- High investment risks (both financial and technical) are incurred by the developer. A means of reducing investor risks must be found.
- Quantifying the impact of siting projects (near well head versus near marketplace or transportation hub).
- The industry needs to analyze the economic benefits of building small versus large plants (scalability).
- Improving efficiencies throughout the process is critical for obtaining technology breakthroughs.
- Need to explore private/public partnerships. Industry no longer has the resources to conduct all of the research.
- The development of qualified personnel to support R&D efforts in this area can be a constraining factor. The education of new scientists in this area is a prerequisite for greater global competitiveness.

### 3.3.6 Level of Technical Gap Impact

The technical gaps are being reduced in the near term because the United States is currently one of the lowest cost producers of NG. In addition, several new NG processing plants (feedstock and product driven) are expected to come online over the next five years, increasing overall U.S. capacity. Longer-term goals may include building larger plants to produce durable goods such as polystyrene, polypropylene, and polyethylene, and expanding into the international space by exporting more products abroad. Successful development of new technologies to improve overall plant operating efficiencies will require significant R&D. A deeper investigation of infrastructure and plant operation improvements may also be warranted. The industry goal is to drive down the costs to build new plants and stabilize the demand for end products. The ultimate goals are to decrease consumer costs over time and achieve greater U.S. energy independence.

***How do you see low-cost NG impacting future chemical/synfuels production?***

- 5 Years
  - Displacement of oil–based polymers by NG-based polymers.
  - No immediate impact (NG will continue to replace coal).
  - Build chemical plants (abundance of construction jobs and more capital expense).
- 10 Years
  - R&D for technology to use C1 fraction is complete, awaiting commercial demonstration (valley of death).
  - Optimization of newly built facilities based on conventional technologies and complete demonstration of novel methane conversion technology.
  - Chemical Production from NG liquids. Limited synfuel production. Export of some plastic production to areas where naphtha is cracked and cheap raw materials are available.
- 20 years
  - If commercialization of new technology is demonstrated in a 10-year time frame, use it to monetize multiple HC sources. If not, revisit methane activation.
  - Low cost NG: replacement of conventional assets at end-of-life and commercialization of a handful of methane conversation plants.
  - Other regions of the world with shale gas catch up with U.S. expansion of technologies to utilize methane to produce petrochemicals.
  - C1 chemistry has an established niche in markets:
    - Fuel mixture/transport
    - Polyolefin Manufacture
    - Bio-refineries

### 3.3.7 Role (Government Programmatic, Academia, National Laboratory, Industry)

***What are the roles in developing a NG-to-chemicals market?***

- Government Role
  - The development of a roadmap and vision.
  - Act as the steward of a sustainable, long-term effort.
  - Facilitate industry, academia, and national laboratory partnerships.
  - Provide basic R&D funding, workforce development, and rational for a regulatory framework.
  - Focus not on picking winners in the technology game, but to support basic research.
- National Laboratory Role
  - Support the development and scale-up of potential breakthrough technologies that are too risky for industry commercialization.
  - The application of its high performance equipment and people.
- Academic Role
  - Teach the petrochemical value chain and train engineers to work in a manufacturing economy.
    - Twenty percent of the effort would focus on immediate needs, while the other eighty percent on blue sky initiatives.
  - Partner with industry to train the workforce, educate the public, and create an innovative science basis for new hydrocarbon (HC) processes.
  - Develop new concepts, catalysts, and processes for future pilot plants.
  - Apply an emphasis on training researchers, testing new ideas, and "targeted research".
  - Provide workforce development by investing locally and partnering with national laboratories and universities.
- Industry Role
  - Use R&D funding to develop and validate novel technologies that show promise of improving normal feedstock conversion or allow conversion of new feedstocks.
  - Provide opportunities for and invest in demonstration projects that support bridging the academia-to-industry "valley of death."
  - Develop a steering committee.
  - Take advantage of existing technology; develop a technology to bridge the gaps between oil and gas feedstocks.
  - Focus on adding value to NG materials and test the practicality of the ideas.

### 3.3.8 Priority of Technical Gaps

***Some of the goals and challenges related to the technical gaps involve the following:***

- Reducing project complexity.
- Reducing capital costs by innovation (technology as well as infrastructure costs).
- Developing a clear, long-term actionable policy. Inconsistent state and federal regulatory policies are disadvantageous for industry growth.
- Providing better mapping of supply/demand for end use products. The capability to quantify the supply of products is needed. The focus can be on both domestic and international demands.
- Evaluate and better define infrastructure improvements.
- Confirm main project drivers and conduct financial analysis (profits, rate of return, financial pro forma analysis).

***What are the most impactful chemicals to consider for NG conversion technologies?***

- 5 Years
  - Propylene from new PDH plants.
  - Ethylene (5 yr.), Polymers (LLDPE, PP) (5–10yr.).
- 10 Years
  - Researching C1 to C2; C1, C2, C3, to BTX; and C1 to alcohols.
  - Focusing on C3-C4-C5 + BTX derivatives.
  - NG to ethylene and aromatics.
- 20 Years
  - Direct production of polyolefins from NG.
  - Gasoline range alkaline.
  - Methanol – not produced from syngas (using only methane and air) – no air plant, no hydrogen peroxide.
  - Methanol has the potential to be highly effective.

### 3.3.9 Metrics

Natural gas, as a source for chemical feedstock, can play a major role in returning advanced manufacturing to the United States. Meaningful metrics to measure progress toward achieving this goal include:

- Identify the domestic and international costs related to NGLs and subsequent polymer manufacturing/commercialization.
- Consider talent and human capital (schooling and subsequent jobs for chemical engineers and NG skilled technicians).
- Measure sustainability and environmental effects (carbon balance).
- Establish milestones that will demonstrate progress, even without success.

An analysis of the current petrochemical industry should be conducted (baseline the industry) in order to properly measure such metrics. A view of the U.S. current demand for manufactured goods and existing U.S. manufacturing capabilities relative to the manufacturing of imported goods will help identify meaningful data years after the conclusions of this road-mapping effort are published.

***How can public/private partnerships make this happen better/faster?***

- Works Well
  - Collaboratives; R&D programs that help communicate commercial goals and economics across industrial/academic boundaries.
  - Strategic partnerships that utilize the strengths of each institution.
  - All stakeholders have a voice in leading a small, focused team. Developing clearly articulated goals and utilizing a go/no go discussion processes.
  - Clear expectations, honesty and transparency, uninhibited debate, transparent funding, shared funding.
- Does Not Work
  - Large consortium with high membership fees. Limited accountability and a U.N. like governance system.
  - Productivity loss caused by paperwork, proposals, and reviews is a significant drag on R&D.
  - Government initiatives based on political agendas (particularly short-term agendas).

# Appendix

## A.1 Participants

NG Final Registration Formatted.xlsx

## A.2 Summary Questionnaires (3)

NG Chem Syn Questionnaire.docx

NG Utilization Transportation Questionnaire.docx

NG Stationary Energy Generation Questionnaire.docx

## A.3 Program Book

NG Program Book merged v.3.pdf

## A.4 Presentation Materials

### A.4.1 Opening Presentation

NG Opening Presentation 10_8_2014.pdf

### A.4.2 Keynote Presentation Slides

#### A.4.2.1 Nick Jones

[1. Nick Jones] 2014 EO - AIChE Natural Gas Workshop (presentation).pdf

#### A.4.2.2 Monty Alger

[2. Monty Alger] 14-10-06AIChEConference-PresentationFinal.pdf

#### A.4.2.3 Frank O'Sullivan

[3. O'Sullivan] AIChE Natural Gas Workshop Presentation.pdf

### A.4.3 Panel Discussion Slides

#### A.4.3.1 Stationary Energy Generation

Pinakin Patel-AIChE-Alt Nat Gas Oct8-9-2014.pdf

[Carolan] Air Products.pdf

[Day_Bill] AIChE Alternative Natural Gas Applications Workshop 10 08 14.pdf

[Kevin Huang] NG Stationary Power Generation V2.pdf

[Ron Munson] Alternative Natural Gas Applications Workshop - Global CCS Institute.pdf

#### A.4.3.2 Transportation Energy Generation

Transport Panel Intro.pdf

#### A.4.3.3 Chemical Synthesis

### A.4.4 Round Table Summary Slides

#### A.4.4.1 Stationary Power

Stationary Power Gen Roundtable Discussion v2.pptx

#### A.4.4.2 Transportation

Transport Roundtable_Discussion_final.pptx

#### A.4.4.3 Chemical Synthesis

Chemical Synthesis Session (10-09-2014).pptx