NATURAL GAS CONVERSION VS. SYNGAS ROUTES: A FUTURE OF CONVERGENCE

A MULTI-CLIENT STUDY SERIES IN TWO VOLUMES

STUDY PRESENTATION

(Vol. 1: completed October 2014)

(Vol. 2: completed November 2014)

Updated December 2014
(includes TofCs from both Vol. 1 and Vol. 2)

TCGR
THE CATALYST GROUP RESOURCES™

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NATURAL GAS CONVERSION VS. SYNGAS ROUTES: A FUTURE OF CONVERGENCE

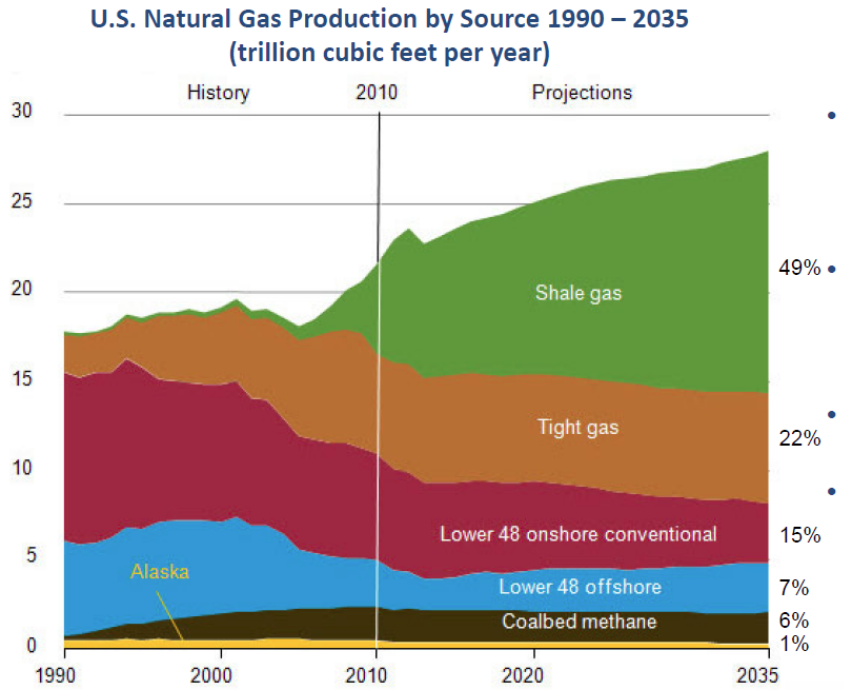
Vol. 1: Natural Gas to Intermediates and Feedstocks to Syngas (completed October 2014)

Vol. 2: Syngas and Natural Gas Conversion to Products (completed November 2014)

I. BACKGROUND

The "revolution" in natural gas (NG) as a result of shale-derived sources has spurred a growing interest in new routes/processes for its conversion to fuels and chemicals, in competition with traditional syngas feedstocks. These include direct/indirect methane conversion, dry reforming and hybrids that are emerging, and indeed converging, to create economic opportunities. Considerable government, academic and industrial R&D investment funding is being channeled into these potential breakthroughs given the tremendous rewards potentially available. As unconventional gas becomes more abundant in China, Eastern Europe and worldwide, the stakes justify a timely and closer look at the scientific and commercial progress as well as competitive and strategic implications.

Figure 1
U.S. Conventional Gas Overview



Source: U.S. Energy Information Administration, Annual Energy Outlook 2012, June 25, 2012.

Adding to this excitement, the potential for pilot and converging science to find new and cheaper routes to olefins and derivatives sets the stage for an interesting competitive future.

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In 2014, TCGR is completing an integrated, strategic technical and commercial assessment of natural gas/C_1 conversion routes with a broadened scope so the impacts of syngas production/conversion routes can be compared. There is no doubt that natural gas routes to a range of intermediates are vying for markets traditionally served by syngas; this "convergence" of feedstocks and routes is worthy of detailed assessment. TCGR is uniquely qualified to assist its subscribers in such an evaluation, whether it is for opportunity identification or threat assessment!

In our study series of two volumes, entitled ***Natural Gas Conversion vs. Syngas Routes: A Future of Convergence,*** TCGR first explores and documents new chemistry and processes involving direct methane conversion to intermediates and products (currently being designed to side-step syngas), as well as progress in reducing the economic cost(s) and GHG/environmental impact of existing, proven technologies. We then assess progress involving natural gas and syngas conversion chemistry and catalysis for the production of intermediates and products, again assessing the costs (energy and other, including CO_2 emissions reductions) relative to existing/proven technologies. Critical in each volume is coverage of the following metrics: commercial status, emerging technologies/catalysts, process licensing and comparative economics, and areas of likely/potential convergence, leading to opportunities and threats.

Serving as the basis for such an assessment, TCGR has utilized the approach and methodology of several critical resources, the first being its comprehensive and detailed two-part benchmarking multi-client study series completed in 2007 entitled "***Syngas Production and Conversion to Products – A Strategic Assessment of the Technologies, Markets and Competitive Landscape."*** This ground-breaking report was the first integrated value chain analysis from feedstock to enduses conducted to our knowledge at that time. It provided a technical/strategic evaluation of routes to syngas and the conversion of syngas to fuels and chemicals. The study scope included gasification of coal, biomass, petcoke/resid, heavy oils and co-feeds, with natural gas (NG) reforming as the benchmark.

TCGR has also benefited from its 2011 multi-client study entitled "***Syngas Production and Conversion to Products – Technology and Commercial Update 2011."*** This update of the 2007 study highlighted what had become most important since the 2007 study's completion and what was expected to become even more important over the period 2011-2015. Additional details on the 2007 report can be found at: www.catalystgrp.com/php/articledetail.php?syngas2007-28; further 2011 study details are available at: www.catalystgrp.com/php/articledetail.php?72.

II. THE NEED FOR THE STUDY

A Future of Convergence…

Innovation is always among the most critical tools for reducing costs while improving margins. Witness the dramatic reduction in ethylene production costs by U.S. chemical manufacturers by switching over to ethane cracking in the last three years, a consequential outcome of the shale gas revolution. With NG abundance now spreading from the U.S. throughout N. America and going international in China, Eastern Europe, and now even the U.K., the opportunity to implement more advanced natural gas conversion process/technologies, in order to take economic advantage of this windfall, is more imperative than ever.

So this poses the following challenge - will the conversion of NG to intermediates and products become cheaper than established syngas routes? Advances in direct NG conversion are emerging from dry reforming, catalytic cracking, oxidative coupling of methane (OCM), catalytic partial oxidation (CPO), etc., and moving beyond R&D into pilot plant development. Witness the increased industrial and government R&D funding, as well as start-ups like Siluria, Carbon Sciences and LanzaTech as well as processes such as Catalyzed-Assisted Manufacture of Olefins or CAMOL (via Quantium Technologies) and

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Advanced Catalytic Olefins or ACO (via SK/KBR), among others. TCGR's study deeply examines this current state-of-the-art (SOA) with its world renowned and leading scientific/commercial Dialog Group® of experts and provides insightful recommendations and conclusions that can help the industry develop unique and profitable pathways forward.

Refiners and energy companies should also take note. If catalytic methane conversion can be advanced practically in the next 5-10 years, then another downstream revolution will emerge! Whether to fuels, chemicals or power (through polygeneration), winners will be in a unique competitive position, challenging cross-industry strategic positions as well. Leaders will also strengthen their global positions in the process, a powerful incentive to participate in this offering.

Based on historical R&D, many believe methane conversion and syngas production are separate and distinct production sciences (i.e., mutually exclusive). There is gathering evidence today that they need not be mutually exclusive, but rather benefit from synergistic science and process engineering convergence. TCGR has shown this same industry trend recently when completing its 2013 multi-client study **Unconventional Catalytic Olefins Production: Commercial Vision and Breakout?** which is receiving growing attention because it challenges the "status quo" thinking. TCGR has a significant track record of providing its customers with powerful breakthroughs in their conventional thinking, allowing them to capitalize on both industry and private advantages (e.g., TCG/TCGR led the industry in characterizing the importance of metallocene and single-site catalytic chemistry for olefin polymerization in the 1980/90's).

Further justification for the study are your organization's specific technical, commercial and competitive/strategic interests. TCGR's multi-client studies are differentiated from others by our working closely with "charter" subscribers (i.e., those that sign-up prior to the study's proposed launch date; see order form) in order to solicit their inputs on scope items of particular importance. This feedback is collected from all "charter" subscribers and incorporated into an expanded and refined Table of Contents (ToC), making the study as valuable as possible.

Lastly, there is a need for this study because it is a timely examination of a large, economically critical opportunity not only for the chemical industry, but for the overall energy industry at large!

This two-part study series, ***"Natural Gas Conversion vs. Syngas Routes: A Future of Convergence,"*** compliments an ongoing portfolio of similarly well-received studies that The Catalyst Group Resources (TCGR) has delivered to clients over recent years. This growing experience demonstrates TCGR's unique capability, resources and expertise to deliver exceptional insight. Past multi-client studies and current membership-directed programs include:

- **Unconventional Catalytic Olefins Production: Commercial Vision And Breakout?** (completed January 2013)
- ***Syngas Production and Conversion to Products – Technology and Commercial Update 2011*** (completed May 2011)
- ***Syngas Production and Conversion to Products – A Strategic Assessment of the Technologies, Markets and Competitive Landscape (Vol.1: Syngas Production Assessment; Vol. 2: Syngas Conversion to Products Assessment)*** *(completed March 2007 and April 2007)*
- ***Carbon Dioxide Capture & Conversion (CO_2CC) Program*** *(ongoing membership-driven program initiated in 2010)*
- ***Catalytic Advances Program, CAP*** *(ongoing membership-driven program initiated in 1995)*

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The value of TCGR's insights comes from nearly 30 years of active participation with leaders in trying to elaborate and define the "key issues for success" based on industrial investment, perspectives and benchmarking developments. We continue to assist our clients through timely information resources. Clients anticipate that when TCG/TCGR offers a study, there is a technology/business opportunity contained therein!

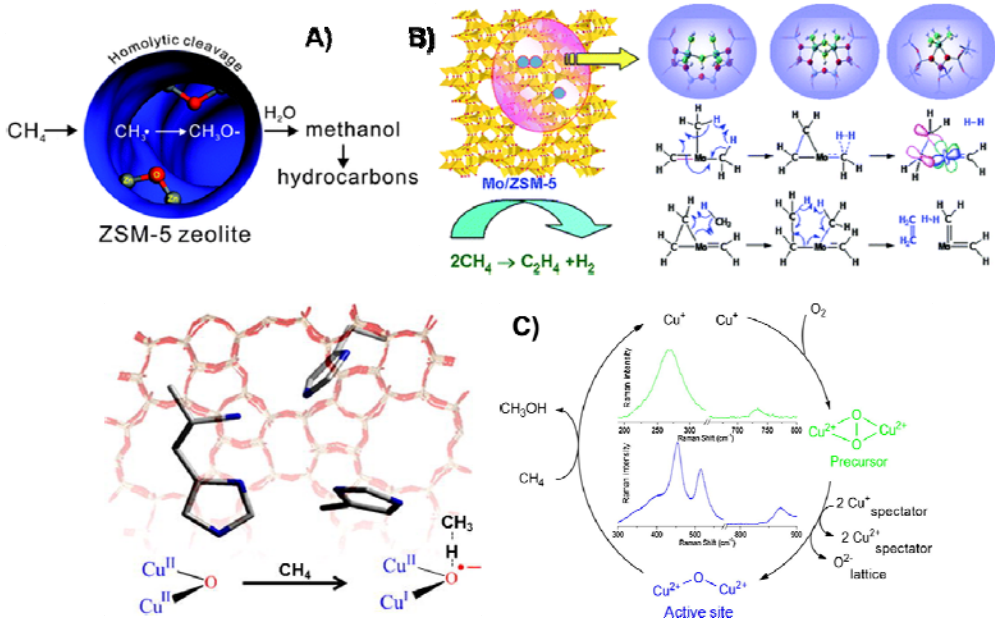
III. SCOPE AND METHODOLOGY

TCGR's two-part study benchmarks, on scientific and techno-economic bases, both direct/indirect natural gas conversion processes against state-of-the-art (SOA) syngas equivalents, with the purpose of providing insightful, timely investment advice in both R&D and commercial directions.

Natural gas (NG) conversion and syngas production/conversion are on converging paths towards lower cost olefins and chemicals. Among the innovations warranting a closer look on their progress include:

- Oxidative coupling of methane (OCM) progress by OCMOL; UNICAT; Siluria Technologies; and Dow.

Figure 2
Examples of Recent Scientific Developments in the Area of Direct Methane Conversion



(A) Room temperature activation of methane over Zn modified H-ZSM-5 zeolites (Xu et al., 2012)). (B) Methane dehydrogenation and coupling to ethylene in Mo/HZSM-5 zeolite catalysts (Zhou et al. (2012). (C) Proposed reaction mechanism and active sites in methane conversion to methanol on Cu-ZSM-5 catalysts.

Source: Vanelderen, P., Hadt, R.G., Smeets, P. J., Solomon, E.I., Schoonheydt, R.A. and Sels, B.F., (2011). Cu-ZSM-5: A biomimetic inorganic model for methane oxidation. J. Catal., 284, 157–164.

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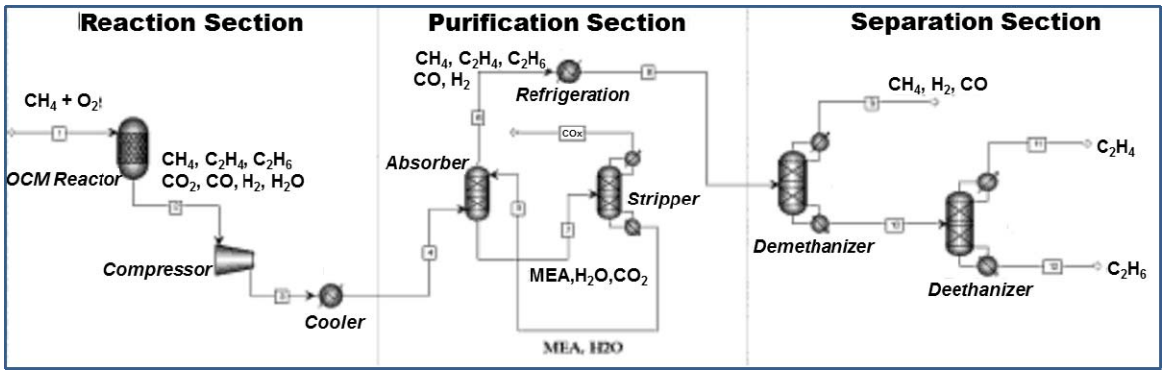
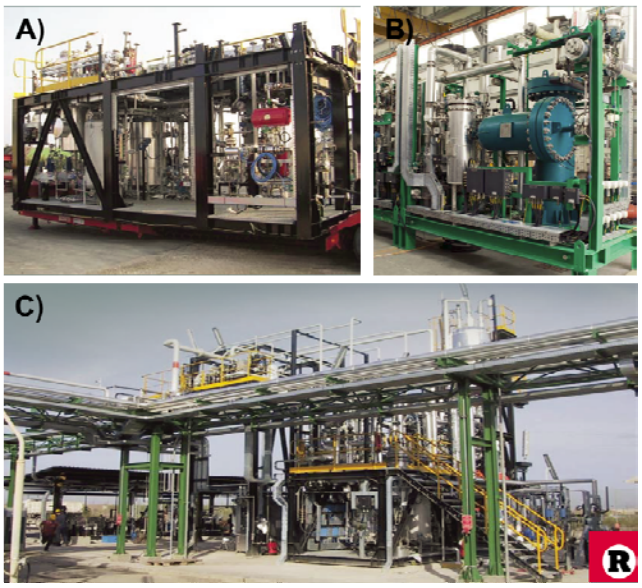
Figure 3
Flowsheet for the Oxidative Coupling of Methane Process



Source: Salerno, D.; Arellano-Garcia, H. and Wozny G. (2012). Techno-Economic Analysis for the Synthesis of Downstream Processes from the Oxidative Coupling of Methane Reaction. Computer Aided Chem. Eng., 31, 410–414.

- Dry reforming by Carbon Sciences, CA; Calcor.
- ENI's CPO technology adaptable from hydrogen.

Figure 4
(A) SCT-CPO Process module (street transportable)
(B) Skid-mounted SCT-CPO Unit (for medium-small hydrogen consumer)
(C) SCT-CPO pilot plant for industrial hydrogen production (99.999%)



Source: Rosetti company web site. http://www.rosetti.it/fileadmin/docs/Tecnoloy/ ROSETTI_hydrogen-A4.pdf.

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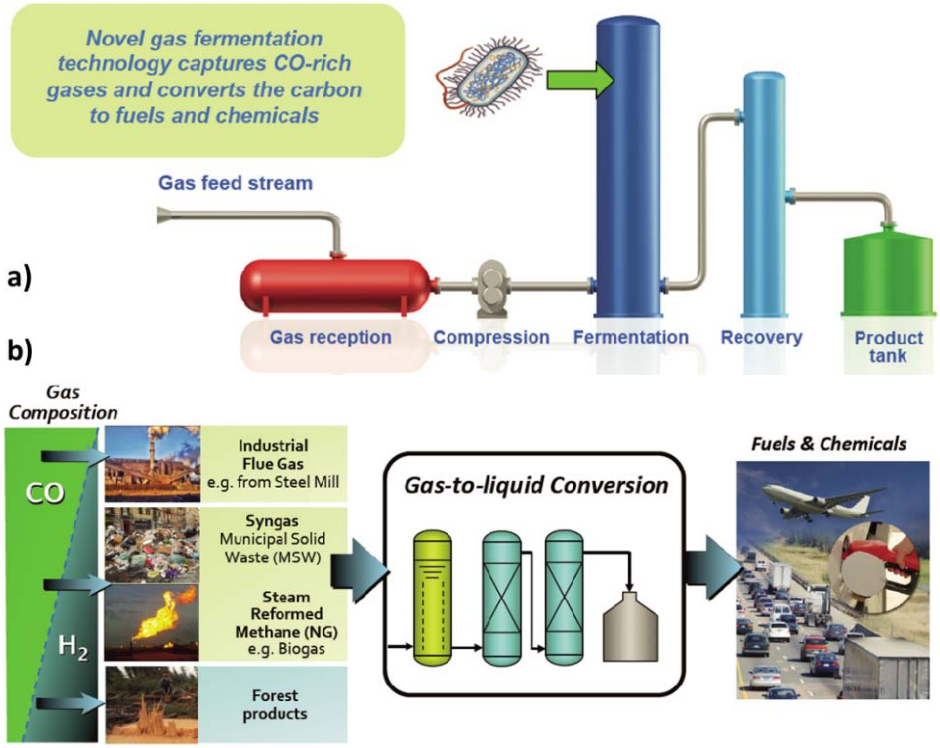
- Synfuels gas-to-ethylene (GTE) via hydrogenation of acetylene.
- Quantium Technologies, Canada, with BASF and IRAP e.g. CAMOL and more advanced research in catalytic olefins.
- BP and Celanese developments in direct acetyls insitu conversion to alcohols and acids. BP's ethanol to ethylene Hummingbird® and SaaBre® acetic acid routes.
- Advanced gasification to syngas approaches e.g. Rocketdyne, Bluegas.
- Off-gases to olefins and alcohols via bio-routes e.g. LanzaTech.
- Methane pyrolysis.

Figure 5
(a) Basic scheme of the Lanzatech process (waste gas to ethanol) to produce alcohols from CO-rich sources (steel mill). (b) Extension of the process to use a broad range of CO:H_2 ratios (from different sources) and downstream upgrading catalytic processes to produce drop-in hydrocarbon fuels



Source: Harmon, L. (2011). Hybrid routes to fuels and chemicals. Presented at Biomass 2011 (National Harbor, MD - US, July 2011). http://www1.eere.energy.gov/biomass/ pdfs/bio2011_harmon_2-1.pdf.

- Mixed olefin/alcohol processes, Matric and Sinopec.

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Vol. 1: Natural Gas to Intermediates and Feedstocks to Syngas

In Volume 1, completed in October 2014, TCGR addresses the commercial and technical progress in direct/indirect natural gas conversion, including definition of the state-of-the-art (SOA). This is compared against advances in syngas routes via reforming and gasification, with comparative advantage/disadvantages noted. The major changes that are occurring involve new more advanced catalysis, but also new engineering designs that increase energy efficiency and reduce GHG production. In the latter, isothermal and microreactors are typical examples. In catalysis, we are seeing heterogeneous zeolite and homogeneous lower temperature organometallic approaches chasing new chemistries.

Vol. 2: Syngas and Natural Gas Conversion to Products

In Volume 2, completed in November 2014, TCGR focuses on the conversion to olefins from methanol and oligomerization technologies to fuels, as well as syngas to chemicals. Specific report contents uniquely explore methane pyrolysis as well as methane and offgases to mixed alcohols from both heterogeneous catalytic and biological routes, e.g. LanzaTech. Coverage also includes an update on energy efficiency, regulatory and environmental economic impacts.

All TCGR studies are characterized by competitive and strategic insights for industrial and financial investment companies to evaluate. These include key trends, concerns, conclusions on the best ROI actions, competitive expectations and strategic SWOT's on the players. TCGR is noted for its sound strategic advice in over 30 years of experience.

For those that understand and appreciate this study undertaking, you will know how important and critically timely this evaluation is! We are standing at a critical crossroads as it pertains to natural gas conversion and syngas production/utilization. The next five years are certain to be telling. Thus, TCGR's study - a comprehensive assessment of their "convergence" - is warranted.

As noted earlier, TCGR has sought substantial input from "charter" subscribers to help shape the final ToCs for both Vol. 1 and Vol. 2 so that they cover and emphasize the most pertinent content due to the large volume of research and the numerous areas that might be of interest.

For details on the breadth and depth of coverage, the actual Vol. 1 Table of Contents appears on pp. 11-18; the actual Vol. 2 Table of Contents appears on pp. 19-27.

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IV. QUALIFICATIONS

The Catalyst Group Resources, a member of The Catalyst Group, works with clients to develop sustainable competitive advantage in technology-driven industries such as chemicals, refining, petrochemicals, polymers, specialty/fine chemicals, biotechnology, pharmaceuticals, and environmental protection. We provide concrete proven solutions based on our understanding of how technology impacts business.

Using our in-depth knowledge of molecular structures, process systems, and commercial applications, we offer a unique combination of business solutions and technology skills through a range of client-focused services. Often working as a member of our clients' planning teams, we combine our knowledge of cutting-edge technology with commercial expertise to:

- Define the business and commercial impacts of leading-edge technologies
- Develop technology strategies that support business objectives.
- Assess technology options through strategy development, including:
  - Independent appraisals and valuations of technology/potential
  - Acquisition consulting, planning and due diligence
- Provide leading-edge financial methodology for shareholder value creation
- Lead and/or manage client-sponsored R&D programs targeted through our opportunity identification process.
- Provide leading information and knowledge through:
  - World-class seminars, conferences and courses
  - Timely technical publications

The client-confidential assignments conducted by The Catalyst Group include projects in:

- Reinventing R&D pipelines
- Technology alliances
- Technology acquisition
- Market strategy

We have built our consulting practice on long-term client relationships, dedication, and integrity. Our philosophy is clear and focused:

We Provide the "Catalysts" for Business Growth by Linking Technology and Leading-Edge Business Practices to Market Opportunities

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V. DELIVERABLES & PRICING

This two-part report series is timely and strategically important to those industry participants and observers considering investment, as well as to process technology companies evaluating natural gas/methane conversion and/or syngas production/utilization. TCGR's report, based on technology evaluations, market assessments and interviews with key players will go beyond public domain information. As a result, subscribers are requested to sign a company secrecy agreement (as part of the "Order Form and Secrecy Agreement" on the following page).

The study series, entitled ***Natural Gas Conversion vs. Syngas Routes: A Future of Convergence,*** is being produced during the third and fourth quarter of 2014, with both Vol. 1 and Vol. 2 available to subscribers.

Participation	Deadline	Price
Post-Production Subscriber		
Vol.1: Natural Gas to Intermediates and Feedstocks to Syngas		$24,000
Vol. 2: Syngas and Natural Gas Conversion to Products/Fuels		$20,000
Both Vol. 1 and Vol. 2		$38,000
Report in PDF format (each Volume), in addition to subscription price		$ 1,000

Notice to Subscribers of TCGR's 2011 and/or 2007
***Syngas Production/Conversion* Multi-Client Studies**

Due to the complementary nature of this study to the 2007 and 2011 studies, we are offering a discounted price to subscribers of those reports. Subscribers are requested to contact John J. Murphy at +1.215.628.4447, or John.J.Murphy@catalystgrp.com for further details. When completing the order form, please make sure to indicate your company's subscription to either/both of the ***Syngas Production/Conversion*** *studies.*

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Please enter our order for ***Natural Gas Conversion vs. Syngas Routes: A Future of Convergence,*** completed in a two Volume series in October 2014 (Vol. 1) and November 2014 (Vol. 2), as follows:

Post-Production Subscriber		**Price**
_____	Volume 1: Natural Gas to Intermediates and Feedstocks to Syngas	$24,000
_____	Volume 2: Syngas and Natural Gas Conversion to Products/Fuels	$20,000
_____	Vol. 1 and Vol. 2	$38,000

_____ Please enter our order for the study in PDF (Adobe Acrobat) format for use across our sites/locations (i.e., site license) for an additional $1,000 (each Volume).

_____ Please send us _____ additional printed copies @ $250 each.

_____ * * * We are subscribers to either/both of TCGR's 2007 and/or 2011 multi-client studies addressing ***Syngas Production/Conversion*** and are therefore entitled to the discounted subscription rate. * * *

In signing this order form our company agrees to hold this report(s) confidential and not make them available to subsidiaries unless a controlling interest (>50%) exists.

Signature: _____ Date:_____

Name: _____ Title: _____

Company: _____

Billing Address: _____

Shipping Address (no P.O. Boxes): _____

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Express delivery services will not deliver to P.O. Boxes

City: _____ State/Country: _____

Zip/Postal Code: _____ Phone: _____

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Natural Gas Conversion vs. Syngas Routes: A Future of Convergence

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Vol. 1: Natural Gas to Intermediates and Feedstocks to Syngas

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FIGURES

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Natural Gas Conversion vs. Syngas Routes: A Future of Convergence

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Vol. 2: Syngas and Natural Gas Conversion to Products/Fuels

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