UNCONVENTIONAL CATALYTIC OLEFINS PRODUCTION II: TECHNOLOGICAL EVALUATION AND COMMERCIAL ASSESSMENT – 2021

UPDATED MULTI-CLIENT STUDY PROPOSAL

July 2021

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This TCGR multi-client study was launched in June 2021 and is slated for completion in October 2021. The study's scope, and specific contents (as depicted in the TofC on pages 10-11 of this updated proposal) reflect the inputs from a group of "charter" subscribers who have indicated their priorities for coverage, areas to be expanded/deepened and focal points for emphasis. These are leading industrial developers, suppliers, and end-users of olefin production technologies.

I. ABSTRACT

The focus of recent R&D for novel processes and catalysts for olefins production goes well beyond traditional thermal steam cracking, fluid catalytic cracking (FCC) and propane dehydrogenation (PDH) routes, to include "green" and circular approaches. Efforts also must address the critical factors affecting technology viability, including CO2 footprint, lifecycle analysis and overall sustainability in a move towards NetZero2050.

Lying at the very center of the petrochemical industry is the production of olefins - ethylene and propylene - which contribute not only to a host of other commodity and building-block chemicals, but to so many of the products and essential parts of daily life for consumers all over the world. As we enter this new decade, refiners and petrochemical companies will see demand for fuels, petrochemical intermediates, plastics/rubbers, and other products change, while calls for increased circularity and environmental consideration will increase.

For decades, steam cracking has been the dominant method to making olefins, but the same pitfalls that existed in the past will continue going forward, such as high energy requirements, large quantities of produced greenhouse gas (GHG) emissions (mainly in the form of CO_2), the ethylene/propylene ratio and propylene deficit, and feedstock inflexibility. Not to mention, despite cheaper feedstocks, CAPEX/OPEX and required process energy haven't changed much in the last decade (see ***Figure 1***, below).

The continuation of the shale oil/gas boom has led to an abundance of light feedstocks, while changing emission regulations (especially in shipping), are both contributing to a decrease in naphtha availability for cracking, thus contributing to a growing propylene deficit.

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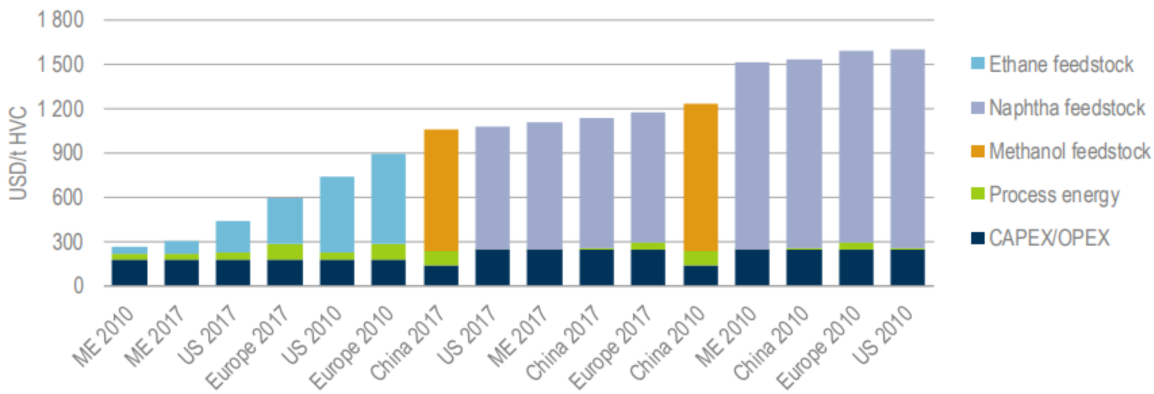

Figure 1: Costs of producing chemicals for selected feedstocks and regions (International Energy Agency, 2018)

All of this has led to a fury of R&D interest in developing novel processes and catalysts that go beyond traditional thermal steam cracking, fluid catalytic cracking (FCC) and propane dehydrogenation (PDH). In 2013, The Catalyst Group Resources (TCGR) completed its study ***"Unconventional Catalytic Olefins Production: Commercial Vision and Breakout?"*** to assist the industry in sorting out numerous catalytic technologies to produce olefins. At that time it was concluded, although a bold undertaking, there were feasible commercial pathways available to produce catalytic olefins that didn't rely solely on thermal cracking technologies. In analyzing the traditional technologies, we emphasized the importance in CAPEX, cost/availability of feedstock, and energy efficiency.

Since that time, however, **it has become clear that the topic of olefins production merits revisiting via a new industry benchmarking study, to both update the progress (or note the lack of advances) made in unconventional technologies, but to also put them up against developments achieved since the 2013 benchmarking report,** addressing such topics as:

- What results have been attained in achieving commercially viable "green" and circular $C_2^=$ and $C_3^=$ products?
- What do process/catalyst improvements yield in CO_2 footprint reductions, life cycle analyses, and overall sustainability towards NetZero2050 objectives?
- What other unconventional catalytic methods have emerged and/or are near commercialization?
- What improvements and updates have taken place over the last several years to traditional thermal methods?
- What is the potential for the "holy grail" of direct C_1 conversion, resid to olefins (via direct oil-to-chemicals routes) and advanced olefin/paraffin separations (e.g., CMS OptiPerm)?

In this recently launched multi-client study, TCGR will answer these questions, clarifying the progress and remaining challenges, and provide technical/commercial guidance regarding the outlook for R&D/capital investments over the next decade.

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II. INTRODUCTION

To emphasize how some of the above drivers play out, we can take a look at how U.S. dry shale gas production has doubled since the beginning of 2013 (U.S. EIA, 2020a). In that same time, regional and global growth rates for ethylene and propylene have remained steady, at over 3% and 4%, respectively. In addition, both are expected to continue this trend over the next several years, and possibly longer, with ethylene even increasing to over 4% CAGR (Dickson et al., 2019). This has led to increasing on-purpose propylene production, due to the ethane rich U.S. shale gas, which is forecasted to continue throughout the decade.

The propylene gap is just one of many areas that needs to be addressed, both from the point of view of understanding the economics and landscape of the current industry status quo, propane dehydrogenation (PDH), in addition to the technology behind other on-purpose methods that are still in the pipeline. Some other drivers behind unconventional olefins technology include better pre-treatment and post-process separations, increased feedstock flexibility (including utilization of in-place assets like FCC units), and also what many consider to be the holy grail, direct methane (C_1) conversion.

TCGR's 2013 study set out to answer the following question: Can catalytic olefins production displace thermal crackers in the next decade, based on improvements in yield and/or energy efficiency and reductions in cost and/or GHG emissions. The answer at that time was simply "no," based on the capital investments in ethane cracking in the US and lack thereof in novel technologies. However, in the current (2021) situation, the answer is more complicated than that.

A. Progress in Commercial Technology

There are numerous technologies in the current commercial landscape, spanning from traditional steam cracking, FCC, and PDH, to newer and more innovative catalytic cracking methods. Re-visiting and updating the technology evaluations in the 2013 report, in addition to ones that have emerged, will be crucial in determining the gaps and drivers for R&D.

- The world has traditionally required approximately 6 mil MT/yr (Tullo, 2020) of ethylene capacity additions, much of this recently achieved through steam cracking investment in the United States. However, some of these planned capacity additions may never come online, and due to the shale boom, these additions have major implications on propylene supply. TCGR will analyze this market and include any major technology updates.
- KBR offers a suite of olefins technologies, of which, the ACO™ Process (as it was called at that time) was featured in the 2013 report. While two units had been built in Asia, KBR has switched focus. The Selective Cracking Optimum Recovery (SCORE™) pyrolysis technology is a type of furnace design for mixed-feed crackers which also includes an enhanced product recovery section. For improved propylene production, KBR offers MAXOFIN™ FCC technology for gas oil/resid feeds, K-PRO™ PDH technology, and K-COT™ (catalytic olefins technology), which can produce up to a 2:1 propylene:ethylene

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ratio depending on the feedstock (see ***Figure 2***). K-PRO™ is designed with a precious-metal-free catalyst for stand-alone propylene production.

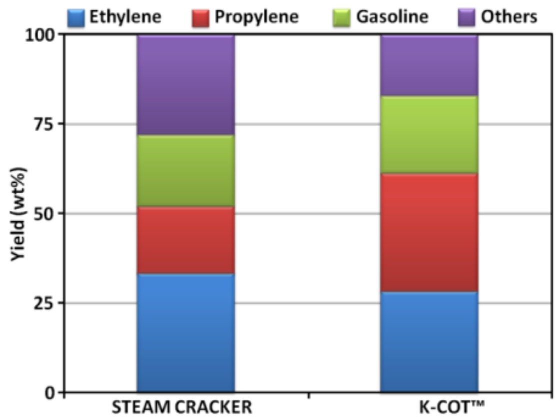

Figure 2: Product yields of conventional steam cracker and KBR K-COT™ process (Corma et al, 2016).

- Sinopec Shanghai Research Institute of Petrochemical Technology (SRIPT) Olefins Catalytic Cracking (OCC) Process – Sinopec began developing the technology in 2000, and now has three commercial plants in operation ranging from 60-200 kT/yr, with another plant scheduled for commissioning in 2020 (Teng, J. et al., 2020). Ideally suited for integration with MTO plants, but also steam crackers or refineries, the OCC Process converts low-value C_4/C_5 by-product streams into polymer grade ethylene and propylene (see PFD in ***Figure 3*** below).

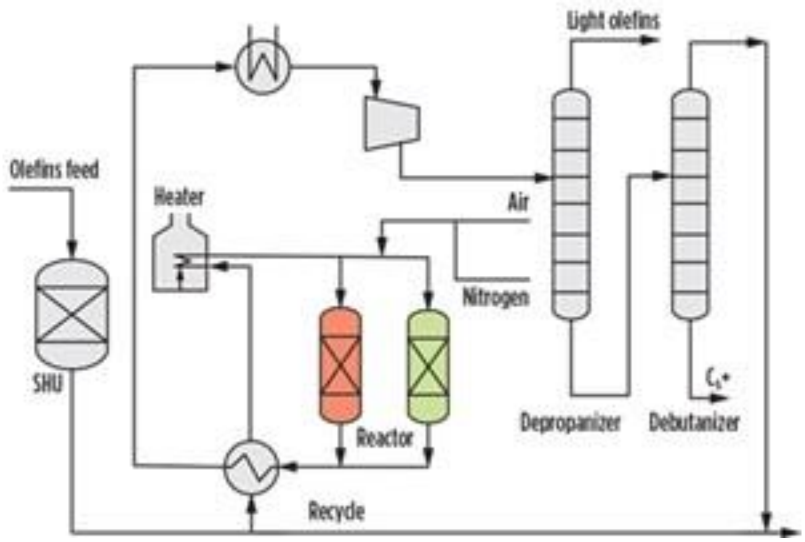

Figure 3: Process flow diagram of SRIPT OCC process (Teng et al., 2020).

- Refinery FCC units have been a source of propylene for many years, and there have been developments to increase yields and tailor units to be more flexible. Some of the levers

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available to refiners to promote increased yields of light olefins include different reactor technology (additional risers, downers), higher reaction temperature, feed atomization, catalyst:oil ratios, recycle streams, and addition of zeolite catalysts/additives (Corma et al., 2016). TCGR will update subscribers on the specifics of these advances across various processes which include, but are not limited to, the KBR MAXOFIN, Indian Oil Indmax, Shell MILOS, and KFUPM/JCCP/Saudi Aramco/Axens Higher Severity FCC (HS-FCC) processes.

- There are several commercialized PDH processes, which include the industry standard UOP Oleflex and Lummus Catofin processes, but also other offerings from Linde/BASF/Statoil, Snamprogetti, KBR, Dow and ThyssenKrupp. Capacity investment in PDH technologies has and will continue to increase, which has led to advances in catalyst and reactor technology.

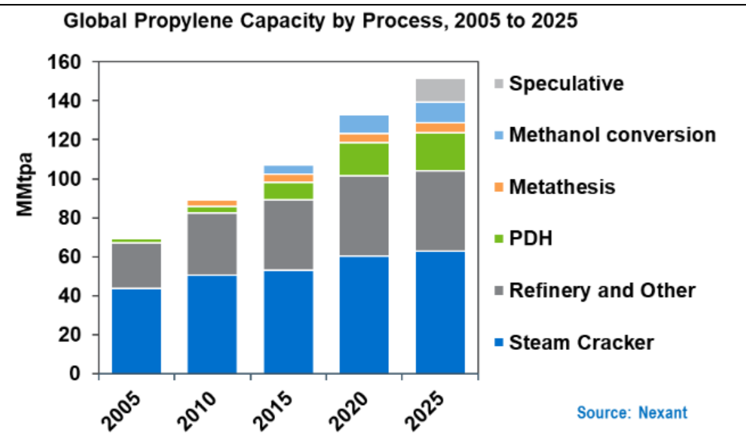

Figure 4: Global propylene capacities by process, 2005-2025. (Rabenhorst, 2019).

B. Development of New Technologies

Critical to this update are the new technologies that have arisen since the 2013 report, addressing such questions as what stage of development they are in, and what would it take to see them commercialized? Progress deemed in the scope of the report include the following, as representative examples:

- Siluria Technologies has entered into multiple joint operations (one with Saudi Aramco, one with Met Gas) to advance/commercialize methane and natural gas to propylene technologies.
- Scientists at the Dalian Institute of Chemical Physics (DICP) have investigated the nonoxidative conversion of methane to ethylene with the use of singe iron sites embedded into a matrix of silica (see ***Figure 5*** below). This has led to a joint agreement by DICP, SABIC, and China National Petroleum Corp. to research catalysts and process development in nonoxidative conversion of methane to olefins (MTO), aromatics, and hydrogen.

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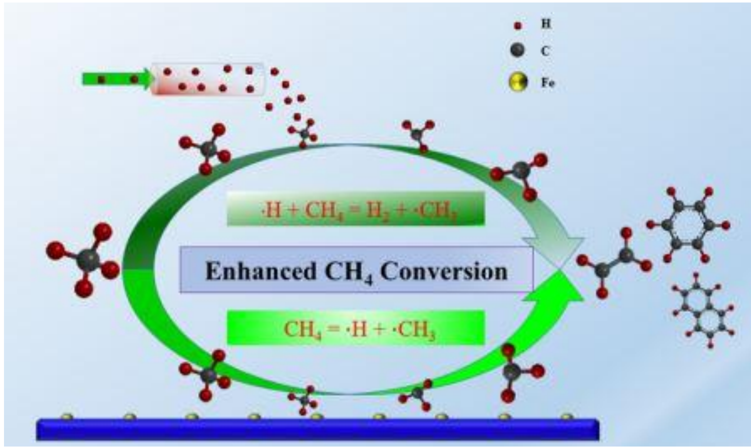

Figure 5: Single Fe sites in a silica matrix generate both methane and hydrogen radicals, which go through gas-phase C-C coupling to form ethylene (in addition to other useful products like aromatics and hydrogen). (Hao et al., 2019)

- Chiyoda has developed a process for catalytically cracking naphtha which doubles $C_3^=$ yield while reducing energy consumption by 15%. It uses a composite (Fe, Ga, Al, silica) zeolite catalyst in a fixed-bed reactor at lower temperature and no steam, producing 30% $C_3^=$ and 20% $C_2^=$. Chiyoda plans to continue pilot operations until 2022 and then move into commercial applications.
- Omega Process – Catalytically cracks C_4/C_5 feeds, ideally integrated through an existing FCC/DCC, to make olefins. Now licensed through TechnipFMC, the first commercial unit at Mizushima Works in Japan was started in 2006.
- ENI and SABIC entered into an agreement in February of 2019 to jointly develop the Short Contact Time Catalytic Partial Oxidation (SCT-CPO) technology for conversion of natural gas to syngas and olefins.
- Mitsubishi Ethylene-to-Propylene (ETP) – Mitsubishi has developed a process to produce propylene in a single step, mainly using ethylene as a feedstock, but also ethanol and methanol. They have also, jointly with JGC Corporation, developed the Dominant Technology for Propylene Production Process (DTP Process) to convert olefins and methanol to propylene in an adiabatic fixed-bed reactor, boasting low energy consumption and CO_2 emissions.
- There are several routes to producing “green” olefins by the catalytic dehydration of ethanol to ethylene. Companies like Braskem, Chematur, BP, and IFP/Axens with Total are in various stages of developing these technologies (Mohsenzadeh et al., 2017).

Indirect, yet potentially important, routes to olefins - utilizing enhanced olefin/paraffin technologies – are worthy of assessment, including:

- CMS/Braskem Optiperm™ - Compact Membrane Systems (CMS) and Braskem are jointly evaluating a pilot plant for the development of their olefin/paraffin separation technology. It is designed to be a bolt-on technology to upgrade stream quality. The pilot plant will evaluate the technology under industrial conditions for an extended period of time.

III. THE NEED FOR THE STUDY

There is much to update the industry on since TCGR's last report on this topic, as it has been a busy decade. The United States has increased its production of crude oil, natural gas, and natural gas liquids, to the point that it has become a net exporter of energy for the first time since the 1950s (U.S. EIA, 2020b). This has led to new petrochemical investment throughout the U.S. that has not been seen in decades. The middle class, along with the overall population, continues to grow globally, as people in Asia, the Middle East, and Africa are increasing demand for petroleum derived products. The effects of a changing global climate and increased awareness for a circular economy have led to calls to reassess how we produce and utilize energy. Lastly, it is projected that over the coming decades, gasoline- and diesel-powered engines will be overtaken by hybrid and electric engines. This has led to the "oil-to-chemicals" trend, one uniquely covered by TCGR (see below), in order to find ways to satisfy the demand for petroleum products, including olefins, in the ever-changing landscape.

Olefins technology licensors and leading olefins producers will always look to capitalize on these trends, by improving their costs of production, energy efficiency, feedstock flexibility, and product yields. The time has come for an update on how these factors will be addressed by the industry over the coming decade. This recently launched study will answer the following key questions:

- What feedstocks will be available by region in the coming years and how are both current/conventional and new technologies equipped to handle these?
- What are the strengths and weaknesses of various process technologies (catalytic-bed reactors, FCC, crude-to-chemicals, etc.)? What engineering and financial hurdles are still needed to be overcome? How far away are specific technologies from commercialization?
- How do the process economics compare under the current state of feedstock price and availability and technology status?

As TCGR has done over the years, we will answer this question "***for the industry***" with contributions "***by the industry***," utilizing our broad and extensive network of DIALOG GROUP® consultants and industry contacts. TCGR is uniquely positioned to provide an independent, thorough analysis that covers the space between the commercial and technical perspectives. This new 2021 update complements a broad library of TCGR multiclient reports from over three decades, as can be seen by the below list of reports since TCGR's 2013 report, ***"Unconventional Catalytic Olefins Production: Commercial Vision and Breakout?"***:

- ***Oil-to-Chemicals II: New Approaches from Resid and VGOs*** (June 2019)
- ***Catalytic Conversion of Syngas to Chemical Products III*** - report exclusively for members of TCGR's Catalytic Advances Program, CAP (2018)
- ***Oil-to-Chemicals: Technological Approaches and Advanced Process Configurations*** (December 2017)

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- ***Advances in Olefin Co-monomer and Polyolefin Production*** - report exclusively for members of TCGR's Catalytic Advances Program, CAP (2016)
- ***Advances in On-Purpose Technology for Mono- and Di-Olefins*** - report exclusively for members of TCGR's Catalytic Advances Program, CAP (2016)
- ***Natural Gas Conversion vs. Syngas Routes: A Future of Convergence***
    - ***Vol. 1: Natural Gas to Intermediates and Feedstocks to Syngas*** (October 2014)
    - ***Vol. 2: Syngas and Natural Gas Conversion to Products*** (November 2014)
- ***Advances in Olefin Purification via Catalysis and Sorbent Materials*** - report exclusively for members of TCGR's Catalytic Advances Program, CAP (2014)

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IV. SCOPE AND METHODOLOGY

TCGR's update will first establish the state-of-the-art of the conventional olefins landscape, discussing any notable improvements made to traditional thermal steam cracking technologies over the last 7-8 years. This **Section III** will include an update on recent capacity additions as well as planned plant openings in the foreseeable future. We will analyze how feedstocks have changed over the years and forecast how they will continue to do so over the next decade. This will have obvious impacts on the strategic commercial and R&D directions that will be utilized.

Section IV and **Section V** will be the core of the study – discussing the improvements and discoveries made to unconventional catalytic olefins production methods since the 2013 study. Unlike that previous study, we will extensively document the growing interest in direct methane/C_1 conversion, in addition to the major on-purpose propylene technologies. We will separate this all into an analysis of currently commercialized and near-commercialized (Section IV) and the directions being undertaken throughout industry and academia in R&D at the lower TRLs (Section V).

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New to this updated study is **Section VI**, a section specifically dedicated to comparing the process economics of various commercialized and near-commercialization technologies. Once both conventional and unconventional technologies have been laid out, they will be benchmarked from the process economics point-of-view. Section VI will also include Life Cycle Assessment (LCA) and overall GHG impact analyses.

Lastly, additional unique value is presented in **Section VII** and **Section VIII**, where TCGR will examine how companies can maximize investment returns and effectively position themselves in the global olefins market. Just as it was 8 years ago, the olefins industry is constantly at a crossroads. There are numerous drivers that are encouraging companies to invest in new catalytic production methods. TCGR's analysis will not only help identify those drivers and provide examples of where and how they are unfolding in the marketplace but will provide invaluable competitive intelligence and strategic analysis.

The timing of this new study is once again critical, as there is an ever-present interest in unconventional technologies despite the growing investments in thermal steam cracking. TCGR will answer and address the many questions surrounding this topic, as well as those that have arisen based on "charter" subscriber input/feedback.

> *In order to heighten the value-added from study participation, TCGR worked with "charter" subscribers (i.e., those who signed up for the study prior to its formal "launch") in order to define the scope of the report by delineating areas of particular interest for inclusion in the assessment. For details on the study scope, the report's revised/expanded Table of Contents appears on the following pages.*

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Unconventional Catalytic Olefins Production II: Technological Evaluation and Commercial Assessment - 2021

Revised/Expanded Table of Contents *

(including charter subscriber inputs: July 7, 2021)

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A. Direct C_1 Conversion (including CH_4, CO/syngas, and methanol to olefins, e.g., Dalian, UniCat, OCMOL)
B. CO_2 Conversion to Olefins (e.g., Voltachem, Opus 12)
C. Light Hydrocarbons to Olefins (e.g., Eni/SABIC SCT-CPO)
D. Naphtha/Resid to Olefins (e.g., Chiyoda)
E. Other (e.g., olefin/paraffin separations via CMS Optiperm; bio and waste feedstocks (including FCC retrofits); bioprocesses including bateria/enzymes; alcohol to olefins; plasma and microwave catalysis – landscape and large-scale feasability of catalysis combined with renewable energy)

VI. Process Economics & Life Cycle Analysis Case Studies *(~15-20 pages)*
A. Process Overviews
B. Cost Estimates (e.g. Fixed, Variable), CO_2/GHG and Energy Footprints, LCAs & Emission Reduction Potentials, and Opportunities for Decarbonization
C. Summary and Comparison

VII. Future Directions and Strategies *(~10 pages)*
– Special emphasis on the role of respective catalysts
A. Key Challenges
B. R&D Directions
C. Commercialization Strategies

VIII. Conclusions and Recommendations *(~10 pages)*

** Charter subscribers (those who signed up for the study prior to launch) had the opportunity to work with TCGR to further refine the scope of the report by delineating areas of particular interest in Sections IV-VI as depicted in the TofC above.*

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V. 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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VI. DELIVERABLES AND PRICING

This report is timely and strategically important to those industry participants and observers both monitoring and investing in the development and implementation of technologies for olefin production, from both established and developing catalytic routes. TCGR's report, based on technology evaluations, commercial/market assessments and interviews with key players will go beyond public domain information. As a result, subscribers are requested to complete and sign the "Order Form and Secrecy Agreement" on the following page.

The study, **"*Unconventional Catalytic Olefins Production II: Technological Evaluation and Commercial Assessment – 2021,"*** was launched in June 2021 and is expected to be available in October 2021.

Participation	Deadline	Price
Post-launch subscribers	after launch (June 17, 2021)	$24,000

Unconventional Catalytic Olefins Production II: Technological Evaluation and Commercial Assessment - 2021

Report in PDF format, in addition to subscription price $1,000

Notice to Subscribers of TCGR's 2013 *"Unconventional Catalytic Olefins Production: Commercial Vision and Breakout?"* Study:

*Due to the complementary nature of this study to TCGR's 2013 report in this area (namely **"Unconventional Catalytic Olefins Production: Commercial Vision and Breakout?"**), TCGR is offering a discount of $1,000 off to subscribers of that earlier study. Subscribers are requested to contact Chris Dziedziak at +1.215.628.4447 or cdziedziak@catalystgrp.com if further details are required or to determine if your organization is entitled. When completing the order form, please make sure to indicate your company's subscription to the earlier report.*

** Charter subscribers (those who signed up for the study prior to launch) had the opportunity to work with TCGR to further refine the scope of the report by delineating areas of particular interest, notably in Sections III-VI, for inclusion in the assessment.*

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Please enter our order for **"*Unconventional Catalytic Olefins Production II: Technological Evaluation and Commercial Assessment – 2021*"** to be completed in October 2021, as follows:

____ **"*Unconventional Catalytic Olefins Production II: Technological Evaluation and Commercial Assessment – 2021*** for $24,000 (after study launch).

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

____ Please send us ______ additional printed copies @ $250 each.

____ * * * We are subscribers to TCGR's 2013 study "***"Unconventional Catalytic Olefins Production: Commercial Vision and Breakout?"*** and are therefore entitled to the $1,000 discount off the subscription rate. * * *

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

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