Ammonia Production: Recent Advances in Catalyst and Process Technology and Impacts on the Competitive Landscape

Proposal
Select-Client Study

April 2018

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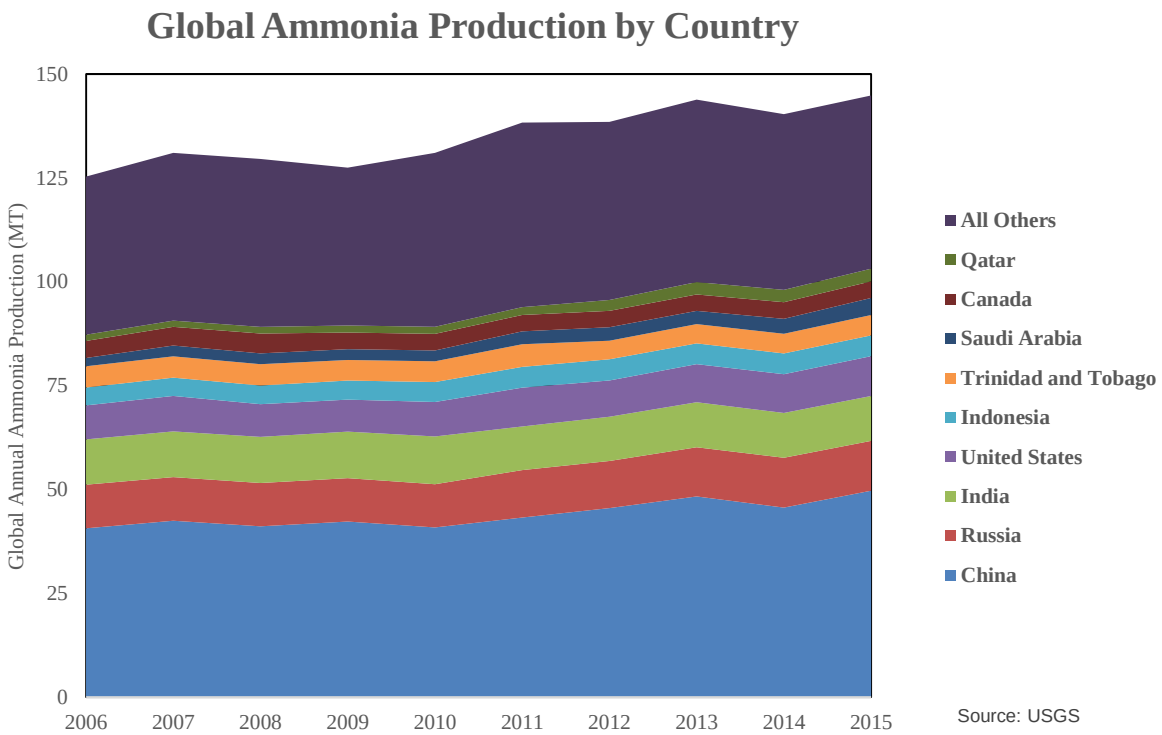
Proposal Table of Contents

The proposed study will cover recent technical developments in ammonia production and assess the implications on the competitive landscape. As always, "charter" subscribers (those who sign up prior to launch) are encouraged to provide feedback on the Table of Contents.

Background – Technology Changes Will Have Broad Competitive Implications

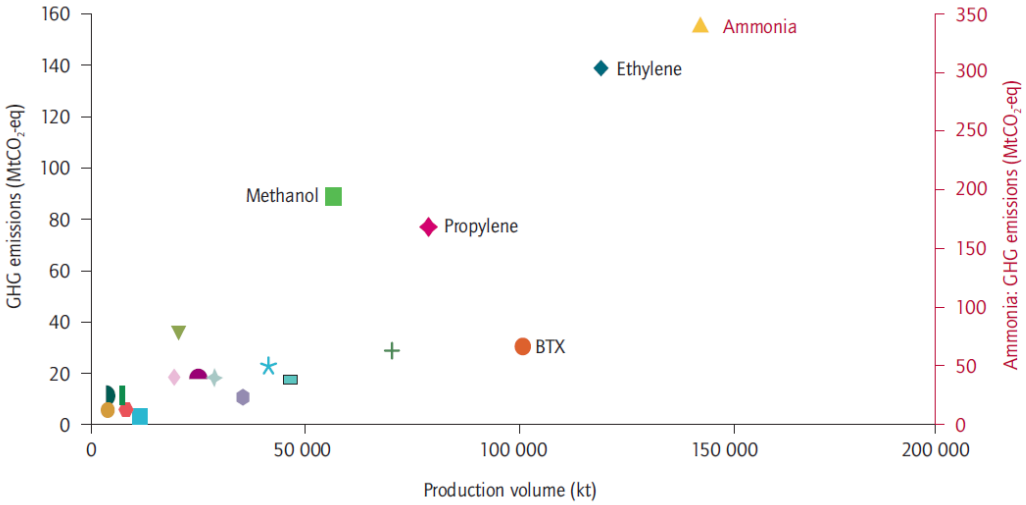
- Ammonia production has been steadily increasing ever since the first large scale production by BASF just over 100 years ago.
- Estimated production in 2017 was over 150 MT and capacity is estimated to be over 230 MT.
- The largest producing countries are China, India, Russia, United States, Trinidad & Tobago, and Indonesia.
- The main uses for ammonia are urea, ammonium nitrate, ammonium phosphates, nitric acid, and ammonium sulfate.
- Global production is expected to continue to grow 3-5%/yr. due to increasing fertilizer demand.



There is a global race to develop a new process technology to replace Haber-Bosch in ammonia production!

There is a Need for an Assessment of Recent Progress by Leaders and Others

- Energy consumption by ammonia production is the largest in the chemical industry. CO_2 emissions are at least 2x the production volume.
- There has been recent progress which goes beyond incremental process technology improvements in ammonia production to yield disruptive, and even breakthrough, advancements.
- Catalyst and related process improvements could reduce energy intensity for chemical manufacturing (ammonia included) by 20 – 40% as a whole by 2050.



Note: GHG emissions for olefins in this figure represent that of the steam cracking process. Ammonia is presented on a different axis on the right.

Source: DECHEMA

There is a global race to develop a new process technology to replace Haber-Bosch in ammonia production.

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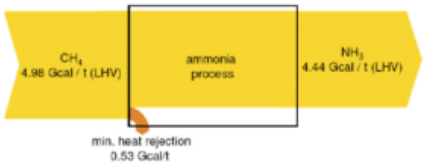
Technology Advances to be Documented Address Both Step-Change and Incremental Progress Toward Future Production Needs

- **Future Requirements**
  - Increased Production Volumes
  - Increased Production Efficiencies
  - Lower Pollutant Emissions
  - Increased Reliability
  - Greater Scale of Production
  - More Operational Flexibility

Companies like Clariant, Casale, ThyssenKrupp, Johnson Matthey, Haldor Topsoe, BASF, KBR, Linde and others are making notable progress and disrupting the competitive environment.

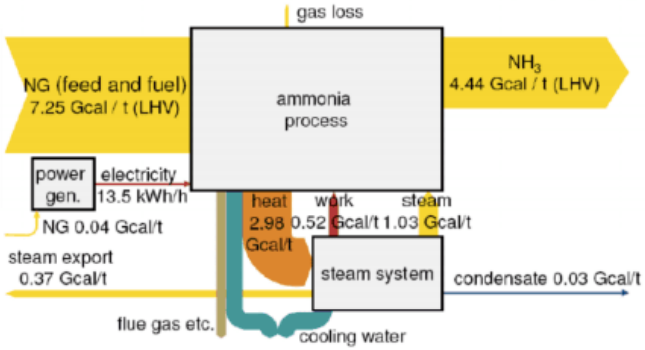
Continuing Advances of Haber-Bosch

Theory



Efficiency: 61 - 66% (SMR)
54% (electrolytic H_2)

Practice



Die Ammoniakfabrik der BASF in Oppau. Gemälde von Otto Bollhagen, 1914. Ludwigshafen, Unternehmensarchiv BASF

First NH_3 plant in Oppau, 9,000 tons/year

BASF plant in Ludwigshafen, 875,000 tons/year

- **Efficiency is still low**
- **Gigantic plant size to be economical**

There have been noteworthy efficiency improvements for large-scale plants and new opportunities for small/medium-scale plants but more progress is needed.

Source: ARPA-E

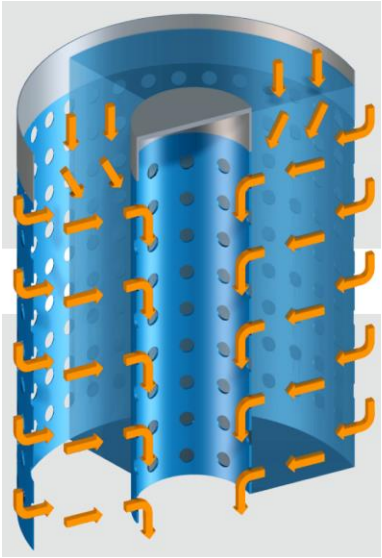
Example Advances in Ammonia - Process

Casale

- A600: 350-900 MTD systems
- A2000: 1,000-3,000 MTD
- A6000: 6,000 MTD

A6000™ drastically debottlenecks all critical items that limit the maximum capacity in conventional plants, thereby permitting a higher single train capacity. A6000™ achieves this result by adoption of three major design concepts:

1. A nitrogen-free front-end based on a pre-reformer and oxygen-blown auto-thermal reformer(ATR)
2. Enhanced carbon dioxide removal, and purification based on Liquid Nitrogen Wash
3. Inert-free ammonia synthesis loop with two Casale synthesis converters.



Haldor Topsoe

- SynCOR Ammonia – 4,000 - 6,000 MTD
- With SynCOR Ammonia™ the use of two high temperature shift reactors in series, a nitrogen wash to remove the CO, and recycling of shift by-products has resulted in numerous benefits such as byproduct formation being reduced close to zero.

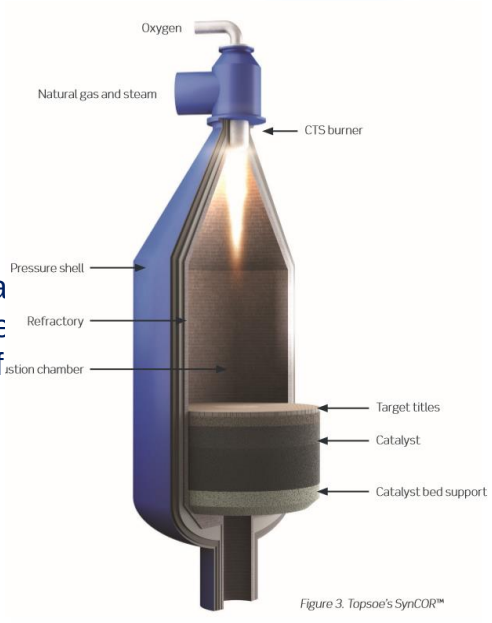


Figure 3. Topsoe's SynCOR™

Process technology licensors continue to increase production efficiency, scale, and reliability

Example Advances in Ammonia - Catalysis

Clariant

- **Shiftmax 820s Presulfided Sour Gas Shift Catalyst**
  - Clariant has started-up its pre-sulfided ShiftMax® 820S Sour Gas Shift (SGS) catalyst at a commercial methanol production facility of Shanghai Huayi Energy Chemical Co. Ltd. - the first industrial application of the newly introduced ShiftMax® 820S catalyst in China. The catalyst employs a proprietary pre-sulfiding process which offers higher activity, reducing syngas and energy requirements and allowing more economical, efficient and simplified operations. (Source: Clariant, 2015).
- **Low Temperature Shift (LTS) chloride guard ShiftGuard™ 200**
  - ShiftGuard 200 effectively adsorbs and retains chlorides so that the downstream main LTS catalyst, such as Clariant's ShiftMax® 217, is protected and can show its superior quality (Source: Clariant, 2016).

Haldor Topsoe

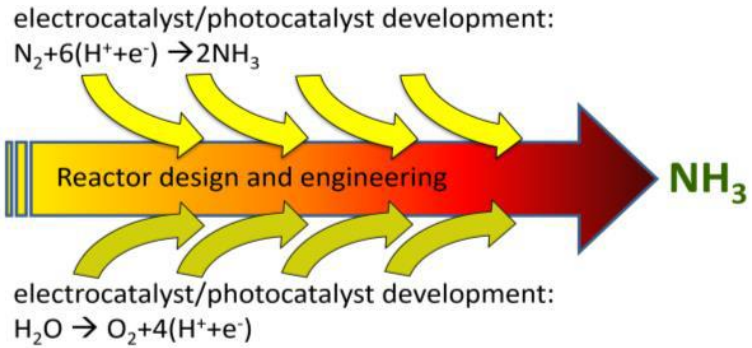
- **SK-501 Flex™ – a high temperature shift (HTS)**
  - Topsoe introduced SK-501 Flex™ – a high temperature shift (HTS) catalyst with the unique ability to operate at any steam-to-carbon ratio. For a large-scale ammonia plant, the improvement in revenue is approximately $11 million per year or $57 million over a typical catalyst lifetime. The SK-501 Flex™ formulation is based on zinc oxide and zinc aluminum spinel. The iron-free formulation prevents formation of unwanted iron carbides that reduce the catalyst strength of conventional iron-based HTS catalysts. (Source: Haldor Topsoe, 2016).
- **Ammonia synthesis catalyst: KM 111**
  - KM 111, a magnetite-based catalyst, developed for lower beds of the ammonia converter possesses an activity that surpasses the market-leading activity of KM1. At existing plants, energy consumption can be reduced by operating at lower loop pressures and lower converter inlet flows with no compromise to production levels. (Source: Haldor Topsøe, 2014).

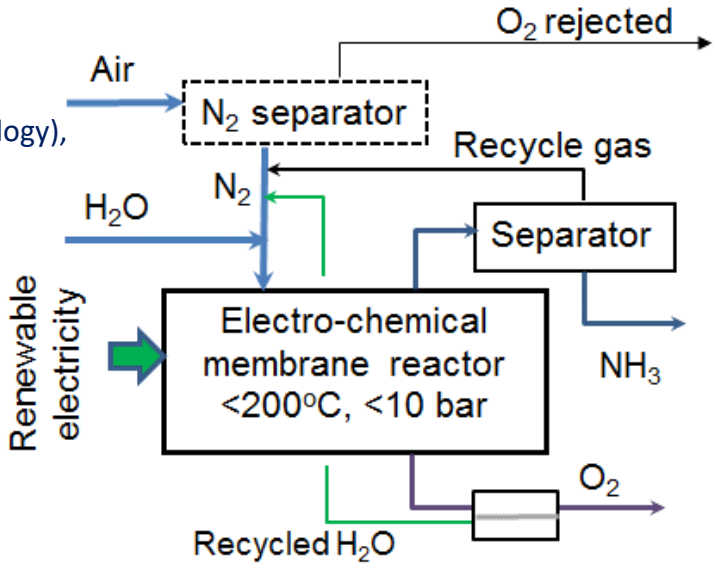
Catalyst advancements are directed towards syngas and ammonia steps

New Technologies Beyond Haber-Bosch

Among the important activities in NH_3 production are novel approaches, include the ARPA-E REFUEL Program in the US. Specific areas include:

- Electrochemical Membrane Reactors
  - Bettergy, Molecule Works Inc., Giner, Ceramatec
- Catalytic
  - RTI (with Ammonia Casale), Tsubame BHB (Tokyo Institute of Technology), QuantumSphere
- Photochemical





This study will review important upcoming technologies and highlight the potential game-changing advancements in the race to replace Haber-Bosch.

Commercial Advances Highlights

- **KBR Announces Completion of Landmark Dyno Nobel Ammonia Plant – Oct. 2016**
  - The project is the first to use an integrated **KBR** solution of KBR's Purifier™ ammonia technology along with KBR's engineering, construction and procurement (EPC) services. It is one of the first onshore ammonia plants built in the United States in the past 20 years, and the first new grassroots ammonia plant in Louisiana in over 30 years.
- **Salalah Methanol Company, a wholly owned subsidiary of Oman Oil Company, announces liquid ammonia plant - March 2017**
  - SNC-LAVALIN has been awarded a contract for the engineering, procurement and construction (EPC) of a 1,000 metric ton ammonia plant using a technology provided by **Linde Group**.
- **Metafrax and Casale sign contract for Russian chemical complex – Oct. 2017**
  - PJSC Metafrax and **Casale** have announced that they have signed a contract for the engineering, equipment supply and construction management of a large chemical complex to be implemented in Gubakha, Perm region, Russia. The project will consist of the following components: One 894 tpd ammonia synloop, utilising A2000 C™ technology, operating on pure hydrogen and nitrogen feedstock. One 1,725 tbd urea plant, using Split Flow™ and Full Condenser™ technologies. One 40,000 tpy melamine plant, utilising LEM™ technology.

The selection of a process licensor reflects importance of technology, with leaders leveraging advantages.

Commercial Advances Highlights

- **Toyo awarded contract for Indian fertilizer complex – March 2018**
  - The fertilizer complex will consist of an ammonia plant with a capacity of 2,200 tpd and a urea plant with a capacity of 3,850 tpd. The ammonia production technology of **KBR** and **Toyo**'s urea synthesis technology, ACES 21®, will be used.
- **Cronus Fertilizer selects Thyssenkrupp Industrial Solutions for its Illinois plant – August 2017**
  - The revised plant design will focus more on ammonia production and on-site delivery than originally anticipated. The Cronus plant will have the capacity to produce 2,300 metric tons per day of ammonia and up to 2,000 metric tons per day of granular urea. The plant's strategic location will benefit Illinois and area farmers by producing fertilizer locally that can be delivered via pipeline or truck, replacing the need for imported products.
- **New Japanese company, Tsubame BHB Co – July 2017**
  - A new company — Tsubame BHB Co., Ltd. (Tokyo, Japan) — has been established to commercialize the world's first on-site production of ammonia for supplying amino-acid synthesis, fermentation materials and fertilizers. The company — a joint venture of Ajinomoto Co., Inc., No. 1 UMI Limited Partnership and professor Hideo Hosono at the Tokyo Institute of Technology — began operations last April, and aims to implement first NH3 production by 2021. The production process will be based on a new catalyst that was developed in the laboratories of professor Hosono.

Commercialization of advanced processes will impact the competitive landscape with implications defining winners and losers.

Strategic Implications

- Ammonia production is projected to continue to grow at > GDP rates. It is a global, fragmented industry offering ample opportunity to process licensors, catalyst suppliers, engineering contractors, operating companies, suppliers, and end-users in the agriculture and chemical industries.
- The ammonia industry currently utilizes an energy-intensive production pathway. Both marginal and major improvements can offer and will provide significant savings in terms of increased production, efficiency, and operational reliability.
- TCGR and its Dialog Group®, which includes industry experts with significant experience, will provide an analysis of the key technological advancements. The completed study will provide valuable intelligence in a succinct format that can be shared with multiple members of your team in a number of different roles (from R&D to operations to strategy).
- From newly announced commercial catalysts and process enhancements to cutting-edge research currently at the pilot-scale (or earlier), look to TCGR and this select-client study to provide the business and engineering knowledge needed by your company.

TCGR reports provide intelligence and analysis on the key technologies that cannot be found elsewhere in the industry.

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Proposed Study: Scope/Methodology

- In this assessment, TCGR will document the current benchmark or incumbent technologies for ammonia production and highlight the major areas where technology development has, can, or will result in both emerging/evolutionary or breakthrough/"game changer" progress towards production scale and cost efficiency/productivity gains.
- Comparisons will be made between current and developmental technologies, including assessments of technology readiness levels (TRLs), timing of potential impacts at commercial scale, and the critical participants in success, whether they be licensors, producers or affiliated consortia/academia/governmental agencies on a global scale.
- Due to the size of ammonia production and its importance in application, notably as a critical component in fertilizers with implications on the ability to address world food needs, this topic merits detailed attention by and for the benefit of industrial players.
- In recognizing the gap between current technologies and the developments towards both 'emerging' and disruptive 'game changer' technologies, TCGR will conduct its assessment addressing both technical and competitive/strategic information, designed to identify competitive opportunities and/or threats for industrial participants and affiliated organizations/institutes

This TCGR study will provide the techno-economic analysis, not available elsewhere, on the best available and developing technologies.

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Proposed Study Outline

I. **Executive Summary**

II. **Ammonia Industry Background**
   A. Market Size and Growth
   B. Key Players and Technology Benchmarks

III. **Process Technology Developments (2008-2018 and 2020+)**
   A. KBR, Haldor Topsoe, Ammonia Casale, etc.
   B. Opportunities for Gains in Productivity and Efficiency

IV. **Catalyst Technology Developments (2008-2018 and 2020+)**
   A. Clariant, Johnson Matthey, Haldor Topsoe, etc.
   B. Catalyst Improvements and Gains

V. **Future Ammonia Production & Drivers for Change**
   A. Catalytic
   B. Electrochemical
   C. Other

VI. **Competitive and Strategic Implications**

"Charter"
subscribers (those who sign up prior to launch) will be able to shape the content of the report including specific companies, technologies and other factors to be included…

The report will be delivered in PowerPoint format and consist of 50-75 slides.

TCGR Experience & Qualifications

- TCGR will leverage its access to chemical/ammonia industry experts that have >30 years' industry experience via its Dialog Group® (a mixture of commercial & technical) in completing this study.
- TCGR will utilize publicly available and in-house information to complete the deliverables as well as patent searches, technical literature reviews, and in-field interviews with catalyst manufacturers and process licensors.
- TCGR Dialog Group® experts have deep experience in the required technology from a process technology, catalyst technology & application perspective.

The Catalyst Group Resources has covered related technical process advancements in similar reports; those can be seen here on our website. Other advancements are also tracked as part of our Catalytic Advances Program and CO_2 Capture and Conversion Program.

The Dialog Group® is a renowned group of industry-leading experts that provide key intelligence and analysis of the chemical industries.

Order Form & Secrecy Agreement

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Please enter our order for **Ammonia Production: Recent Advances in Catalyst and Process Technology and Impacts on the Competitive Landscape** to be completed within 8-10 weeks of launch (i.e., July/August 2018), as follows:

_____ **Ammonia Production: Recent Advances in Catalyst and Process Technology and Impacts on the Competitive Landscape,** as a "charter" subscriber (i.e., prior to May 18, 2018) for US$15,500 (US$18,000 after study launch) to be delivered as a PDF file containing PowerPoint slides, which includes use across locations (i.e. site license).

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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Dedicated to monitoring and analyzing technical and commercial developments in catalysis as they apply to the global refining, petrochemical, fine/specialty chemical, pharmaceutical, polymer/elastomer and environmental industries.

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