The Investment Case for Sustainable Ammonia Synthesis Technologies

Trevor Brown

13th Annual NH3 Fuel Conference
September 20, 2016

Trevor Brown: independent ammonia industry analyst

- December 2011: began tracking global ammonia capacity & expansions
- June 2013: published online dataset for North America
- November 2013: launched website AmmoniaIndustry.com
- June 2016: passed final exams in Chartered Financial Analyst program

Raw data for all tables/charts available from https://ammoniaindustry.com
The Investment Case

- Part 1: History
  - Innovations, #1 to #5
- Part 17: Current Technology Deployment
  - Growth Drivers
  - Problems
  - Recent industry trends
    - Plant Size
    - Feedstock Mix
- Part 42: Future Technology Deployment
  - Innovations, #1 to #5

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HISTORY: Innovation #1
Haber-Bosch Process

• Haber-Bosch:
  – 1909: Laboratory demonstration: 125 ml/hour
  – 1913: Industrial demonstration: 20 tonnes/day
  – 1920: Industrial deployment: 300,000 tonnes/year
• “Bellwether” inorganic chemistry
  – Fritz Haber
• High-pressure, high temperature industrial processes
  – Carl Bosch / BASF
• Catalyst development
  – Alwin Mittasch: systematic optimization: ~20,000 individual attempts / iterations
    • Osmium → Uranium → Iron → decades later (KBR), Ruthenium
HISTORY: Technology Pathways (1918)

Inorganic Ammonia
1. Mined:
   Chilean Saltpeter: NaNO₃
2. Byproduct:
   Steel production / coke ovens: \((\text{NH}_4)_2\text{SO}_4\)

~ 46% Total Ammonia Source

3. Synthesized:
   Cyanamid Process: CaCN₂

SOURCE: [https://babel.hathitrust.org/cgi/pt?id=uiug.30112019245163;view=1up;seq=7](https://babel.hathitrust.org/cgi/pt?id=uiug.30112019245163;view=1up;seq=7)

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HISTORY:
Inorganic Nitrogen (1920)

SOURCE: https://books.google.com/books/about/Production_of_atmospheric_nitrogen.html?id=-NwuAAAAMAAJ
Trevor Brown: https://ammoniaindustry.com
HISTORY: Atmospheric Nitrogen (1920)

SOURCE: https://books.google.com/books/about/Production_of_atmospheric_nitrogen.html?id=-NwuAAAAAMAAJ
Trevor Brown: https://ammoniaindustry.com
HISTORY: Innovation #2
Feedstocks

• “Crazy” – the adoption of natural gas feedstock in the US: 1940
  – “Before the war, when ammonia was made chiefly from coal, the plants were built in coal producing areas, generally near the coke ovens. Some industrial chemists and Ordnance officers, particularly Maj. John P. Harris, were convinced that in time of war enough ammonia for the mass production of explosives and smokeless powder could never be produced from coal. The pre-1940 Ordnance plans therefore called for the production of ammonia from natural gas and the location of new ammonia plants in the Southwest rather than in the Pennsylvania-West Virginia-Kentucky coal region. ‘People told me I was crazy when I proposed the idea,’ Harris declared, ‘but it succeeded and today all the ammonia producers use natural gas.” [http://history.army.mil/html/books/010/10-10/CMH_Pub_10-10.pdf]
HISTORY: Technology Pathways (1935)

- Technology mix:
  - One process
  - Many practitioners / IPs
- Feedstock mix:
  - Transition → diversification

<table>
<thead>
<tr>
<th>Source</th>
<th>1926–27</th>
<th>1933–34</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water gas</td>
<td>89.0</td>
<td>57.0</td>
</tr>
<tr>
<td>Coke-oven gas</td>
<td>3.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Electrolysis of water</td>
<td>6.4</td>
<td>16.0</td>
</tr>
<tr>
<td>Other (natural gas, fermentation, etc.)</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Total</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**POTENTIAL FERTILIZER PRODUCTION**

<table>
<thead>
<tr>
<th>Process</th>
<th>Percentage of world production of synthetic nitrogen</th>
<th>Countries using this process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Haber-Bosch</td>
<td>44</td>
<td>Soviet Union, I.G. Farben in Germany and Norway, modification by Imperial Chemical Industries in Great Britain.</td>
</tr>
<tr>
<td>Casale</td>
<td>15</td>
<td>Japan, Belgium, France, Germany, United States, Soviet Union, Yugoslavia, Italy, Switzerland.</td>
</tr>
<tr>
<td>Fauser</td>
<td>11</td>
<td>Montecatini in Italy and Netherlands, Poland, Mining and Smelting in Trail, Canada, Belgium, Japan.</td>
</tr>
<tr>
<td>Mont Cenis</td>
<td>8</td>
<td>Germany, Manchuria, Japan, California in the United States, France.</td>
</tr>
<tr>
<td>Claude</td>
<td>9</td>
<td>France, Belgium, United States, Germany, Czechoslovakia.</td>
</tr>
<tr>
<td>Nitrogen Engineering Corporation</td>
<td>7</td>
<td>France, Germany, Belgium, Poland, Norway.</td>
</tr>
<tr>
<td>General Chemical Company</td>
<td>6</td>
<td>United States.</td>
</tr>
</tbody>
</table>

Source: [https://books.google.com/books?id=v9unAAAAIAAAJ&printsec=frontcover#v=onepage&q&f=false](https://books.google.com/books?id=v9unAAAAIAAAJ&printsec=frontcover#v=onepage&q&f=false)

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HISTORY: Innovation #3
Air Separation Technologies

- Because: Ammonia = Anchor Customer for 100 years of R&D Investment

http://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1704&context=open_access_dissertations
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HISTORY: Innovation #4
Carbon Capture ... & Sequestration

• **Carbon Capture ...**
  Because: Ammonia + Urea = colocation of supply + demand
  – Girbotol Process / MEA (monoethanolamine: RNH₂)
  – Benfield / Hot Pot (hot potassium carbonate) / Benfield LoHeat
  – Selexol (solvent = DMPEG) / Rectisol (solvent = methanol)
  – aMDEA (BASF)
    • “It all started with ammonia. BASF wanted to reduce the cost of producing ammonia. In the early 1970s, BASF was therefore exploring methods for separating carbon dioxide (CO₂) more efficiently from the synthetic gas used in the production process.” [http://www.intermediates.basf.com/chemicals/topstory/amdea](http://www.intermediates.basf.com/chemicals/topstory/amdea)

• **... and Sequestration**
  – Koch Industries: Enid, OK: 1982: 0.7 million tonnes / year (Benfield)
  – Dakota Gas: Beulah, ND: 2000: 80% of 3 million tonnes / year (Rectisol)
    • NOTE: ammonia production secondary to syngas production
  – CVR Partners: Coffeyville, OK: 2013, 1 million tonnes / year (Selexol)
  – Agrium: Redwater, AB: 2017, 0.3-0.6 million tonnes / year (Benfield)
• **NOTE:** Current action: Yara, Norway: 100% National Carbon Capture & Sequestration by 2022

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HISTORY: Innovation #5
Deployment at Massive Scale

- Demonstration of massive technology deployment, infrastructure investment
- aka The Green Revolution

**China, Ammonia Capacity:**
(million metric tons N)
- 1960: 0.36
- 1970: 4.98
- 1980: 12.28
- 1990: 17.5
- 2000: 27.5
- 2010: 40

Roughly +1 million tons ammonia every year for 50 years

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TODAY:

“Cheap” Gas → Capacity Expansion

- 2013: EPC contractors stop giving fixed-price construction contracts (labor costs).
- 2015: Nitrogen prices plummet, jeopardizing project financing. Projects remain on hold.
- 2016: EPC contractors start giving fixed-price agreements again (e.g., Fatima, Cronus).
- Despite cancellations, active pipeline still expanding.

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TODAY:
Questionable Industry Ability

- Engineering, Procurement, Construction performance:
  - Actual Builds: Schedules & Budgets way off target
  - Risks to Technology Transfer: from Laboratory Scale to Industrial Deployment

<table>
<thead>
<tr>
<th>Location</th>
<th>Original CapEx</th>
<th>Latest CapEx</th>
<th>+/- $</th>
<th>+/- %</th>
<th>Original Start-up</th>
<th>Latest Start-up</th>
<th>+/- months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waggaman, LA</td>
<td>$850 million</td>
<td>same</td>
<td>—</td>
<td>—</td>
<td>mid-late 2016</td>
<td>Q3 2016</td>
<td>—</td>
</tr>
<tr>
<td>Donaldsonville, LA</td>
<td>$2.1 billion</td>
<td>$2.3 billion</td>
<td>+$200 M</td>
<td>+10%</td>
<td>early 2016</td>
<td>June/July 2016</td>
<td>+3</td>
</tr>
<tr>
<td>Port Neal, IA</td>
<td>$1.7 billion</td>
<td>$2.3 billion</td>
<td>+$600 M</td>
<td>+35%</td>
<td>mid 2016</td>
<td>Q3 2016</td>
<td>—</td>
</tr>
<tr>
<td>Wever, IA</td>
<td>$1.4 billion</td>
<td>$2.25+ billion</td>
<td>+$850 M</td>
<td>+60%</td>
<td>mid 2015</td>
<td>Q3 2016</td>
<td>+12—14</td>
</tr>
<tr>
<td>Greeneville, TN</td>
<td>$240 million</td>
<td>$250++ million</td>
<td>? &gt;$10 M</td>
<td>??</td>
<td>March 2014</td>
<td>?? Q3 2016</td>
<td>+27</td>
</tr>
<tr>
<td>El Dorado, AR</td>
<td>$300 million</td>
<td>$510 million</td>
<td>+$210 M</td>
<td>+70%</td>
<td>late 2015</td>
<td>May 2016</td>
<td>+6</td>
</tr>
<tr>
<td>Freeport, TX</td>
<td>$750 million</td>
<td>$600 million</td>
<td>-$150 M</td>
<td>-20%</td>
<td>late 2017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spiritwood, ND</td>
<td>$1.4 billion</td>
<td>$3.3 billion</td>
<td>+$1900 M</td>
<td>+135%</td>
<td>2018</td>
<td>cancelled</td>
<td></td>
</tr>
</tbody>
</table>

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TODAY: Capital Intensity

- CapEx per metric ton Ammonia...
  ...beware apples:oranges comparisons

- $1,000/ton rule of thumb still valid

- Yara/BASF @ Freeport:
  25% CapEx reduction by using H₂
  No need for reformers / front end

- Lawsuits over construction costs:
  - Greeneville, TN
  - El Dorado, AR
  - Wever, IA

- Note: Spiritwood, ND cancelled

<table>
<thead>
<tr>
<th>Location</th>
<th>Latest CapEx</th>
<th>$ per ton Ammonia</th>
<th>$ per ton product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waggaman, LA</td>
<td>$850 million</td>
<td>$1,063</td>
<td>$1,063</td>
</tr>
<tr>
<td>Donaldsonville, LA</td>
<td>$2.3 billion</td>
<td>$1,737</td>
<td>$786</td>
</tr>
<tr>
<td>Port Neal, IA</td>
<td>$2.3 billion</td>
<td>$2,605</td>
<td>$1,012</td>
</tr>
<tr>
<td>Wever, IA</td>
<td>$2.25+ billion</td>
<td>$2,568</td>
<td>$937</td>
</tr>
<tr>
<td>Greeneville, TN</td>
<td>$250++ million</td>
<td>$3,788</td>
<td>$1,786</td>
</tr>
<tr>
<td>El Dorado, AR</td>
<td>$510 million</td>
<td>$1,360</td>
<td>$1,360</td>
</tr>
<tr>
<td>Freeport, TX</td>
<td>$600 million</td>
<td>$747</td>
<td>$747</td>
</tr>
<tr>
<td>Spiritwood, ND</td>
<td>$3.3 billion</td>
<td>$4,110</td>
<td>$1,828</td>
</tr>
</tbody>
</table>

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TODAY: Diversification
Business Models & Feedstocks

- 2016 New US Ammonia Capacity:
  6 plants, +4.6 million tons
  Average Size: 650,000 metric tons / year
  Max Size: 1,300,000
  CF Industries, D’ville, LA
  Min: 67,000 mtpy
  US Nitrogen, Greeneville, TN

- 2017-18 New US Ammonia Capacity:
  9 plants, +3.3 million tons
  Average Size: 370,000 metric tons / year
  Max: 803,000
  Yara/BASF, Freeport, TX
  Min: 33,500
  Fortigen, Geneva, NE

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FUTURE: Ammonia Innovation #1 + / - Haber-Bosch

• Avoidance
  – Nutrient Addition: Cover crops / Organic Systems / Biofertilizer (biosolids)
  – Biomimicry: GMO (legume traits in commodity crops)
• Efficiency
  – Nutrient Retention: No Till / Irrigation Systems
  – Precision Ag (beware Jevons Paradox)
  – Food Waste Reduction / Diet Changes / Synthetic Meat
  – Nutrient Loss Remediation
• Feedstock Diversification
  – Low / Zero-Carbon H₂
• Technology Diversification
  – Incremental Innovation, Haber-Bosch:
    • Efficiency: catalysts, temperature, pressure
    • Operations: intermittency
  – Radical Innovation: Solid State / Liquid State Electrochemical processes, etc
Innovation v. Invention:  
**eg: Waste Plastic Feedstock**

- **ERS: Antwerp, Belgium**
  - Investment: Saudi Arabia  
  - Technology: China  
  - Announced: 2015  
    - CapEx: €3.7 billion ($>$4 billion)  
    - Feedstock: 3.485 million tonnes / year  
    - Ammonia: 645,500 tonnes / year NET (4,500 tonnes / day GROSS)  
    - Urea: 1,231,500 tonnes / year  

- **NOTE! Showa Denko: Ogimachi, Kawasaki**
  - Producing ammonia from plastic since 2003  
  - CapEx: ¥7.4 billion ($>$73 million)  
  - Ammonia: 175 tonnes / day  

- **2015 = 2x 2003 CapEx per ton, at 10x scale**  
  - What efficiency of scale?

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FUTURE: Ammonia Innovation #2
Carbon Reduction: Fertilizer

• **Ammonia production causes 1% of global GHG emissions** (2012 data):
  – 170 million metric tons ammonia produced
  – 2.867 tons CO2 / ton ammonia (global average)
    • US industry average: 2.129 tons CO2 / ton ammonia
    • China industry average: 4.429 tons CO2 / ton ammonia
      NOTE: improving! Closed 24.2 million tons capacity in last 3 years, mainly coal.
  – 33,843 million metric tons CO2 emissions → **1.44% global CO2 emissions**
  – 47,599 million metric tons GHG emissions → **1.024% global GHG emissions**
  – NOTE: refers ONLY to fossil carbon input, NOT life-cycle carbon

• 1% is a big number
FUTURE: Ammonia Innovation #3
Carbon Reduction: Energy

- **Sustainable Ammonia Synthesis Technologies**
  = “debottlenecking” opportunity for global transition to low carbon economy
- Once decoupled from fossil extraction, potential GHG impact far exceeds 1%
- Multiple Business Models:
  - Anchor Customer (technology demand)
    - Commercialization of large scale renewable H2 technologies / captured carbon
  - New Products
    - Liquid Fuel
    - Energy Distribution
    - Energy Storage
    - Resilience / Risk Mitigation / Diversification / Renewable Energy Market Penetration
    - Multiple / Flexible Revenue Streams
  - New Byproducts
    - Water, Fertilizer, O₂, CO₂
  - New Customers & New Markets
FUTURE: Ammonia Innovation #4
Carbon Reduction: Biosphere

- Traditional Ammonia-Urea carbon “cycle”:
  - Fossil $C_xH_y$ to Ammonia + $CO_2$
  - Ammonia + $CO_2$ to Urea
  - Urea to $CO_2$ to air

- CCS Proposed Pathway: “Urea Yield Boosting”
  - Note: nonsense carbon accounting
  - See: “Urea Production is Not Carbon Sequestration”
    [https://ammoniaindustry.com/urea...not-sequestration/](https://ammoniaindustry.com/urea...not-sequestration/)

- BECCS Technology Pathway: “Carbon Negative Urea”
  - Note: C:H ratio higher in biomass
  - Thus greater capture potential: carbon harvesting
  - Requires commercialized sequestration technology

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FUTURE: Ammonia Innovation #5
Deployment at Massive Scale

• Bill McKibben, New Republic, August 2016
  https://newrepublic.com/article/135684/declare-war-climate-change-mobilize-wwii
  – “Even if every nation in the world complies with the Paris Agreement, the world will
    heat up by as much as 3.5 degrees Celsius by 2100 – not the 1.5 to 2 degrees promised.”
  – Mark Z. Jacobson, Civil & Environmental Engineering, Stanford University
    • Demonstrates how all 50 US States could achieve 100% renewable energy.
      Level of detail: eg, Alabama: 59.7 km² residential rooftops unshaded by trees and
      pointed in the right direction for solar panels.
    • Similar “national blueprints” for 139 countries.
      US data: http://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf & Global data:
      http://www.scientificamerican.com/article/139-countries-could-get-all-of-their-power-from-renewable-sources1/
  – US Deployment Scale: Required Renewable Power Generation
    • 6,448 GW total by 2050. At current pace (16GW in 2015), would take 405 years.
    • SolarCity’s “GigaFactory” (manufacturing 1GW solar panels per year)
      35 Year Requirement → 295 GigaFactories across US, 6 per State. Same for Wind.
  – Global Investment Scale:
    • Current global investment in fossil fuel infrastructure: $20 trillion installed
    • Thus: replacement infrastructure investments, 2016 to 2050: $570 billion per year
– Work in Progress –
Please send corrections / additions

Trevor Brown

tb@ammoniaindustry.com
https://ammoniaindustry.com