The Investment Case for Sustainable Ammonia Synthesis Technologies

Parts 1, 17, and 42 of ±99

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

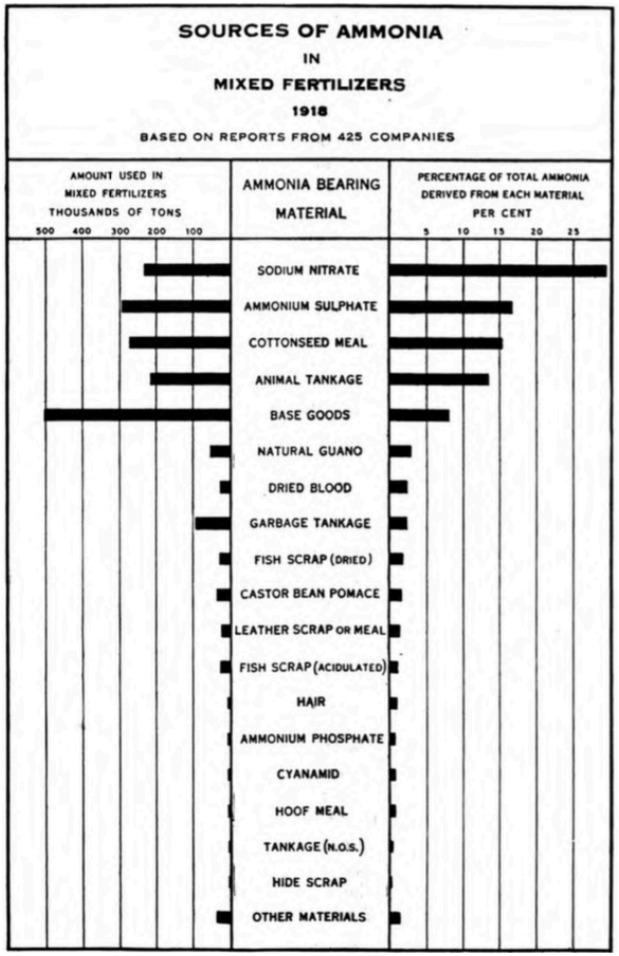
The Investment Case

- 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

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

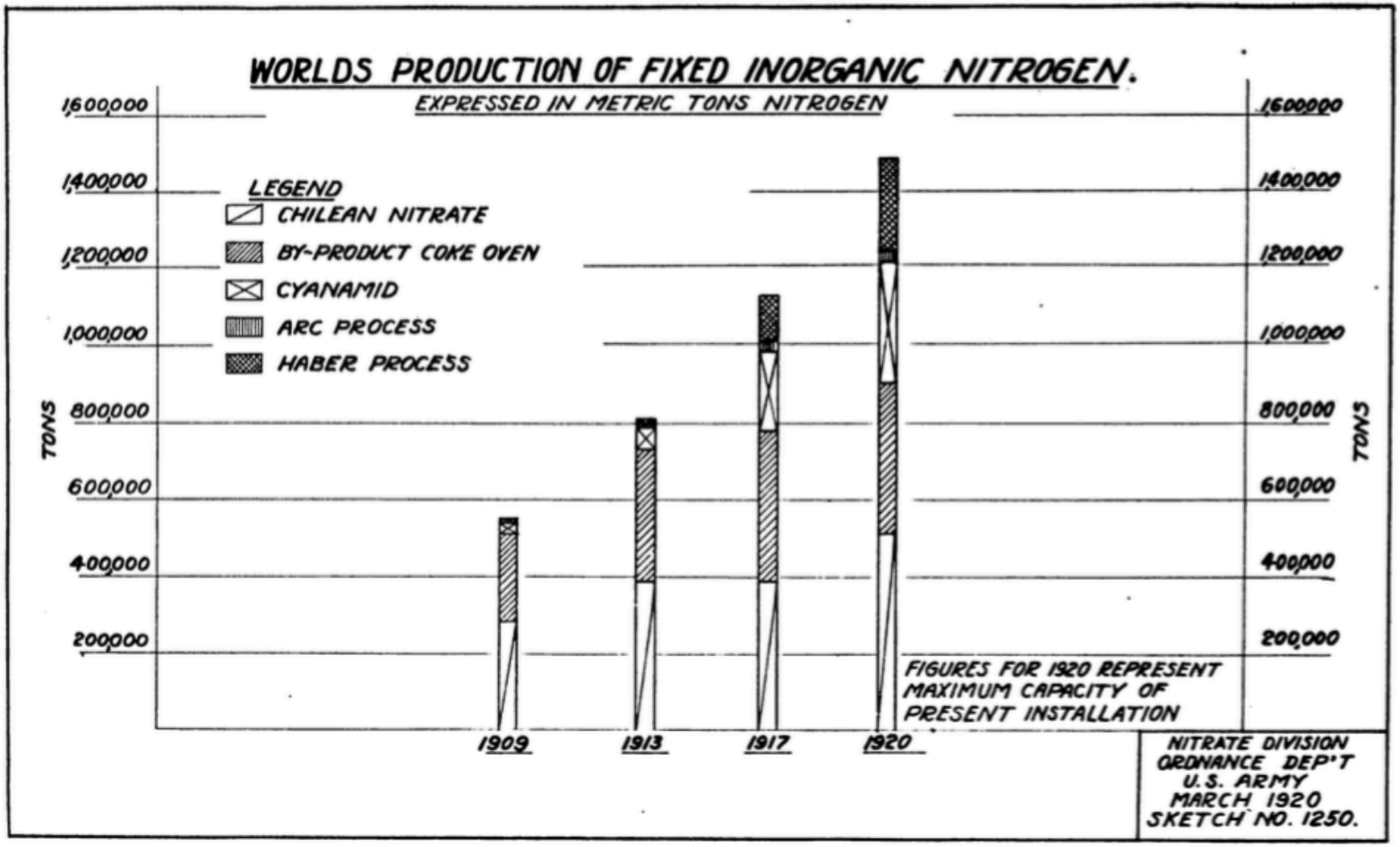
1. Mined:
   Chilean Saltpeter: $NaNO_3$
2. Byproduct:
   Steel production /
   coke ovens: $(NH_4)_2SO_4$

~ 46% Total Ammonia Source

3. Synthesized:
   Cyanamid Process: $CaCN_2$

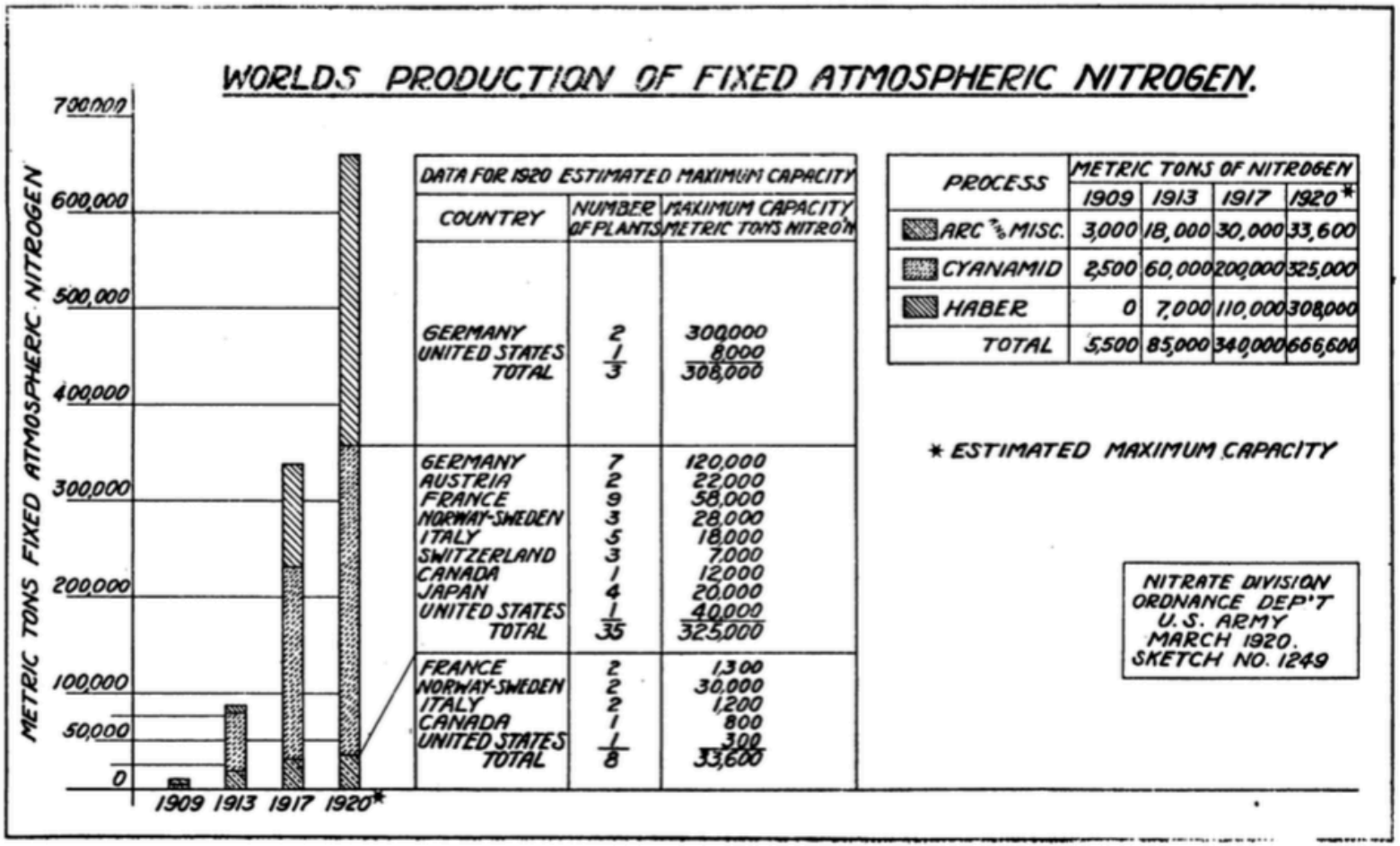
SOURCE: https://babel.hathitrust.org/cgi/pt?id=uiug.30112019245163;view=1up;seq=7

HISTORY:
Inorganic Nitrogen (1920)



SOURCE: https://books.google.com/books/about/Production_of_atmospheric_nitrogen.html?id=-NwuAAAAMAAJ

HISTORY:
Atmospheric Nitrogen (1920)



SOURCE: https://books.google.com/books/about/Production_of_atmospheric_nitrogen.html?id=-NwuAAAAMAAJ

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

Source	1926–27	1933–34
Water gas	89.0	57.0
Coke-oven gas	3.0	25.0
Electrolysis of water	6.4	16.0
Other (natural gas, fermentation, etc.)	1.6	2.0
Total	100.0	100.0

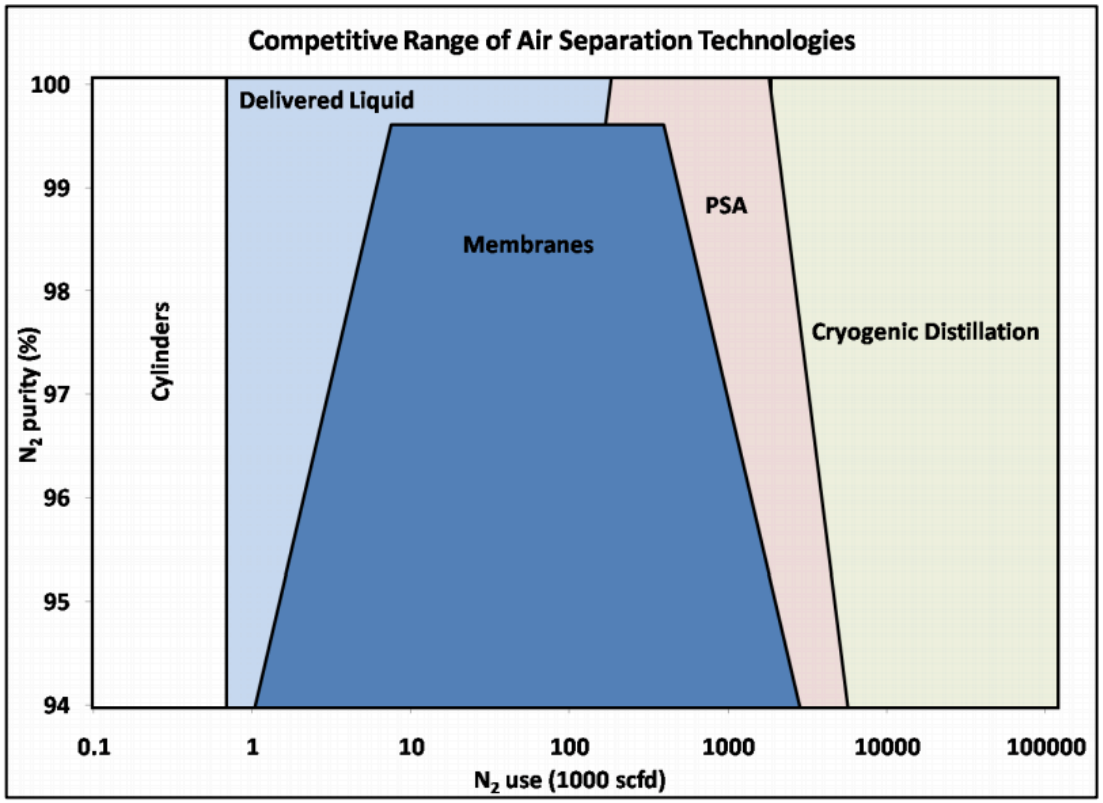
POTENTIAL FERTILIZER PRODUCTION 103

Process	Percentage of world production of synthetic nitrogen	Countries using this process
Haber-Bosch	44	Soviet Union, I.G. Farben in Germany and Norway, modification by Imperial Chemical Industries in Great Britain.
Casale	15	Japan, Belgium, France, Germany, United States, Soviet Union, Yugoslavia, Italy, Switzerland.
Fauser	11	Montecatini in Italy and Netherlands, Poland, Mining and Smelting in Trail, Canada, Belgium, Japan.
Mont Cenis	8	Germany, Manchuria, Japan, California in the United States, France.
Claude	9	France, Belgium, United States, Germany, Czechoslovakia.
Nitrogen Engineering Corporation	7	France, Germany, Belgium, Poland, Norway.
General Chemical Company	6	United States.
Total	100	

SOURCE: https://books.google.com/books?id=v9unAAAAIAAJ&printsec=frontcover#v=onepage&q&f=false

HISTORY: Innovation #3
Air Separation Technologies

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



SOURCE: Eric Morgan, U.Mass-Amherst, "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind"
http://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1704&context=open_access_dissertations

HISTORY: Innovation #4
Carbon Capture … & Sequestration

- **Carbon Capture …**

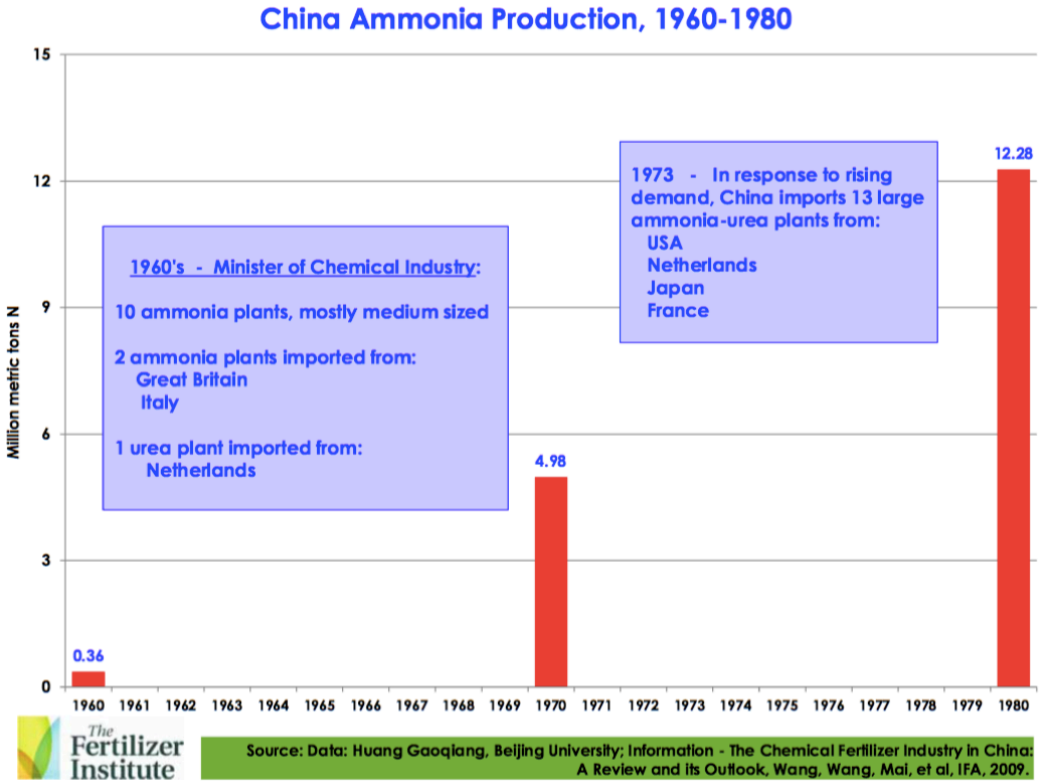
  Because: Ammonia + Urea = colocation of supply + demand

  - Girbotol Process / MEA (monoethanolamine: RNH_2)
  - 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
- **… 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

  https://www.regjeringen.no/globalassets/departementene/oed/pdf/summary.pdf

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)

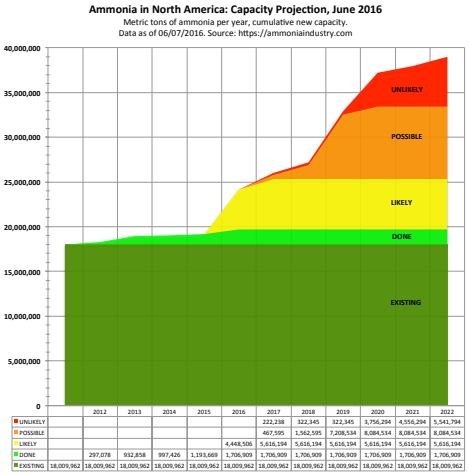
- 1960: 0.36
- 1970: 4.98
- 1980: 12.28
- 1990: 17.5
- 2000: 27.5
- 2010: 40

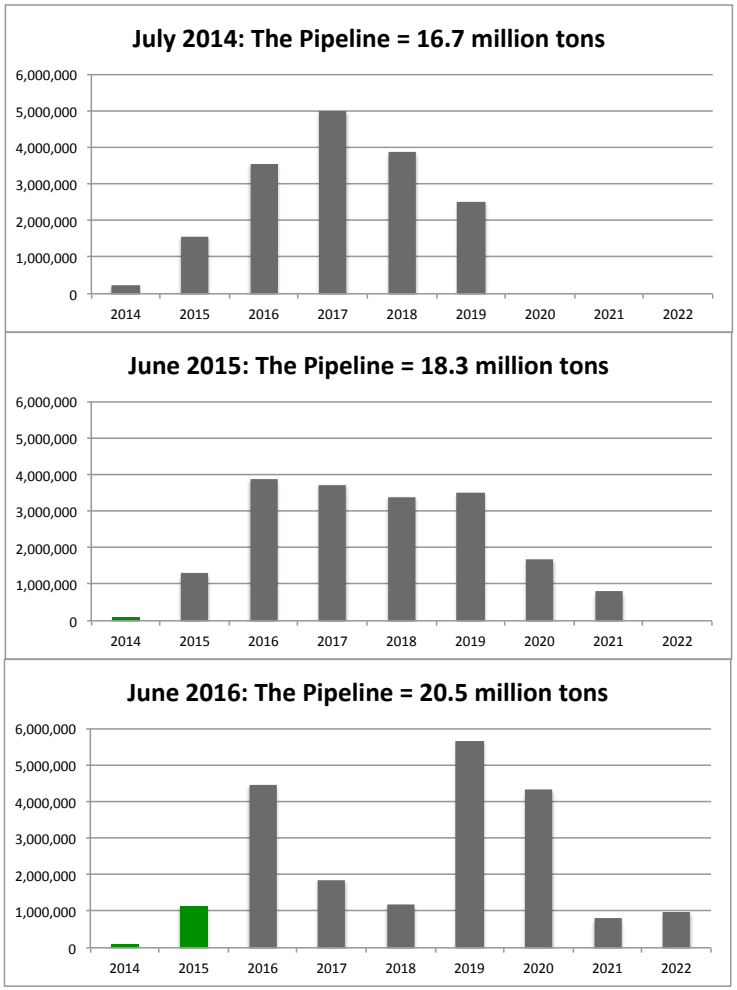
Roughly +1 million tons ammonia every year for 50 years

SOURCE: Harry Vroomen, TFI "The History of Ammonia to 2012": http://www.firt.org/sites/default/files/2Vroomen.pdf

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.
- Most projects in financing limbo: start-up pushed back from 2017/18 to 2019/2020.
- 2016: EPC contractors start giving fixed-price agreements again (eg: Fatima, Cronus).
- Despite cancellations, active pipeline still expanding.





Trevor Brown: https://ammoniaindustry.com
"The Investment Case For Sustainable Ammonia Synthesis Technologies," NH3 Fuel Conference, September 20, 2016

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

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

Trevor Brown: https://ammoniaindustry.com
"The Investment Case For Sustainable Ammonia Synthesis Technologies," NH3 Fuel Conference, September 20, 2016

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 H_2
  No need for reformers / front end

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

- Note: Spiritwood, ND cancelled

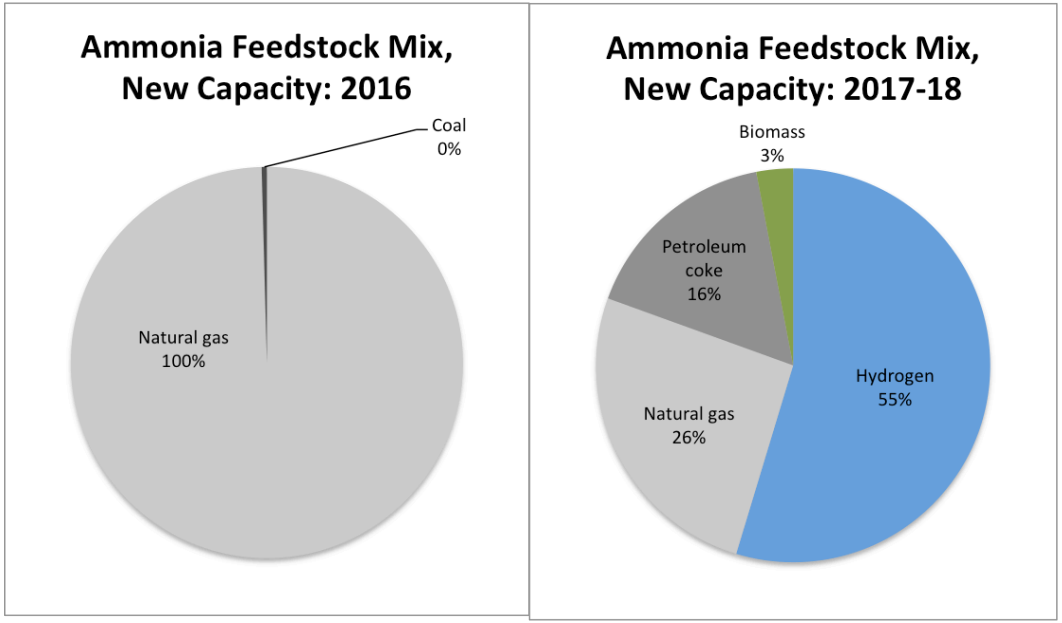
	Latest CapEx	$ per ton Ammonia	$ per ton product
Waggaman, LA	$850 million	$1,063	$1,063
Donaldsonville, LA	$2.3 billion	$1,737	$786
Port Neal, IA	$2.3 billion	$2,605	$1,012
Wever, IA	$2.25+ billion	$2,568	$937
Greeneville, TN	$250++ million	$3,788	$1,786
El Dorado, AR	$510 million	$1,360	$1,360
Freeport,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

Trevor Brown: https://ammoniaindustry.com
"The Investment Case For Sustainable Ammonia Synthesis Technologies," NH3 Fuel Conference, September 20, 2016

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



Trevor Brown: https://ammoniaindustry.com
"The Investment Case For Sustainable Ammonia Synthesis Technologies," NH3 Fuel Conference, September 20, 2016

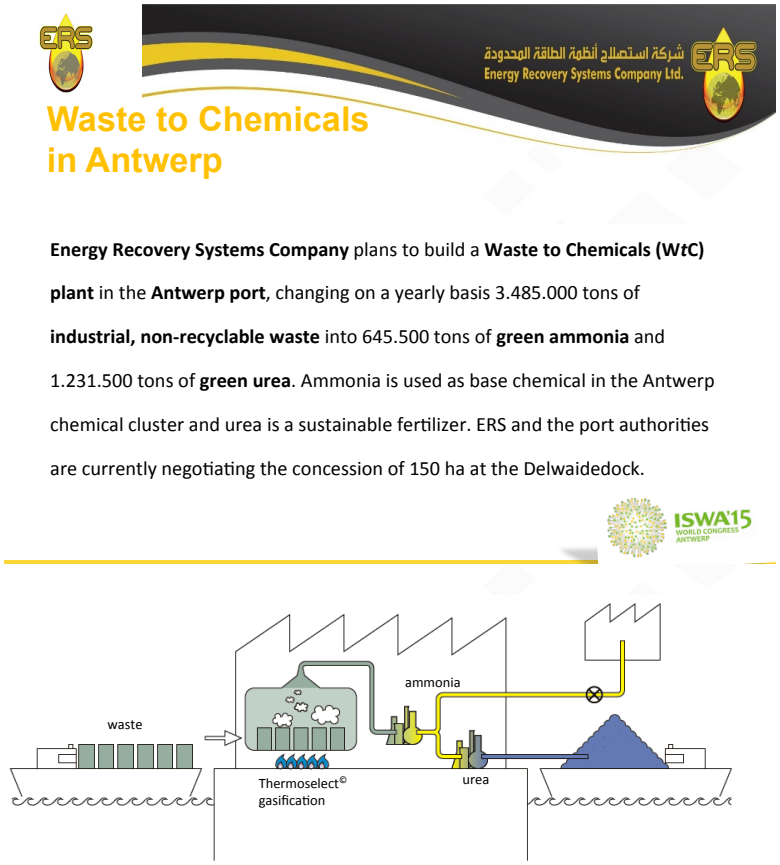
FUTURE: Ammonia Innovation #1 + / - Haber-Bosch

- 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
  - Carbon Recycling: Biomass, Biogas, Waste (beware: GDP Growth v. Circular Economy)
  - Low / Zero-Carbon H_2
- Technology Diversification
  - Incremental Innovation, Haber-Bosch:
    - Efficiency: catalysts, temperature, pressure
    - Operations: intermittency
  - Radical Innovation: Solid State / Liquid State Electrochemical processes, etc

Trevor Brown: https://ammoniaindustry.com
"The Investment Case For Sustainable Ammonia Synthesis Technologies," NH3 Fuel Conference, September 20, 2016

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?



Trevor Brown: https://ammoniaindustry.com
"The Investment Case For Sustainable Ammonia Synthesis Technologies," NH3 Fuel Conference, September 20, 2016

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

  See: https://ammoniaindustry.com/ammonia-production-causes-1-percent-of-total-global-ghg-emissions/

- 1% is a big number

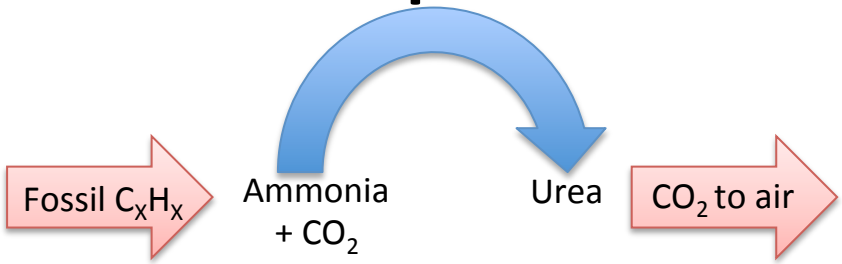
FUTURE: Ammonia Innovation #3 Carbon Reduction: Energy

- **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, O_2, CO_2
  - New Customers & New Markets

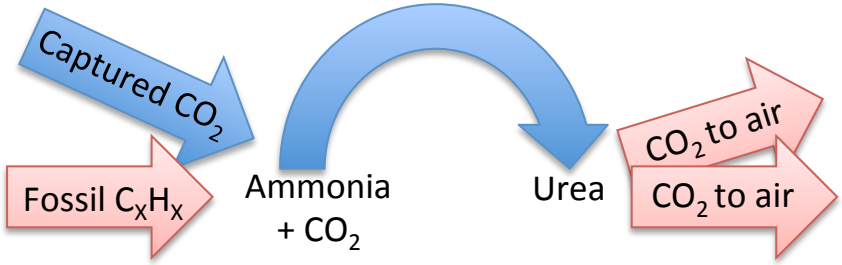
Trevor Brown: https://ammoniaindustry.com
"The Investment Case For Sustainable Ammonia Synthesis Technologies," NH3 Fuel Conference, September 20, 2016

FUTURE: Ammonia Innovation #4 Carbon Reduction: Biosphere

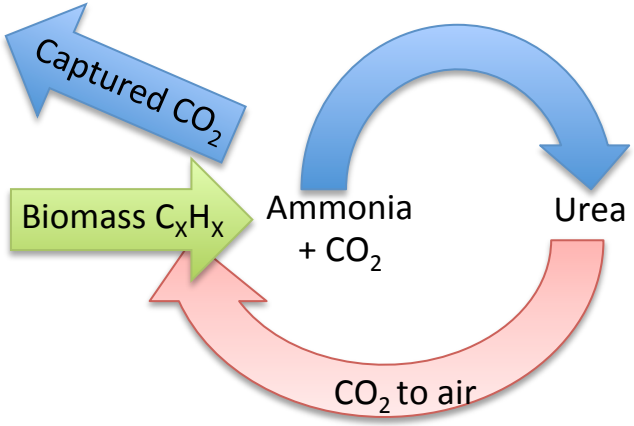
- Traditional Ammonia-Urea carbon "cycle":



- CCS Proposed Pathway:
  "Urea Yield Boosting"
  - Note: nonsense carbon accounting
  - See: "Urea Production is Not Carbon 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



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 km^2 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