Ammonia: Bottled Sunshine

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Ammonia as energy vector

- Truly zero-carbon fuel:
  - can be produced anywhere from nitrogen (78% in air), water and renewable energy or from fossil fuels with carbon capture
- Energy dense (liquid):
  - 4.3 kWh/L, 5.25 kWh/kg
  - 17.75% hydrogen, 121 kg H/m³
- World production 180MM tons per year (~1,000,000 GWh) for fertilizer and chemicals
- Can be easily transported and indefinitely stored as liquid at 10 bar or -33°C
- Can be utilized by multiple ways (electricity, motive power, hydrogen carrier):
  - internal combustion engines
  - turbines
  - solid oxide fuel cells
  - heat generation
  - hydrogen generation for FCEVs
- Excellent safety record
Drivers for clean ammonia

• Decarbonization of fertilizers production – decrease carbon intensity of food and biofuels - ammonia synthesis constitute 1.44% of global CO₂ emissions

• Decarbonization of transportation fuels
  - maritime shipping presents the greatest opportunity
  - hydrogen generation from ammonia enables remote FCEV fueling stations

• Energy delivery
  - the least expensive way for long distance energy delivery

• Long duration energy storage
  - offsetting intermittency of renewable energy sources
  - utilizing unused generating capacity and waste heat of nuclear plants/CSP

• Decarbonization of industrial processes
  - replacing fossil fuels in heat intense processes (steel/cement/grain drying)

• Falling renewable electricity price makes zero-carbon ammonia cost competitive
Clean ammonia synthesis pathways

“Green” ammonia

Renewable electricity

Water → Electrolysis

“Turquoise” ammonia

Natural gas or biogas → Cracking

Steam methane reforming

H₂ → Haber-Bosch

H₂O and N₂ → ASU

Air → ASU

H₂ → Haber-Bosch

Separation

NH₃ → NH₃

Green ammonia

✓ True zero-carbon
✓ No need in CO₂ storage, no leaks
✓ No long-term liability
✓ High energy consumption and CAPEX

Blue ammonia

✓ Abundant and cheap feedstock
✓ Established SMR technology
✓ Easy scaleup
✓ High carbon footprint

Turquoise ammonia

✓ Abundant and cheap feedstock
✓ No CO₂ leaks
✓ Carbon may be a valuable product
✓ High temperature process/CAPEX

• Carbon intensity is an ultimate measure
• Clean ammonia certification is a key
Clean ammonia use

- **Transportation fuel**
- **Fertilizer**
- **Heating**
- **Power generation**

NH₃
Clean ammonia market potential

- Currently ammonia is used mostly for fertilizers and chemicals production
- Market size is $71.2B in 2019 and expected to grow to $81.4B by 2025 at a CAGR of 5.59%
- Green and blue ammonia predicted CAGR is 54.9%
- Green and blue ammonia will dominate by 2050
- The use as maritime fuel will double current ammonia production by 2050
- The use for energy storage and hydrogen delivery will multiply this number even further

MacFarlane et al., A Roadmap to the Ammonia Economy, Joule, 2020
World attitude to low carbon ammonia is changing

Number of publications increased 3-5x in last five years
Multiple feasibility studies by industry, professional societies and governments
• The Netherlands, UK, US, Australia, Germany
Pilot demonstrations underway
• Japan, the Netherlands, UK, US
Several large-scale green and blue ammonia plants announced
• Australia, Chile, Denmark, Kazakhstan, Kenya, New Zealand, Norway, Oman, Russia, Saudi Arabia, UAE, US
Green/blue ammonia on the roadmap of major ammonia players
• Casale*
• CF Industries
• Haldor Topsoe
• KBR
• Nutrien*
• thyssenkrupp Industrial Solutions
• Yara
Ammonia utilization under fast development
• Power generation and energy storage (turbines, ICEs, fuel cells)
• Low carbon fuel (maritime, rail, off-road vehicles)
  *

*participate in REFUEL
CSP for ammonia production technologies

- Use solar heat to energize conventional Haber-Bosch process
  - requires CCS or integration with urea plant
- High temperature steam electrolysis integrated with Haber-Bosch process
  - most advanced but energy consuming
- High temperature steam electrolysis combined with thermochemical cycle
  - high temperature materials required, cyclic process
- Photo- and electrocatalytic direct conversion of H₂O and N₂
  - very early stage
- Use of ammonia for thermal storage
- Thermochemical air separation
CSP enabled Haber-Bosch processes

Ammonia synthesis

Air separation unit

Air

O₂

N₂

H₂ + N₂

H₂

O₂

HX

Ammonia synthesis

SOEC stack

H₂O

Compressor

H₂

O₂

Ammonia separation

Ammonia storage

Air

Electricity

Electricity

Electricity

Solar heat

Ammonia based thermal storage

700°C

450°C

700°C

450°C

Source: K. Lovegrove et al., 2017

The projected installed cost of ammonia based CSP with six hours of storage $13/kWhᵣ (less than SunShot target of $15/kWhᵣ)
CSP enabled thermochemical synthesis

Thermochemical ammonia synthesis

Coupled thermochemical hydrogen generation

Major goal to reduce CAPEX and increase energy efficiency

- Research focus:
  - novel catalysts for low pressure ammonia synthesis
  - chemical looping materials (cycling, morphology), high temperature materials
  - methods for ammonia separation from reaction mixture (membranes, adsorbents)
  - direct methods for ammonia synthesis (electrochemical, plasma, nitrogen reduction)

- Development and deployment focus:
  - reactor design
  - heat integration of all process steps
  - algorithms for transient operations
  - demonstration of whole system in the field

- More R&DD investment needed in renewables generation (CSP), hydrogen production, ammonia synthesis and utilization
Mission
Reduce transportation and storage costs of energy from remote renewable intermittent sources to consumers and enable the use of existing infrastructure to deliver electricity or hydrogen at the end point.

Investment areas and impacts

1. **Area:** Small- to medium-scale synthesis of energy-dense carbon-neutral liquid fuels using water, air, and renewable energy source.
   **Impact:** Develop technologies to produce fuels at cost <$0.13/kWh to enable long term energy storage.

2. **Area:** Electrochemical processes for generation of hydrogen (2a) or electricity (2b) from energy-dense carbon-neutral liquid fuels.
   **Impact:**
   a) Develop catalytic or electrochemical fuel cracking to deliver hydrogen at 30 bar at the cost <$4.5/kg enabling hydrogen fueling stations;
   b) Develop fuel cell technologies for conversion of fuels to electricity with source-to-use cost <$0.30/kWh.

<table>
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<tr>
<th>Program Director</th>
<th>Dr. Grigori Soloveichik</th>
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<tbody>
<tr>
<td>Year</td>
<td>2017</td>
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<tr>
<td>Projects</td>
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<tr>
<td>Total Investment</td>
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REFUEL+IT (Integration and Testing) Program

- Leverages success of several REFUEL projects in NH$_3$ synthesis and isolation
- Utilizes excess renewable power that would otherwise be curtailed (“load following”)
- Low carbon ammonia can be used for agriculture, energy storage and transportation
- Target scale: ~1 ton/day, ~500kWh of renewables; estimated cost ~ $ 15MM
  - Test site location: wind and solar farm site(s)
  - Slipstream for demonstration of ammonia use (hydrogen production and ammonia fuel cells)

Water ($\text{H}_2\text{O}$) flows through an electrolysis process to produce hydrogen ($\text{H}_2$) and oxygen ($\text{O}_2$). The hydrogen is then used in a modified reaction process to produce ammonia ($\text{NH}_3$). A modified separation unit is used to separate the ammonia. The diagram highlights the integration and testing of new and commercially available technologies in a real-life modular and flexible plant.

A modular, flexible plant to validate technologies in real life
Ammonia: bottled sunshine

Ammonia is an ideal energy carrier to be produced by CSP

• High production efficiency due to heat utilization
• Low operating costs
• Inexpensive ammonia based thermal storage
  - thermal storage and ammonia generation could use the same reactors/BOP
• Design flexibility (both Haber-Bosch and thermocycle approach could be used)
  - hydrogen could be generated by thermal cycling or HT steam electrolysis
• Feedstock availability
  - easy to separate nitrogen present everywhere including deserts
• Internationally traded commodity, developed infrastructure and market