Ammonia-Based Energy Storage (NH3-BEST)

Critical Challenges.

Presented at:
U.S. Department of Energy
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Integrated Energy Storage via NH₃-BEST

Ammonia assets as energy storage medium
- High hydrogen/energy content
- Low storage cost
- Near-zero explosivity hazard
- Carbon-free composition means no CO₂ emitted when converted to electricity, via fuel cell or combustion
- Long-established globally fungible commodity, offers economic flexibility via selling and/or buying to capitalize on market conditions or address production/supply challenges

Major project outcomes
- Preliminary design of NH₃-BEST subsystem and associated EGU integration requirements
- Modeled demonstration of NH₃-BEST performance, including estimated round-trip efficiency and preliminary economics when integrated with an EGU
- Road map for bringing ammonia energy storage to commercial deployment
NH₃-BEST Unit Operations

1-Step Electrolytic NH₃ Synthesis (Power Consumption)
- Under development at EERC

Direct NH₃ Fuel Cell (Power Generation)
- Commericially available
- Under development around the world
Nameplate Capacity: 435 MW
Major Deep Cycle: 250 MW (185 MW spread)
Yearly Net Generation (MW) – EGU-2

Nameplate Capacity: 427 MW
Major Deep Cycle: 150 MW (277 MW spread)
Nameplate Capacity: 437 MW
Major Deep Cycle: 180 MW (257 MW spread)
Objectives/assumptions for building NH3-BEST model

• Plant/EGU operates at nameplate capacity (NPC)
• Plant follows load until demand drops to 25 MW below NPC (NPC – 25 MW)
• When demand drops to NPC – 25 MW, NH3 electrolyzer kicks in, plant ramps up to NPC, and excess power is diverted to NH3 production and storage
• During NH3 electrolyzer operation, EGU runs at NPC, with electrolyzer modulating all demand fluctuations, until demand increases to NPC
• When demand increases to NPC, electrolyzer shuts down until demand again drops to NPC – 25 MW
• Stored NH3 utilization options:
  ▪ Sell into NH3 fertilizer market
  ▪ Conversion to power in direct NH3 fuel cell (or NH3 turbine) to meet grid call for more power
  ▪ Pipeline to planned Hydrogen Hub (near EGU-2) resulting from conversion of DGC coal gasification plant (major NH3 producer) to natural gas-fueled hydrogen plant
Ammonia synthesis unit (electrolyzer) operational strategy

- Demand = NPC
- Demand = NPC – 25 MW
- Demand = EGU minimum acceptable operational capacity

Electrolyzer: off on off
EERC Low-Pressure Electrolytic Ammonia Production (LPEA) via Integrated (in single cell) Water Electrolysis/N2 Reduction

Targeted availability 2024 – total energy input requirement of 7.9 MWh/tonne NH₃

All energy values based on amount needed to produce 1 tonne NH₃

[Diagram description]

- Air flows through N₂ Separation, producing N₂.
- O₂ Storage captures O₂.
- NH₃ Synthesis via LPEA Process: (300°C, 15 psi)
  - NH₃ Synthesis
  - Dehydration?
  - NH₃ Separation (Compressive Condensation)
- Water Treatment
- H₂O Production
- N₂, H₂ Recycle
- NH₃ Storage: 200 psia
- Sales: Electricity Generation

Energy Values:
- 0.4 MWh: N₂ Separation
- 6.4 MWh (target): NH₃ Synthesis
- 0.9 MWh: NH₃ Separation
- 0.1 MWh: Dehydration
- 0.1 MWh: Water Treatment
- 0.4 MWh: O₂ Storage

Sales? Water? H₂O? N₂, H₂ Recycle
NH3 Synthesis via Water Electrolysis + Electrically Driven Haber-Bosch
Technology available today – total energy input requirement of 12 MWh/tonne NH₃*
All energy values based on amount needed to produce 1 tonne NH₃

*NProton Ventures NFuel 20 (60 t/d) plant, 2017
According to the U.S. Energy Information Administration (EIA), annual average electricity prices in 2020 were:

- Residential: 13.15¢ per kWh
- Commercial: 10.59¢ per kWh
- Transportation: 9.90¢ per kWh
- Industrial: 6.67¢ per kWh

*Based on $28/MWh electric rate determined as follows:
From: Otter Tail Power Electric Rate Schedule – 2019,
Winter (May–October) Residential Rate = 5.446 ¢ per kWh.
So, using 5.446 and EIA Residential/Industrial (13.15/6.67) ratio,
North Dakota Industrial Rate estimated at $28/MWh.

**MacFarlane, 2020, A roadmap to the ammonia economy; and
Torrente-Murciano, 2020, Current and future role of Haber Bosch ammonia in a carbon-free energy landscape.
<table>
<thead>
<tr>
<th>Technology Pathway</th>
<th>Commercial</th>
<th>Challenges, Considerations, Limitations</th>
<th>Attributes: Known and Likely</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolysis + electrically driven Haber Bosch</td>
<td>Today</td>
<td>Max plant size available today? cost? Economics of intermittent operation</td>
<td>Economics workable @≥10 t/d, near HB-competitive @ ≥60 t/d. Modularity for scale-up as needed.</td>
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<tr>
<td>Electrolysis/N2 reduction (EERC target)</td>
<td>2024</td>
<td>≥300°C H⁺ exchange electrolyte needed for temp/heat to break N₂ bond. Water electrolysis at anode, NH₃</td>
<td>Direct use of H⁺ (versus going through H₂ intermediate) in single electrolytic reactor means lower capex/opex, energy consumption</td>
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<td>synthesis at cathode → tough kinetics.</td>
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<tr>
<td>SMR/Haber Bosch (Included for comparison)</td>
<td>Today</td>
<td>Economic viability→≥1000t/d→big capex Constant operation for economic viability</td>
<td>Mature technology, near max energy efficiency</td>
</tr>
</tbody>
</table>
Next steps for building NH3-BEST models (LPEA and Electrolysis + HB)

• Establish (preliminary) capacity of NH3 synthesis reactor
• Establish accurate efficiency, reactant utilization, and overall energy consumption values for all NH3-BEST unit operations (NH3 synthesis module plus balance-of-plant units)
• Establish capacity, capex, and opex values for all NH3-BEST unit operations
• Establish utility-sanctioned electricity cost values
• Integrate NH3 synthesis/storage (front end) with NH3 utilization (back end) options:
  1) Power generation via direct NH3 fuel cell (SOFC viable today? near term? operating temp impact on response time?)
  2) Power generation via NH3 turbine (Mitsubishi says 2025 for 40-MW unit)
  3) Sell to regional and/or export markets (Japan building ammonia energy economy)
  4) Pipeline to planned Beulah ND hydrogen hub (facility currently producing NH3 from coal)
“Considering the current status of the market, prices would appear to have peaked in February with the latest and largest Tampa ammonia settlement on record, leaving us with a stable-to-softening short-term price outlook heading into spring.”

2/11/2022
Illinois ammonia price was $1,498 on February 10, $1,503 on February 24 (Russia invaded Ukraine). On March 23, price was $1,516.