Ammonia: Bottled Sunshine

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Ammonia as energy vector

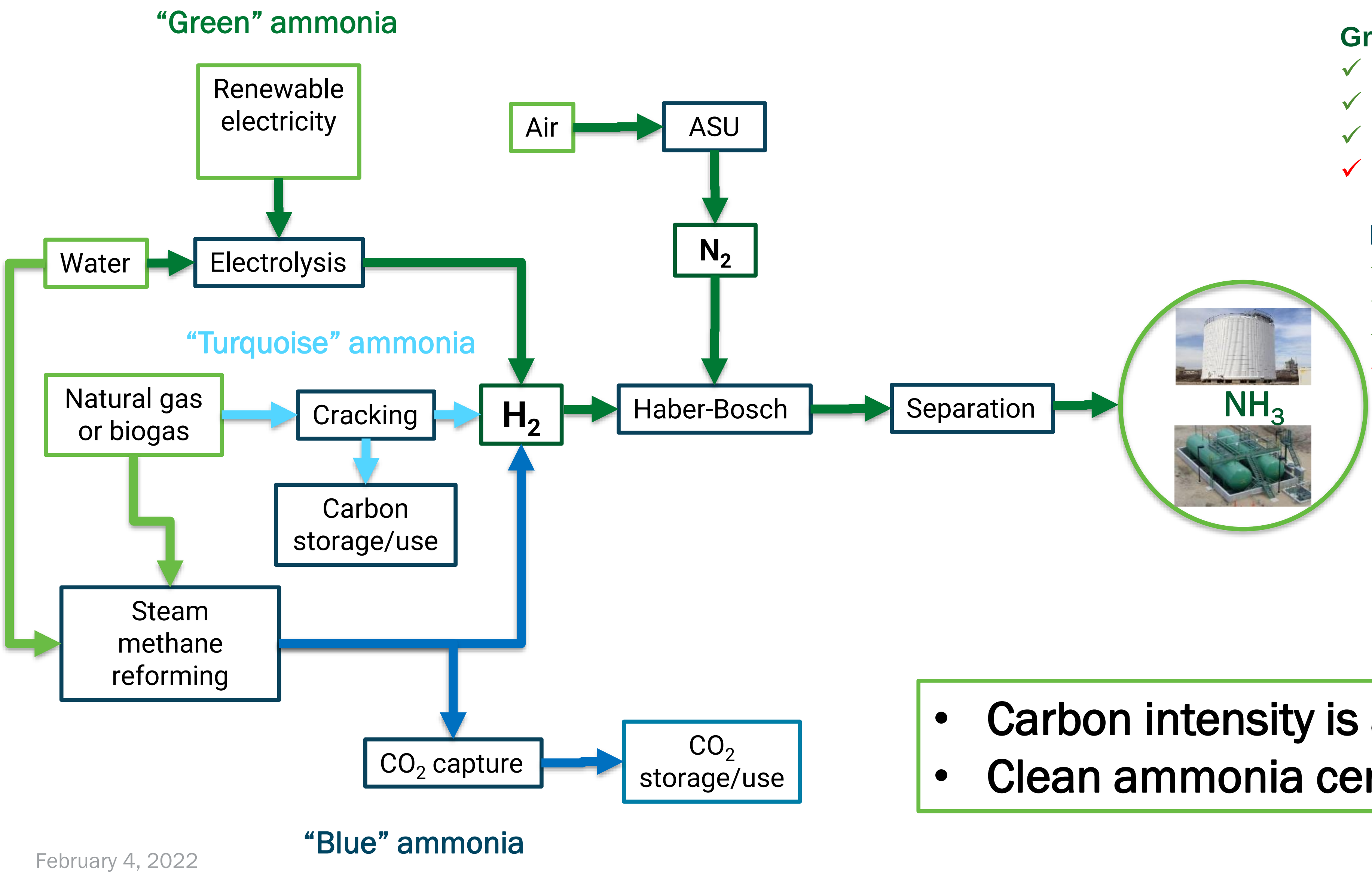
- **Truly zero-carbon fuel:**
  - can be produced anywhere from nitrogen (78% in air), water and renewable energy or from fossil fuels with carbon capture
- **Energy dense (liquid):**
  - 4.3 kWh/L, 5.25 kWh/kg
  - 17.75% hydrogen, 121 kg H/m^3

- **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^{o}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 CO_2 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



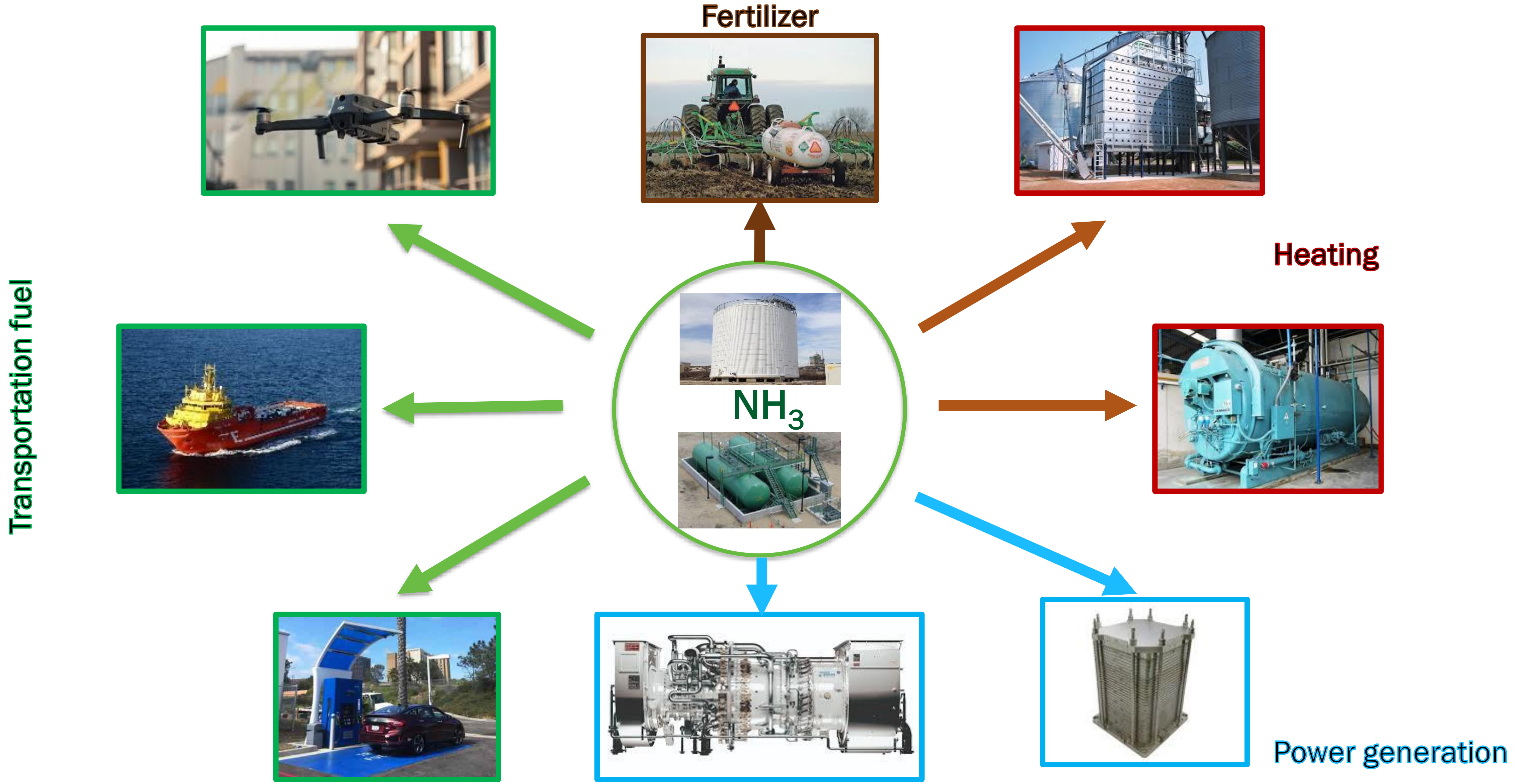
Green ammonia
- ✓ True zero-carbon
- ✓ No need in CO_2 storage, no leaks
- ✓ No long-term liability
- ✓ High energy consumption and CAPEX

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

Turquoise ammonia
- ✓ Abundant and cheap feedstock
- ✓ No CO_2 leaks
- ✓ Carbon may be a valuable product
- ✓ High temperature process/CAPEX

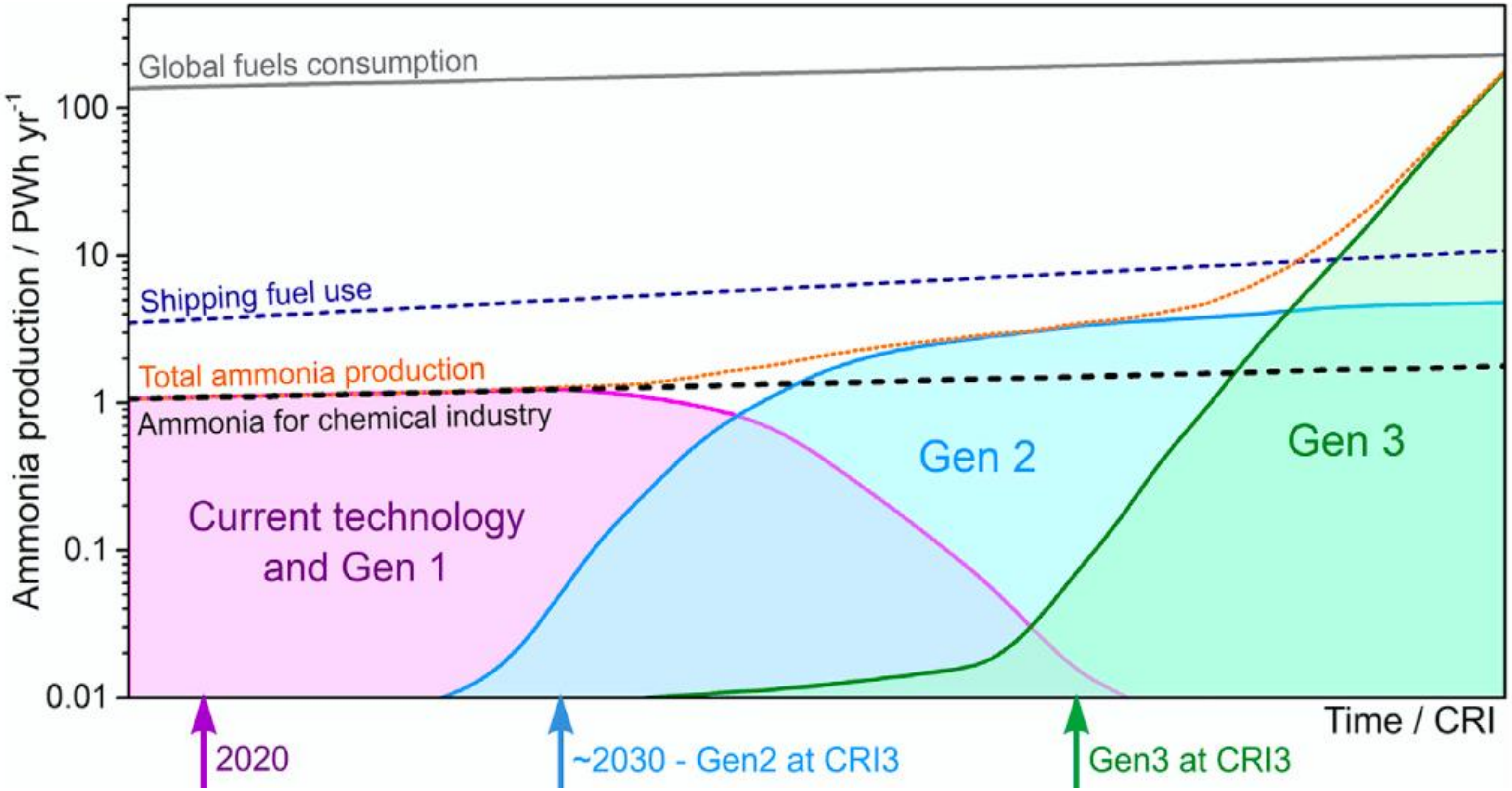
- **Carbon intensity is an ultimate measure**
- **Clean ammonia certification is a key**

Clean ammonia use



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

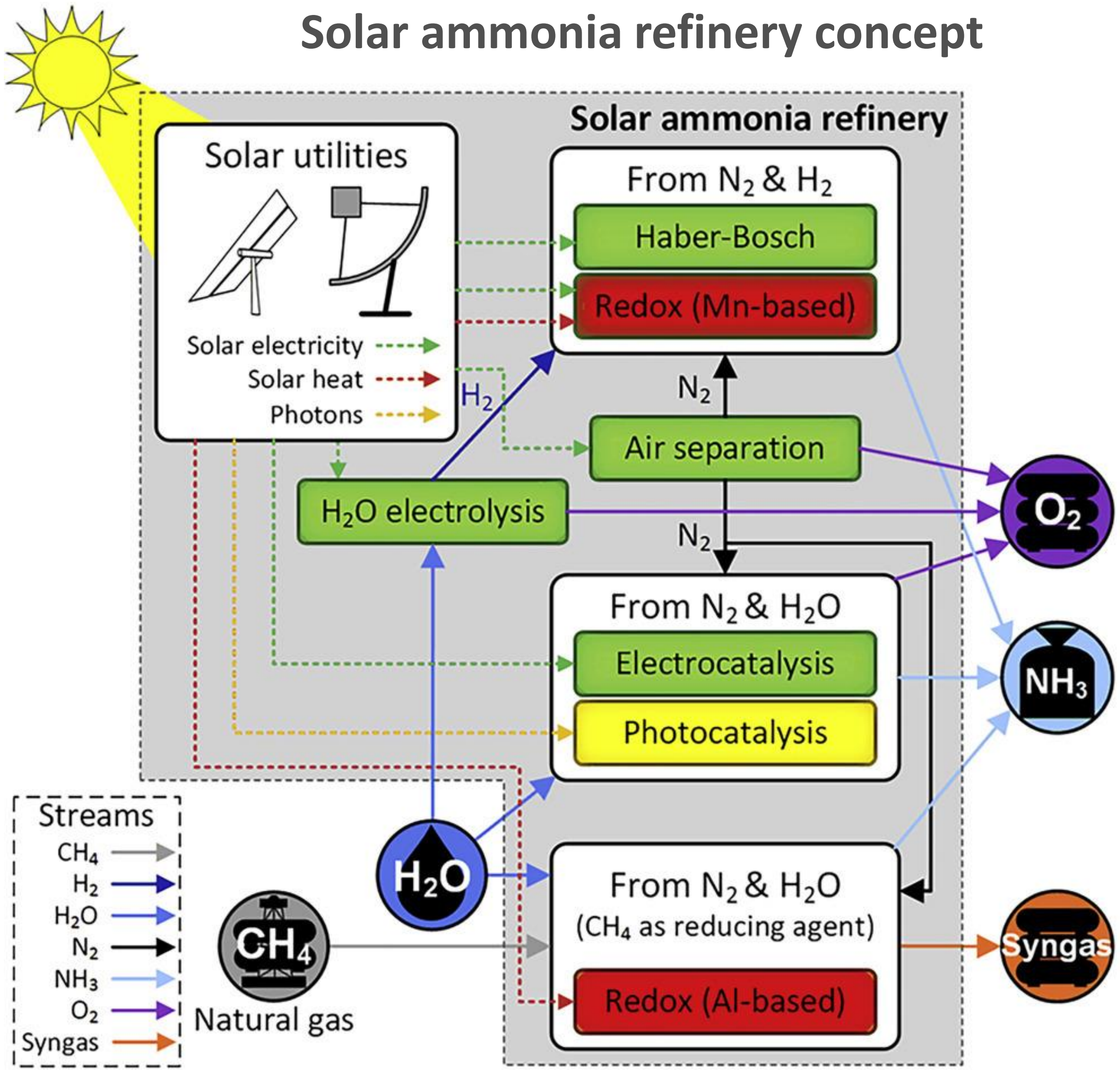
- Casale*
- CF Industries
- Haldor Topsoe
- KBR
- Nutrien*
- thyssenkrupp Industrial Solutions
- Yara

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 and ammonia alliance



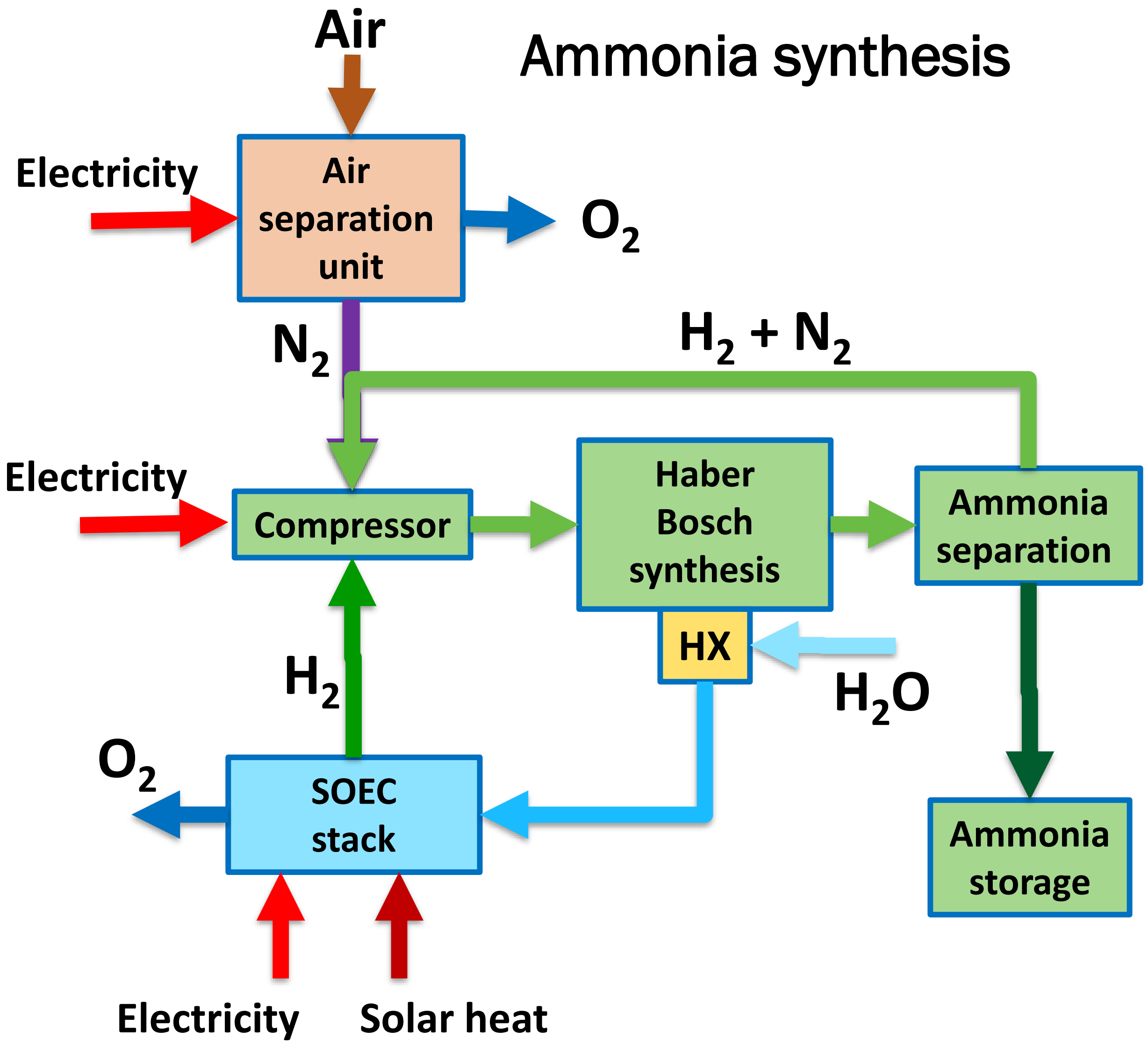
L. Wang et al., *Joule* **2** (2018) 1055

CSP for ammonia production technologies

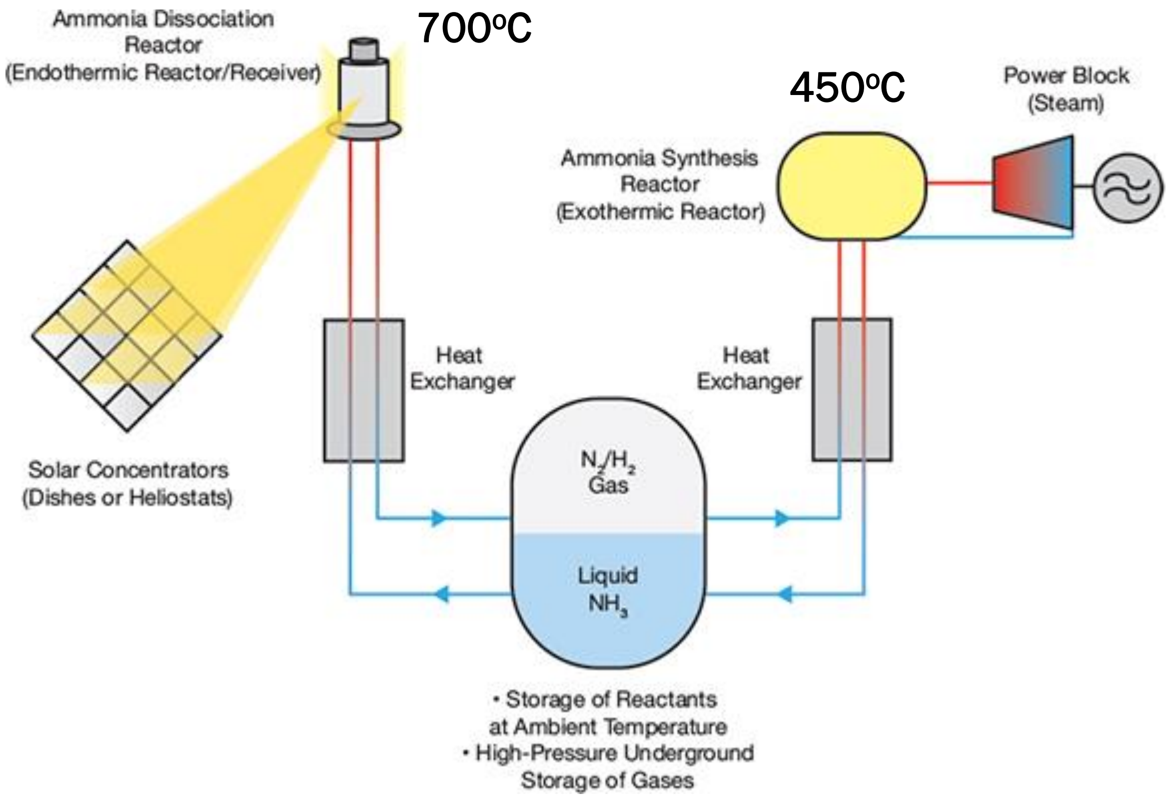
- Use solar heat to energize conventional Haber-Bosch process
  - requires CCS or integration with urea plant
- High temperature steam electrolysis integrated with Haber-Bosch process
  - most advanced but energy consuming
- High temperature steam electrolysis combined with thermochemical cycle
  - high temperature materials required, cyclic process
- Photo- and electrocatalytic direct conversion of H_2O and N_2
  - very early stage
- Use of ammonia for thermal storage
- Thermochemical air separation

CSP enabled Haber-Bosch processes

Ammonia synthesis



Ammonia based thermal storage

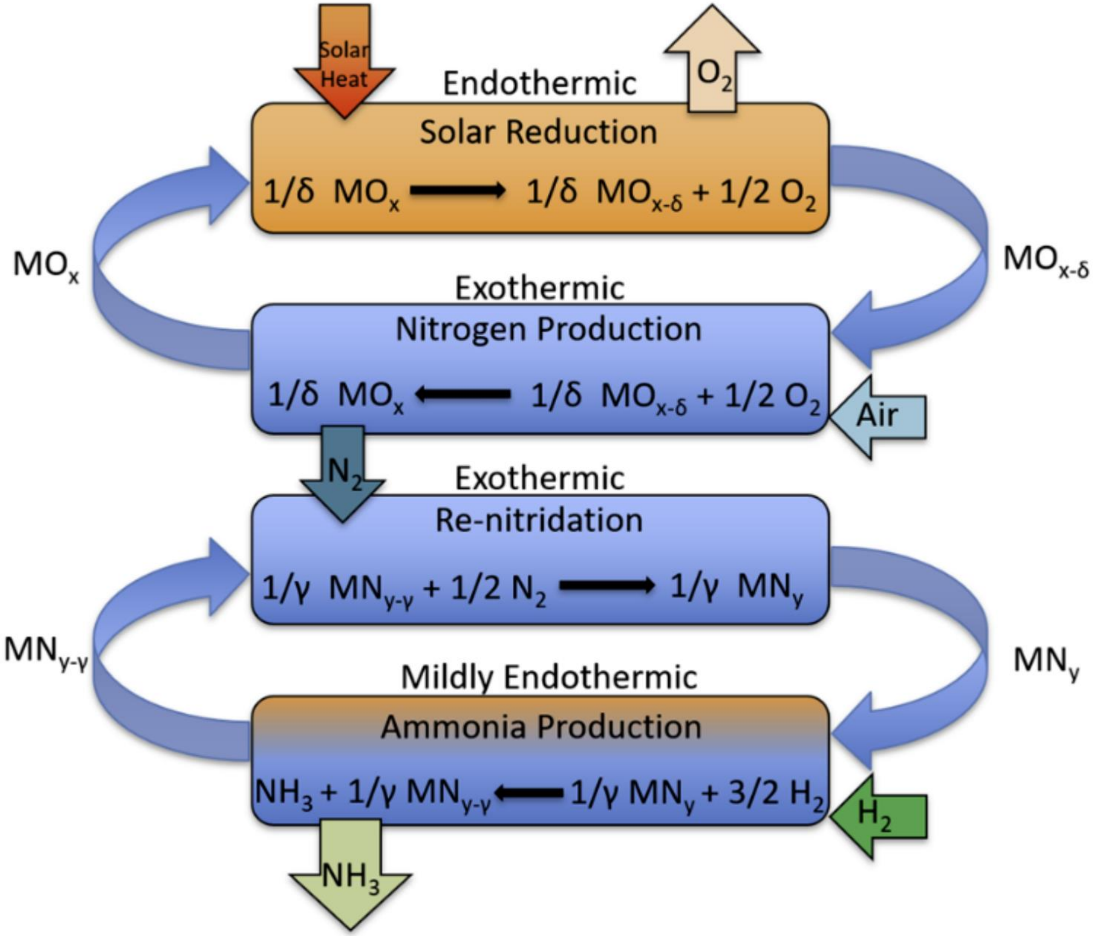


The projected installed cost of ammonia based CSP with six hours of storage $13/kWh$_{th}$ (less than SunShot target of $15/kWh$_{th}$

Source: K. Lovegrove et al., 2017
https://www.aiche.org/resources/publications/cep/2017/july/leveraging-ammonia-industry-solar-energy-storage

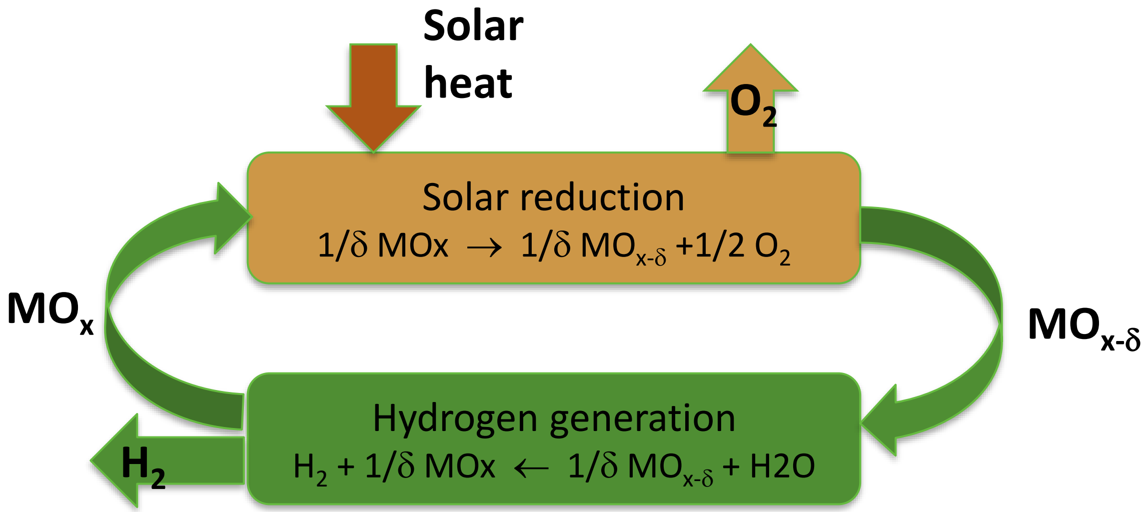
CSP enabled thermochemical synthesis

Thermochemical ammonia synthesis



https://www.solarpaces.org/to-make-zero-emissions-ammonia-us-researchers-design-a-novel-solar-reactor/

Coupled thermochemical hydrogen generation



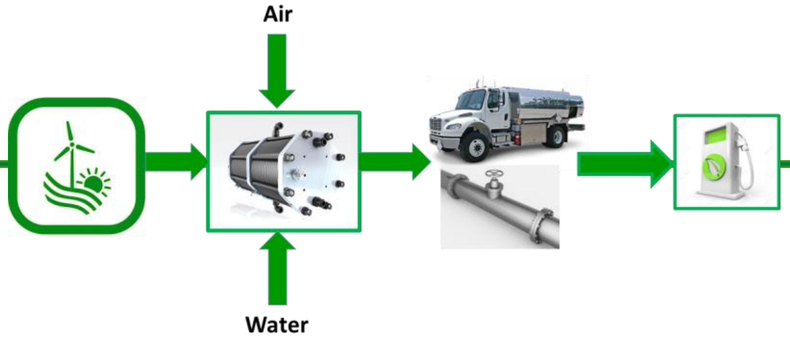
Research and investment needs for CSP ammonia

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

REFUEL

Renewable Energy to Fuels through Utilization of Energy-dense Liquids



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

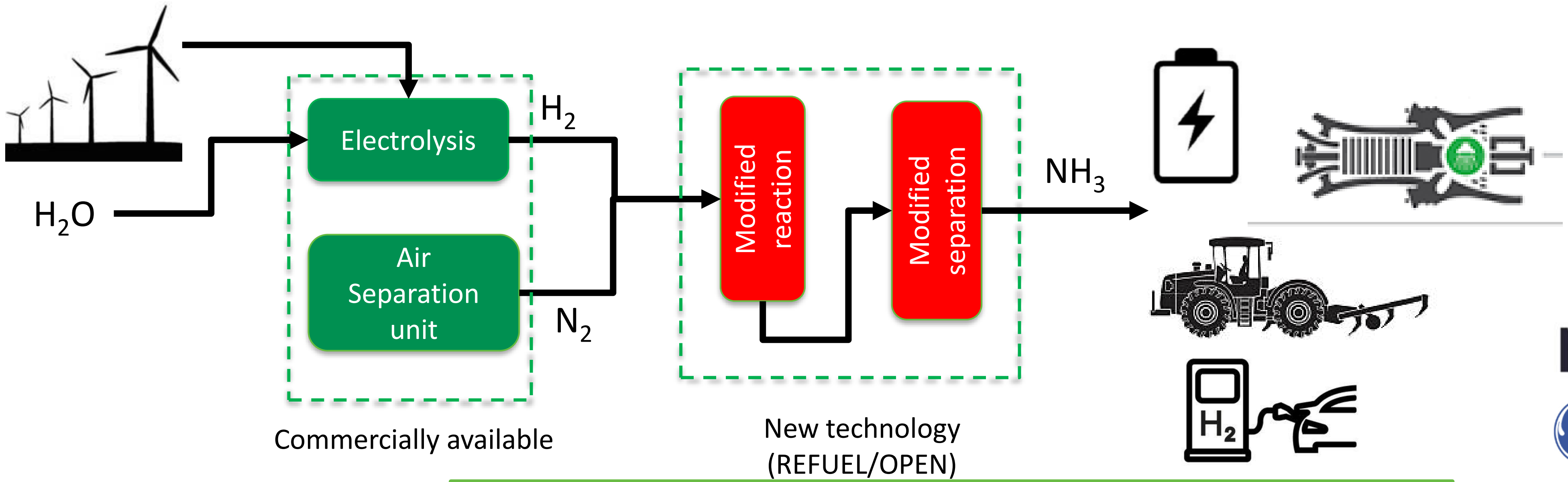
Program Director	Dr. Grigorii Soloveichik
Year	2017
Projects	16
Total Investment	$36 Million

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 .

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)



A modular, flexible plant to validate technologies in real life

RTI INTERNATIONAL
CASALE
UNIVERSITY OF MINNESOTA MORRIS
nel
GE Global Research
Chemtronergy

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**