PROTON® ON SITE
nel· number one by nature
YOUR SOURCE FOR ALL THINGS HYDROGEN

"Nitrogenase Inspired Peptide-Functionalized Catalyst for Efficient, Emission Free Ammonia Production"

NH3 Fuel Conference 2017, Minneapolis

Stephen Szymanski, Director – Business Development

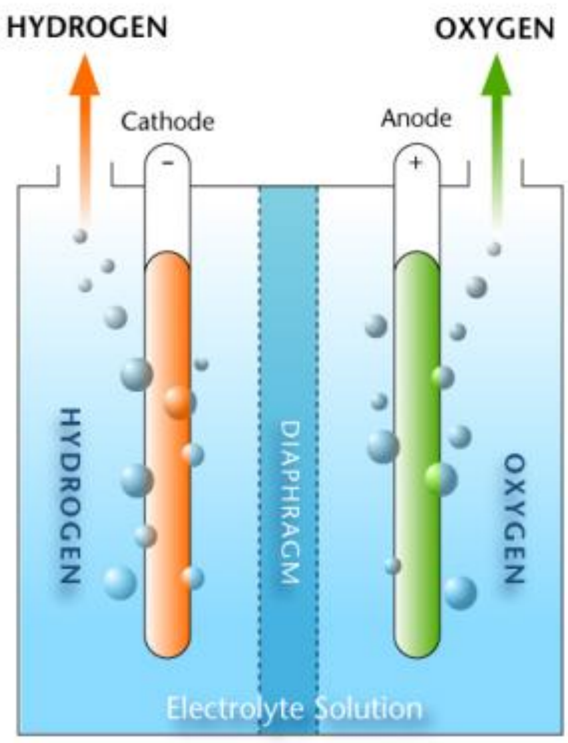
November 8, 2017

Proton OnSite Overview

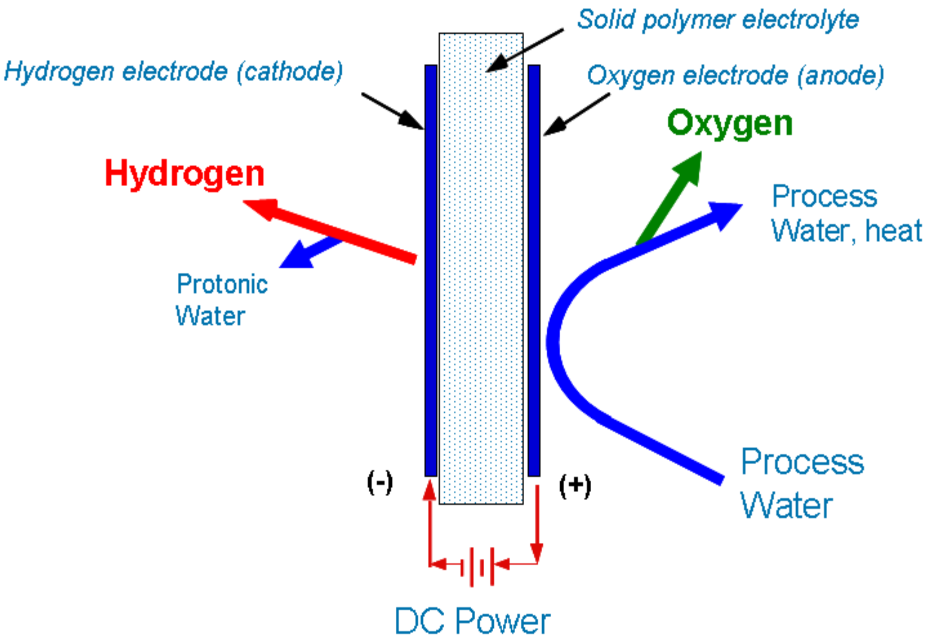
- World leader in PEM water electrolysis
- Subsidiary of Nel ASA, based in Oslo, Norway
- 2,700 Systems delivered in 75 countries for:
  - Industrial applications
  - Laboratory markets
  - Military customers
  - Fueling and energy storage
- ISO 9001:2008 certified
- ~ 100 employees at U.S. operations

Commercial Electrolysis Technologies

- Liquid KOH
  - Enables non-noble metals
- PEM = solid electrolyte
  - Simple, low maintenance BOP



Liquid KOH



Proton Exchange Membrane (PEM)

Scalable Technology

From Single to Multi-Stack Systems

HOGEN® GC

HOGEN® S Series

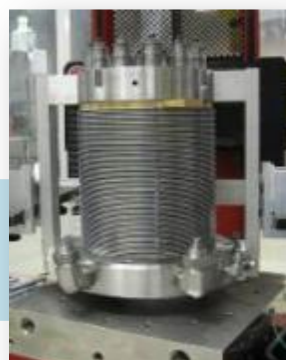
HOGEN® H Series

HOGEN® C Series

HOGEN® M Series

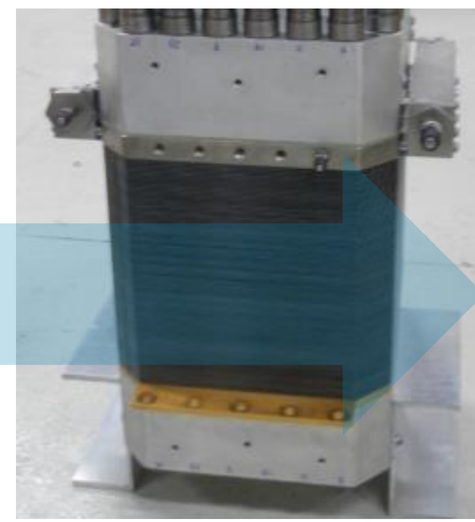
28 cm^2
0.05 Nm^3/hr
0.01 kg/day

86 cm^2
2 Nm^3/hr
4.3 kg/day



210 cm^2
10 Nm^3/hr
21.6 kg/day

680 cm^2
50 Nm^3/hr
100 kg/day



Renewable ammonia production yesterday…

Rjukan, Norway; 1927 – 1970's

Glomfjord, Norway; 1953 – 1991

- Two largest electrolyser plants worldwide
- Capacity: 30 000 Nm^3/h each
- Energy consumption: approximately 135 MW each
- Supplied by renewable hydro power

Source: NEL Hydrogen

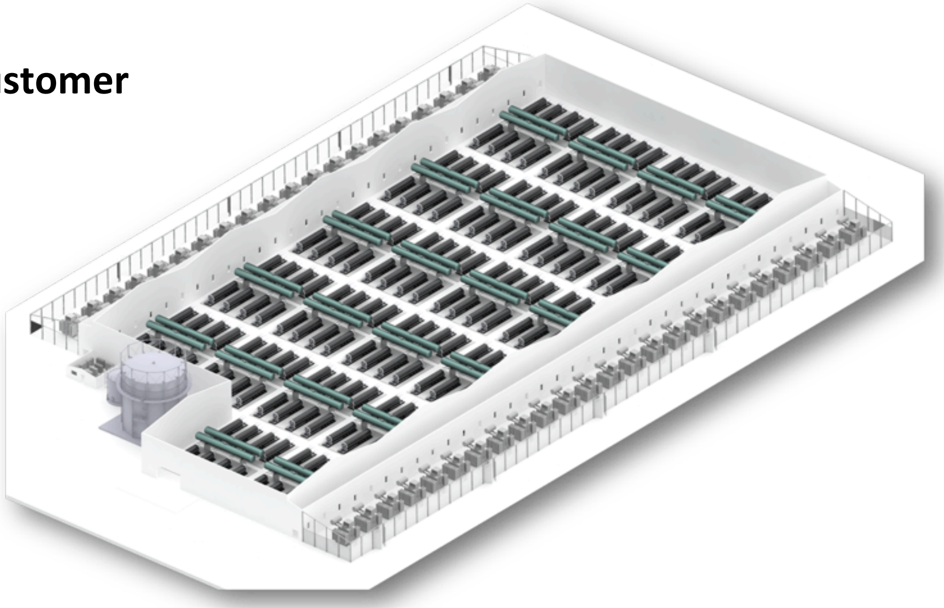
… and large scale electrolysis plants for today’s energy markets

Nel Hydrogen GIGA Factory concept:
400 MW system design study for commercial customer

Largest electrolyser plant ever designed

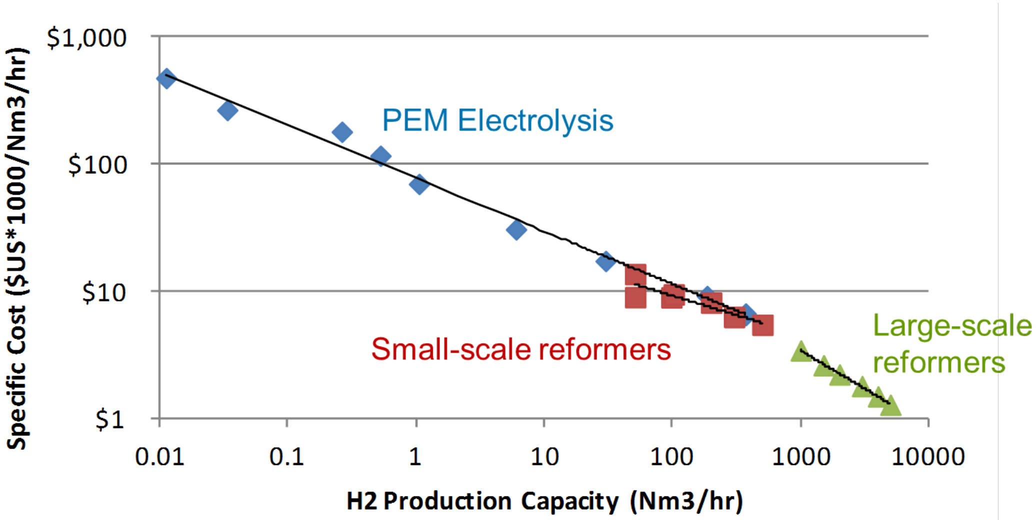
- International industrial customer
- Tied to solar power
- CAPEX: ~$175M
- Benchmark CAPEX ratio: $450/kW

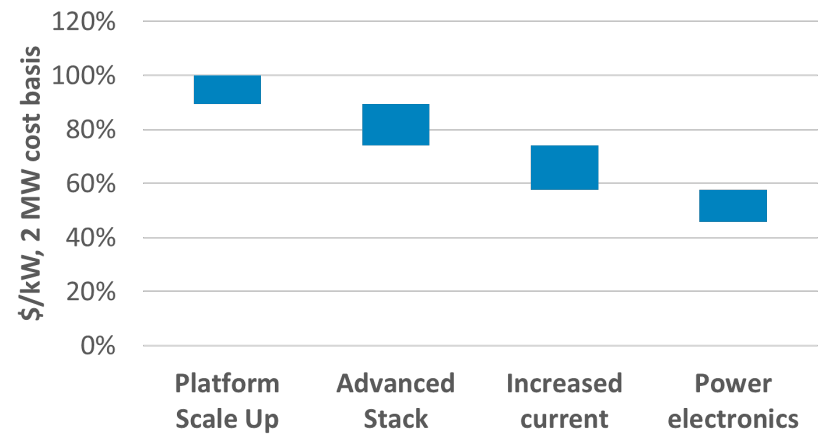
- **Capacity for more than 300,000 FCEVs**
  - Plant intended primarily for power-to-gas applications



Research needs: large scale, renewable H_2

- Smallest HB reactors are 3-10 tons/day
- Larger reactors are currently more cost effective
- Distributed options will need advancements for both steps
  - H2 production scale up; efficient scaled down HB
- Electrolysis shows capital cost pathway but work needed across multiple areas

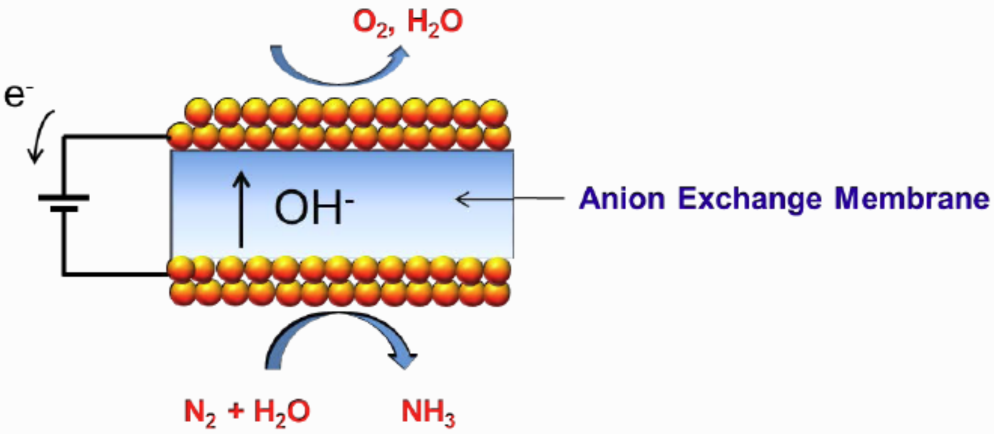




Low Temperature Electrochemical Ammonia Synthesis Approach

<u>Concept:</u>

- Electrolysis anode, ammonia generation at cathode
- Alkaline membrane to enable range of catalysts



<u>Challenges:</u>

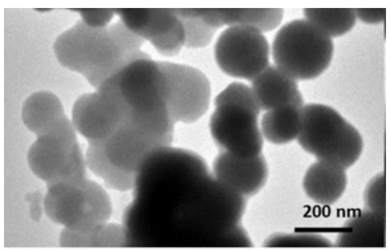
- Breaking N_2 triple bond
- Competing H_2 reaction
- Efficiency measurement at low production
- Efficiency requirements for cost targets

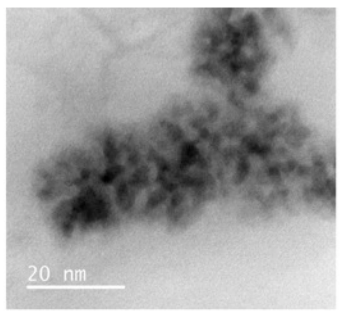
Catalyst design approaches

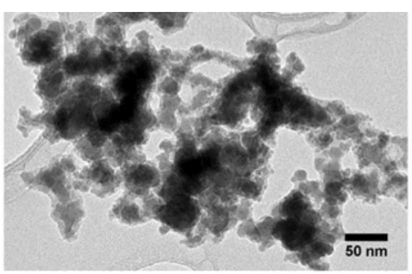
Further details in talks from L. Greenlee and J. Renner

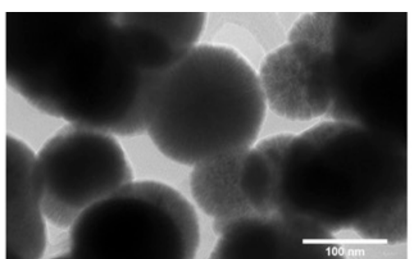
- Nanoparticle alloying

Control over size and composition



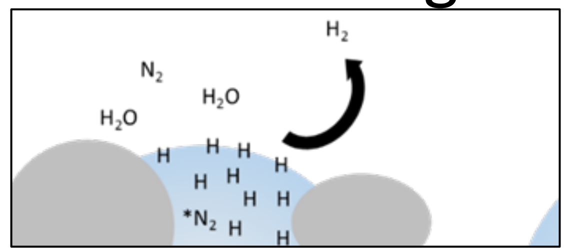






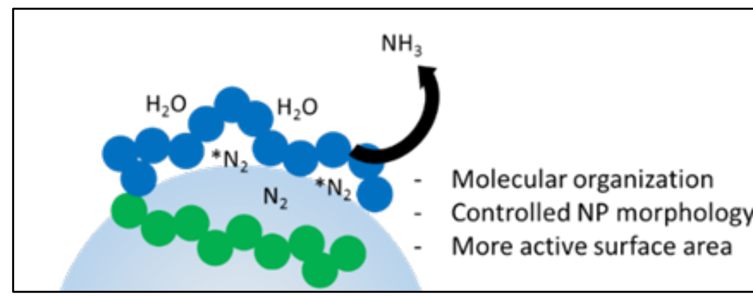
- Peptide templating

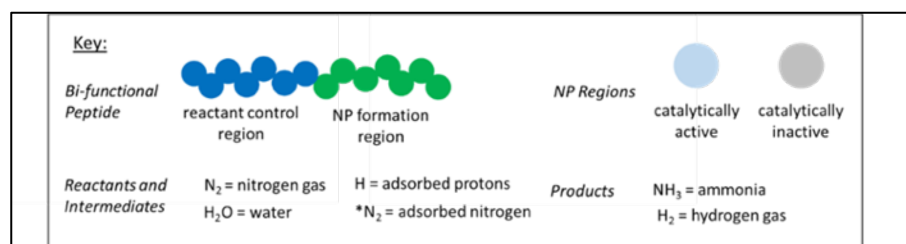
Molecular organization



Traditional Approach

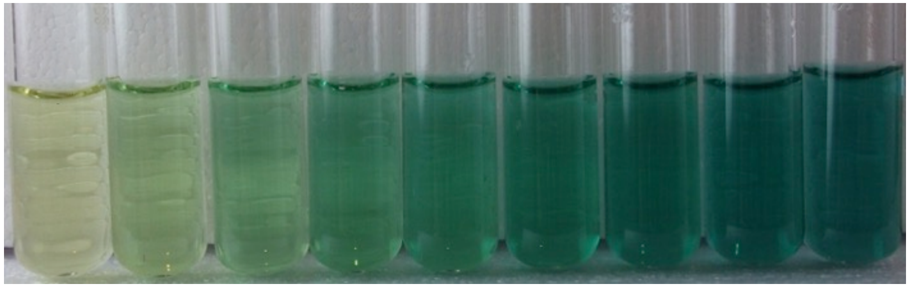
Peptide-modified nanoparticle approach

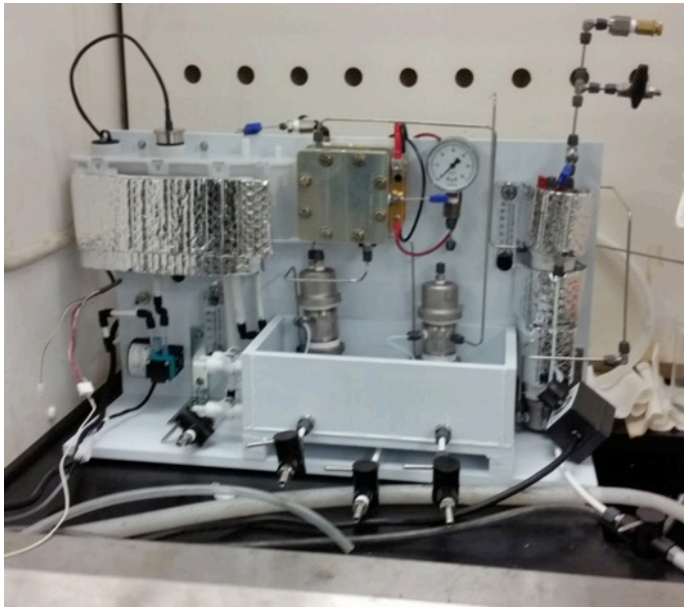




Test Development

- Pressurized low temperature electrochemical test stand
- Bake out process before build to remove N_2 contamination
- Argon controls for all experiments
- Assay for measurement of NH_3 quantity produced





Importance of Controls

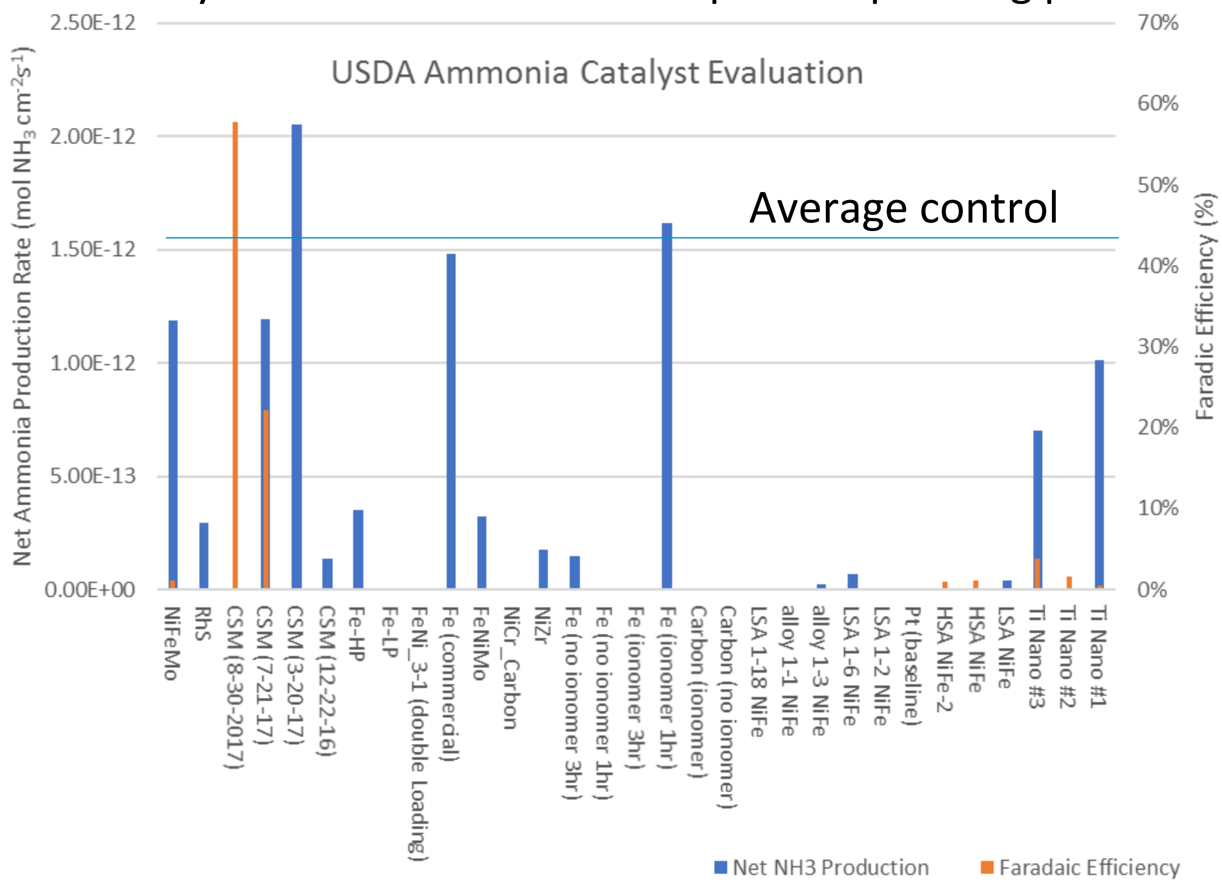
Sources of Contamination:

- Membrane backbone degradation: many AEMs have quaternary ammonium anions or other N sources
- Catalyst absorption/desorption of N2; decomposition of nitride-based catalysts
- Dissolved gases in flow fields, gas diffusion layers, cell parts
  - Can vary from day to day with environmental conditions
- Low generation levels make detection harder

Example Results

- Gross NH_3 measurement only 2X net generation
- Some samples with lower current are higher efficiency – larger net ammonia generation
  - Importance of H_2 suppression
- Pressurized cell showed better conversion

All measurements at constant potential; different catalysts could have different optimal operating points



Future Directions

- Catalyst architecture critical; need to tailor N_2 access, absorption strengths, and H_2 affinity
  - Programs to date have provided good direction
  - Need to suppress H_2 generation while designing active site for N_2 splitting
- Optimization of operating conditions
  - Upgrades to test stand for pressurization improved efficiency
- Need controls and accurate means for NH_3 detection
  - Direct GC integration needed for generation rate
  - Assay only provides total amount

Conclusions

- Renewable H_2 generation (via water electrolysis) reaching relevant scale for "green ammonia"
  - Will lead any transition
- Direct electrochemical pathway could be long term option
  - Promising directions being identified
  - Requires precise catalyst design and synthesis
- Industry-academia collaboration accelerates learning
  - Early device integration provides insights
  - Importance of operating conditions

Acknowledgements

Funding:

- USDA/NIFA
- DOE/AMO

Collaborators:

Lauren Greenlee
Univ. of Arkansas

Andrew Herring
Colorado School of Mines

Julie Renner
Case Western Reserve