Clean NH₃ fuel from wind & solar power to replace fossil fuels

- Wind & Solar become Fuel
- Raw materials: Air & Water
- Emissions: Nitrogen & Water
- Pollution: None
Wind & solar power plants – variable output

- 0 → 100% in a few hours
- Throttling wastes energy
- Fast-ramp NH\(_3\) plant best
Wind & solar power plants – variable output

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Existing NH$_3$ technology won’t work well

- Uses fossil fuel for feedstock & fuel
- Emits CO$_2$
- Cannot ramp quickly to follow wind & solar
Existing NH₃ technology won’t work well

- Uses fossil fuel for feedstock & fuel
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```
Fossil Hydrocarbon

<table>
<thead>
<tr>
<th>Water</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil Hydrocarbon</td>
<td>Steam Reforming</td>
</tr>
<tr>
<td>Air</td>
<td>Energy</td>
</tr>
<tr>
<td>Fossil Hydrocarbon</td>
<td>CO₂</td>
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</tbody>
</table>

Steady-State Reactor
```
Existing NH$_3$ technology won’t work well

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NH₃ liquefaction constrains operation

- NH₃ condenses from vapor to liquid just like water does
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- Need 21 atm pNH₃ for condensation at 50 °C
\( \text{NH}_3 \) liquefaction constrains operation

- \( \text{NH}_3 \) condenses from vapor to liquid just like water does.
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Fossil Hydrocarbon

Water

Air

CO₂

Steam Reforming

Energy

Fossil Hydrocarbon

CO₂

N₂

H₂

NH₃

Steady-State Reactor

It was a good run...
Existing \( \text{NH}_3 \) technology won’t work well

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\begin{align*}
\text{Water} & \quad & \text{Fossil Hydrocarbon} & \quad & \text{Air} \\
\text{CO}_2 & \quad & \text{Steam Reforming} & \quad & \text{Energy} \\
\text{N}_2 & \quad & \text{H}_2 & \quad & \text{NH}_3 \\
\text{Fossil Hydrocarbon} & \quad & \text{CO}_2 & \quad & \text{Steady State Reactor}
\end{align*}

It was a good run...
Rapid Ramp NH₃ solves the problems

- N₂ from air (air is 79% N₂)
- H₂ from water (water is H₂O)
- Fast ramping reactor follows wind & solar variation
- No fossil fuels, no CO₂
Rapid Ramp NH₃ solves the problems

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“Green” Haber-Bosch

Water → Electrolyzer → H₂
Air → N₂ Extraction → N₂
Oxygen

Rapid Ramp Reactor → NH₃

Patents Pending
Fast catalyst
No liquefaction
Rapid Ramp NH$_3$ solves the problems

- N$_2$ from air (air is 79% N$_2$)
- H$_2$ from water (water is H$_2$O)
- Fast ramping reactor follows wind & solar variation
- No fossil fuels, no CO$_2$
**Fast NH$_3$ catalyst**

- 1 wt% Ru on proprietary support
- Max. rate: 220 mmol/(g·h) at 10 atm
- Industrial rates: 20 mmol/(g·h) at 100 atm
- 10x industrial rate at 1/10 industrial pressure
- Moderate ramp with temp.
- Fast rate ramp with flow
**NH₃ removal by adsorption**

- Non-dispersive infrared NH₃ detector gives “real time” data
- NH₃ and unused reactants flared for disposal
NH₃ removal by adsorption

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- NH₃ removal cannister bypassed to measure reactor output
NH₃ removal by adsorption

- Non-dispersive infrared NH₃ detector gives “real time” data
- NH₃ and unused reactants flared for disposal
- NH₃ removal cannister bypassed to measure reactor output
- Reactor output directed through removal cannister to test capability
**NH₃ removal by adsorption**

- Complete NH₃ removal at 140 mmol/(g·h) synthesis rate
- 9 wt% NH₃ capacity
Prototype reactor

- Reactor makes $\text{NH}_3$
- $\text{NH}_3$ removed by one of adsorption cannisters
- Unused reactants recirculated
- Adsorber regeneration makes liquid $\text{NH}_3$
• Reactor makes NH₃
• NH₃ removed by one of adsorption cannisters
• Unused reactants recirculated
• Adsorber regeneration makes liquid NH₃
• Reactor makes NH$_3$
• NH$_3$ removed by one of adsorption cannisters
• Unused reactants recirculated
• Adsorber regeneration makes liquid NH$_3$
Prototype reactor fabrication

- Assembly complete in a few weeks
- Testing will include:
  - Synthesis rate
  - Rate ramp
  - Catalyst stability
  - NH\textsubscript{3} removal
  - Adsorbant stability
### Risk reduced by staged development

<table>
<thead>
<tr>
<th>Project</th>
<th>Purpose</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast-ramping reactor</td>
<td>Compatible with wind &amp; solar.</td>
<td>2018-Q1</td>
</tr>
<tr>
<td>Prototype system</td>
<td>Very small scale (0.003 T/day). System integration, automation. Equipment conversion to NH$_3$.</td>
<td>2019-Q2</td>
</tr>
<tr>
<td>Field System</td>
<td>Scale up (0.03 – 0.3 T/day). Remote automated operation. More accurate cost model. Partner engagement.</td>
<td>2020-Q4</td>
</tr>
<tr>
<td>Demonstration System</td>
<td>Scale up (0.3-3 T/day). Tailor to likely first customers. Increase customer confidence. Cost model scale dependence.</td>
<td>2021-Q4</td>
</tr>
</tbody>
</table>
Next step: system integration

- Experience operating \( N_2 \) and \( H_2 \) equipment
- Optimize system control methods
- Begin clean \( NH_3 \) fueled equipment development
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- Experience operating $N_2$ and $H_2$ equipment
- Optimize system control methods
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Questions?