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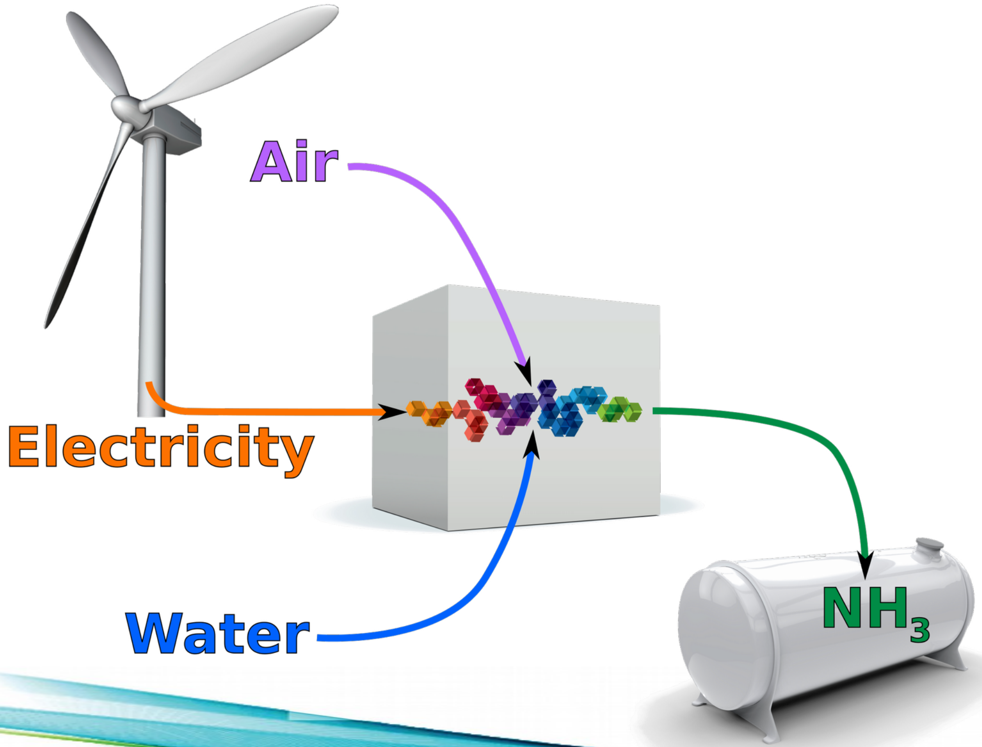
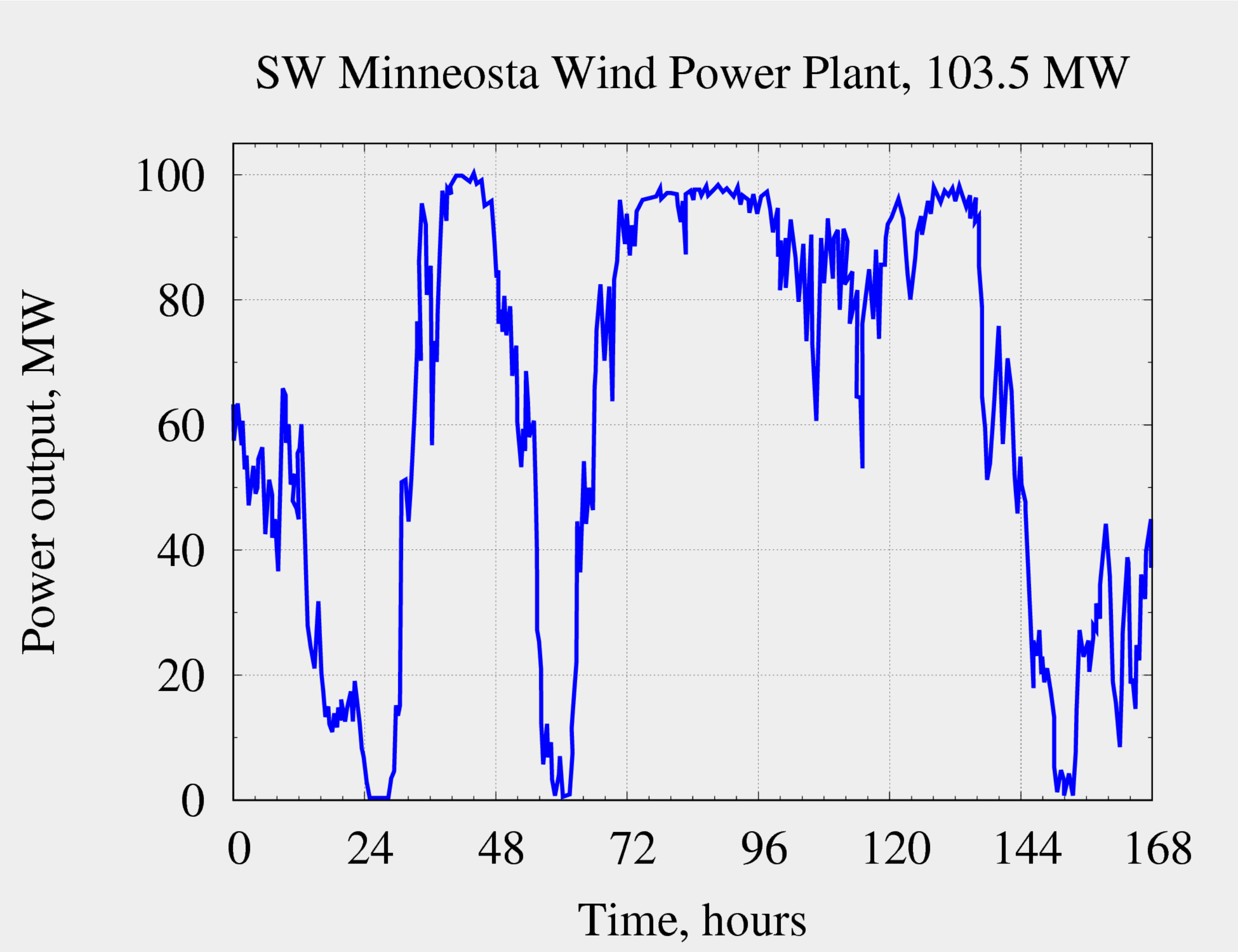
Clean NH_3 fuel from wind & solar power to replace fossil fuels



- 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

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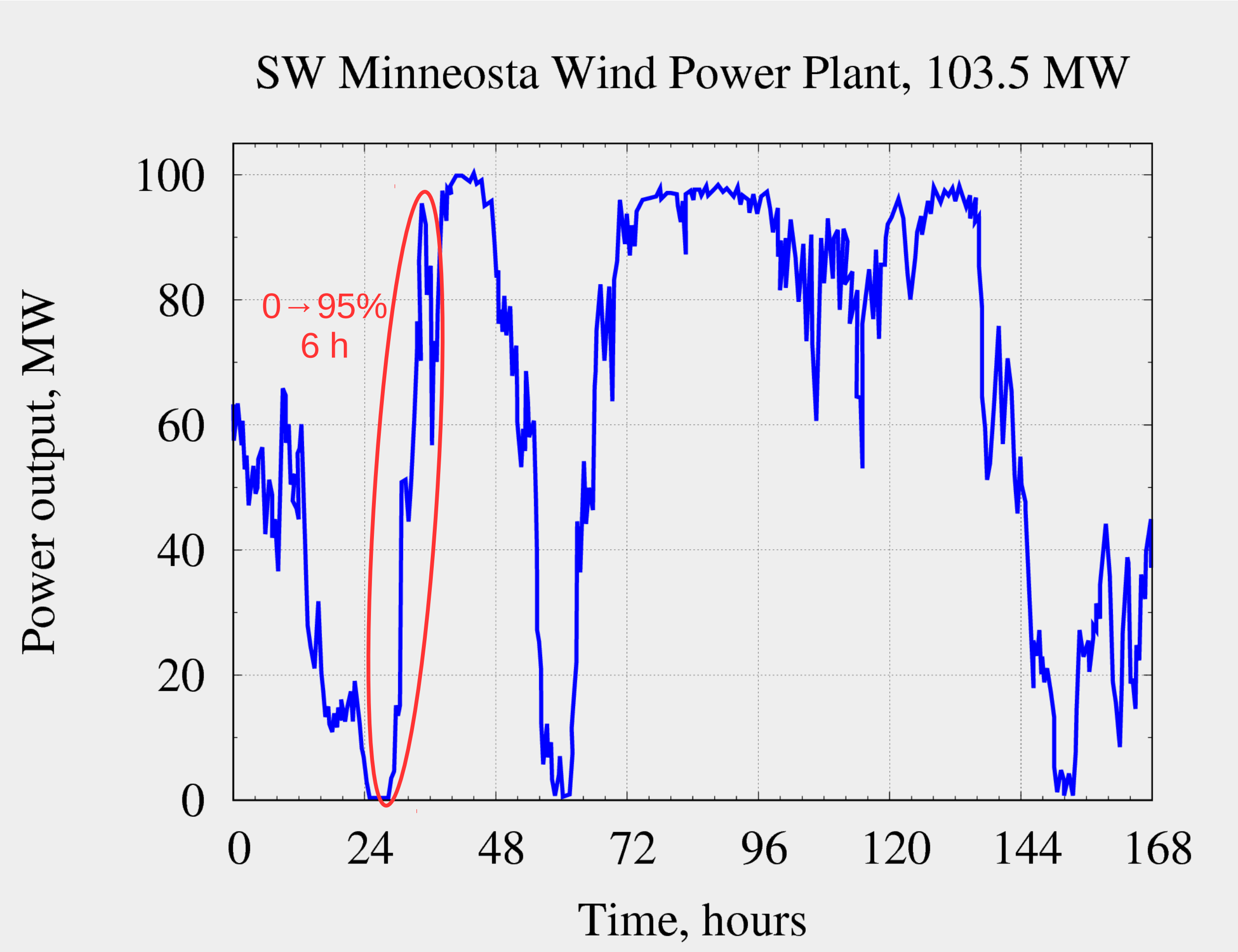
Wind & solar power plants – variable output



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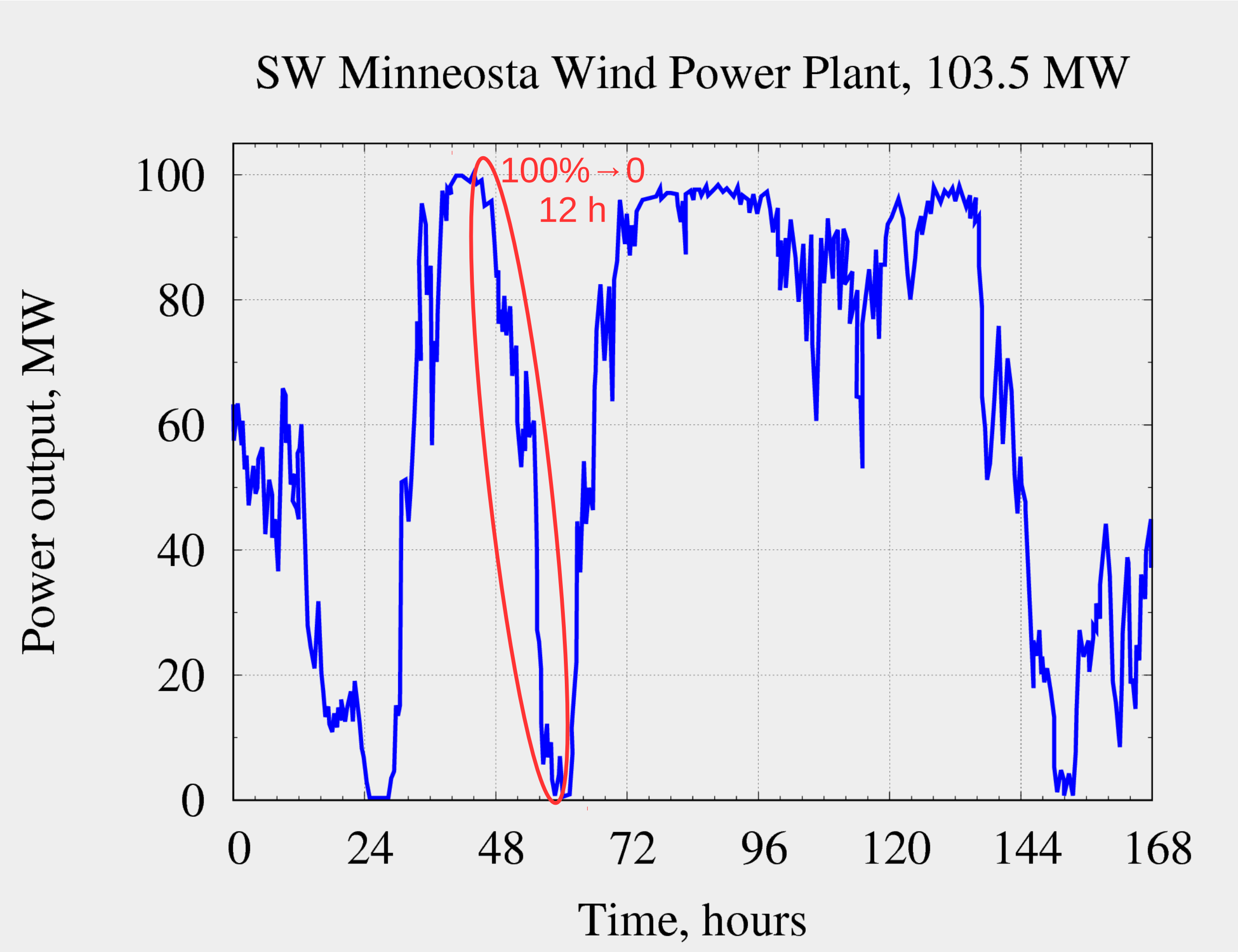

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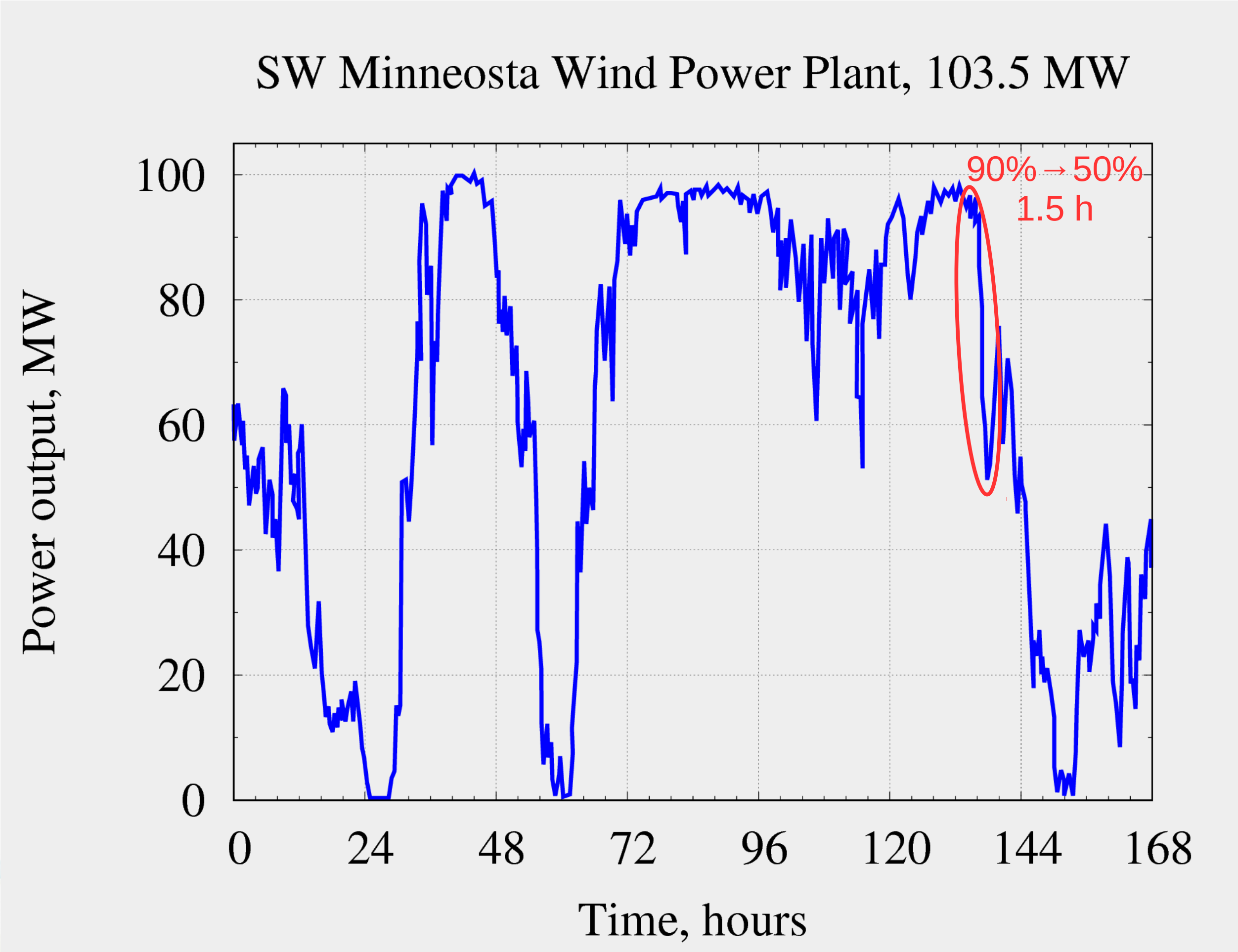

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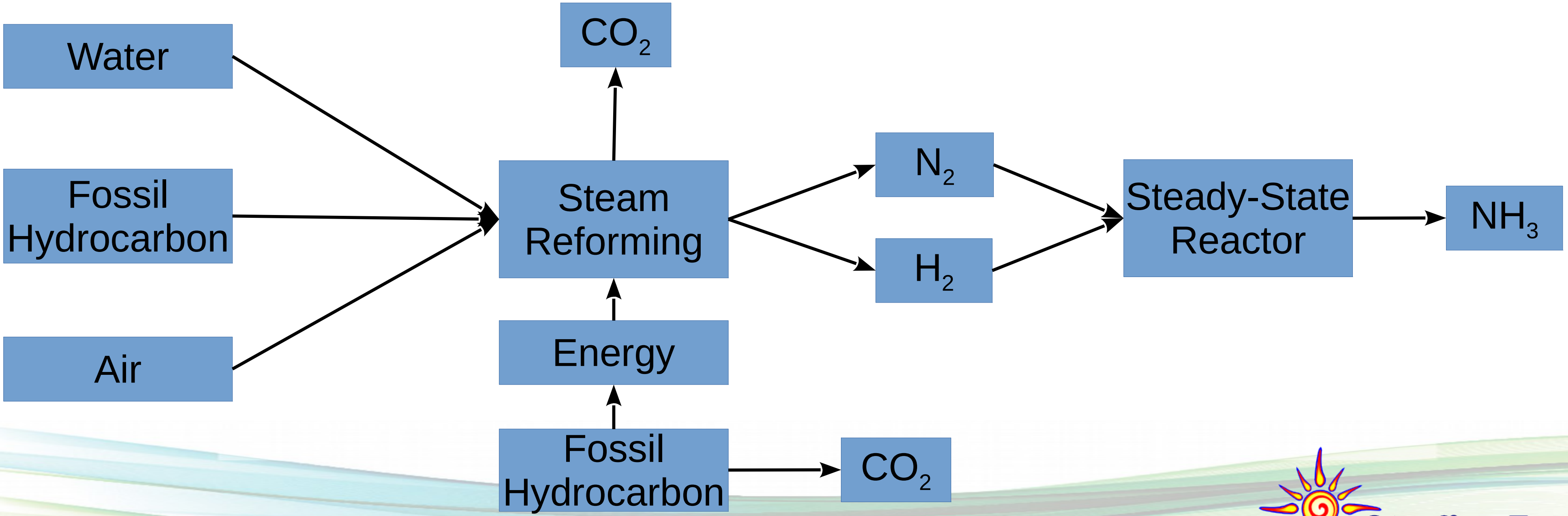
Existing NH_3 technology won't work well

- Uses fossil fuel for feedstock & fuel
- Emits CO_2
- Cannot ramp quickly to follow wind & solar



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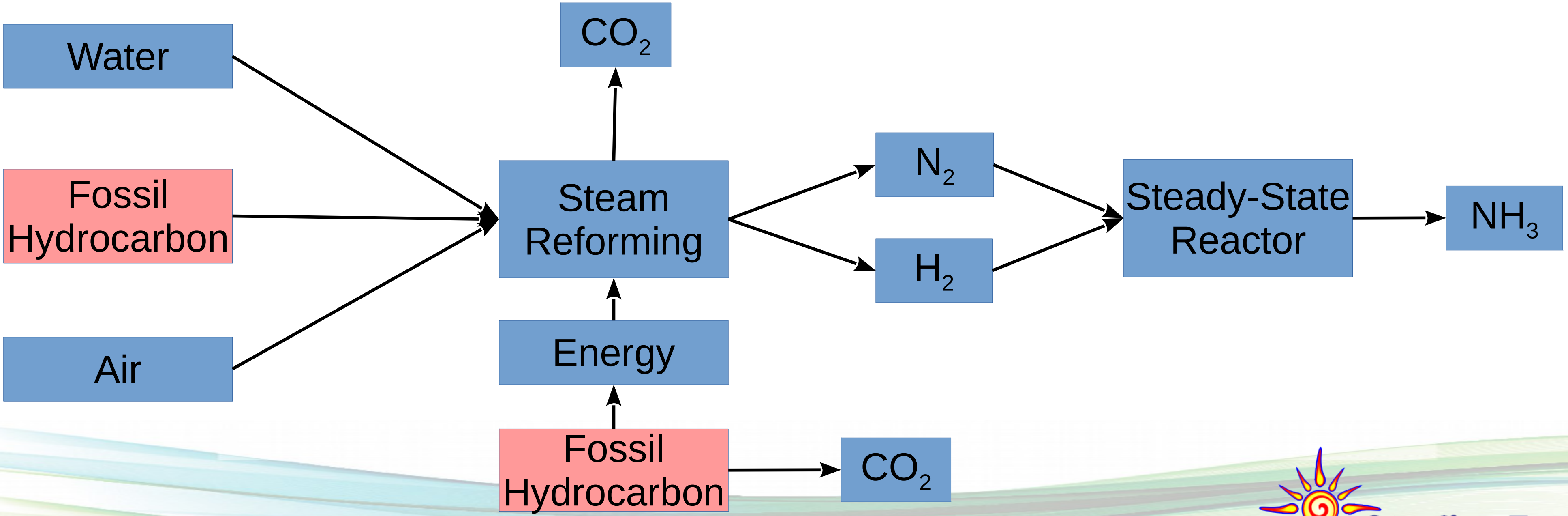

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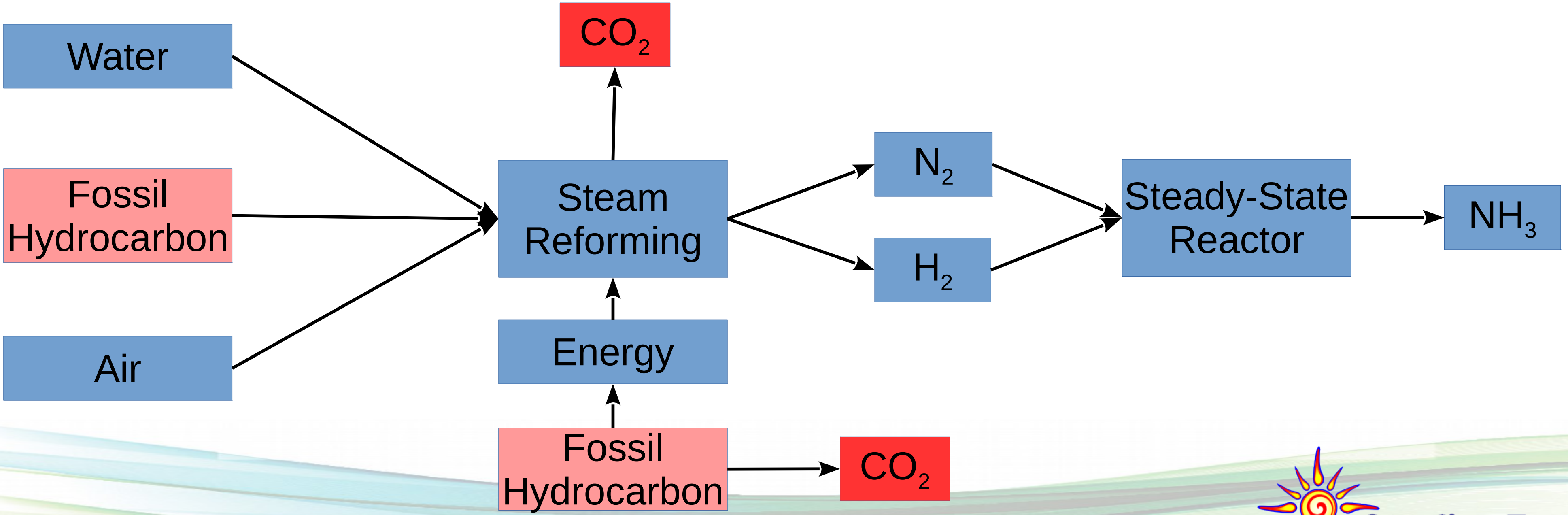

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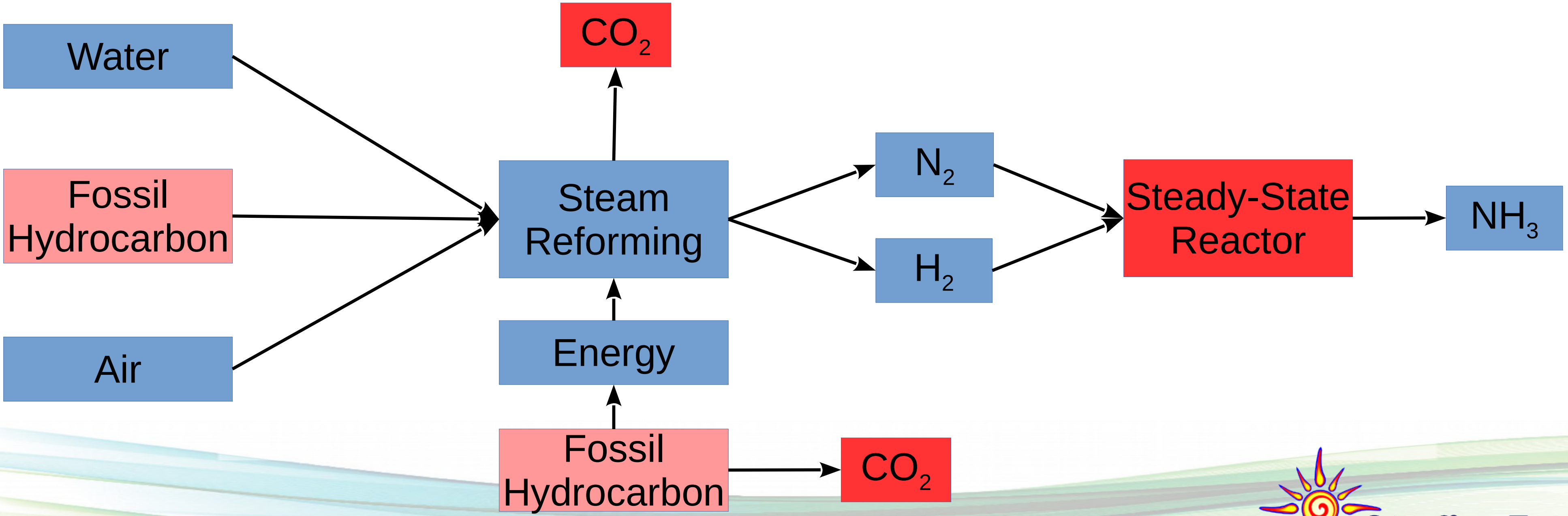
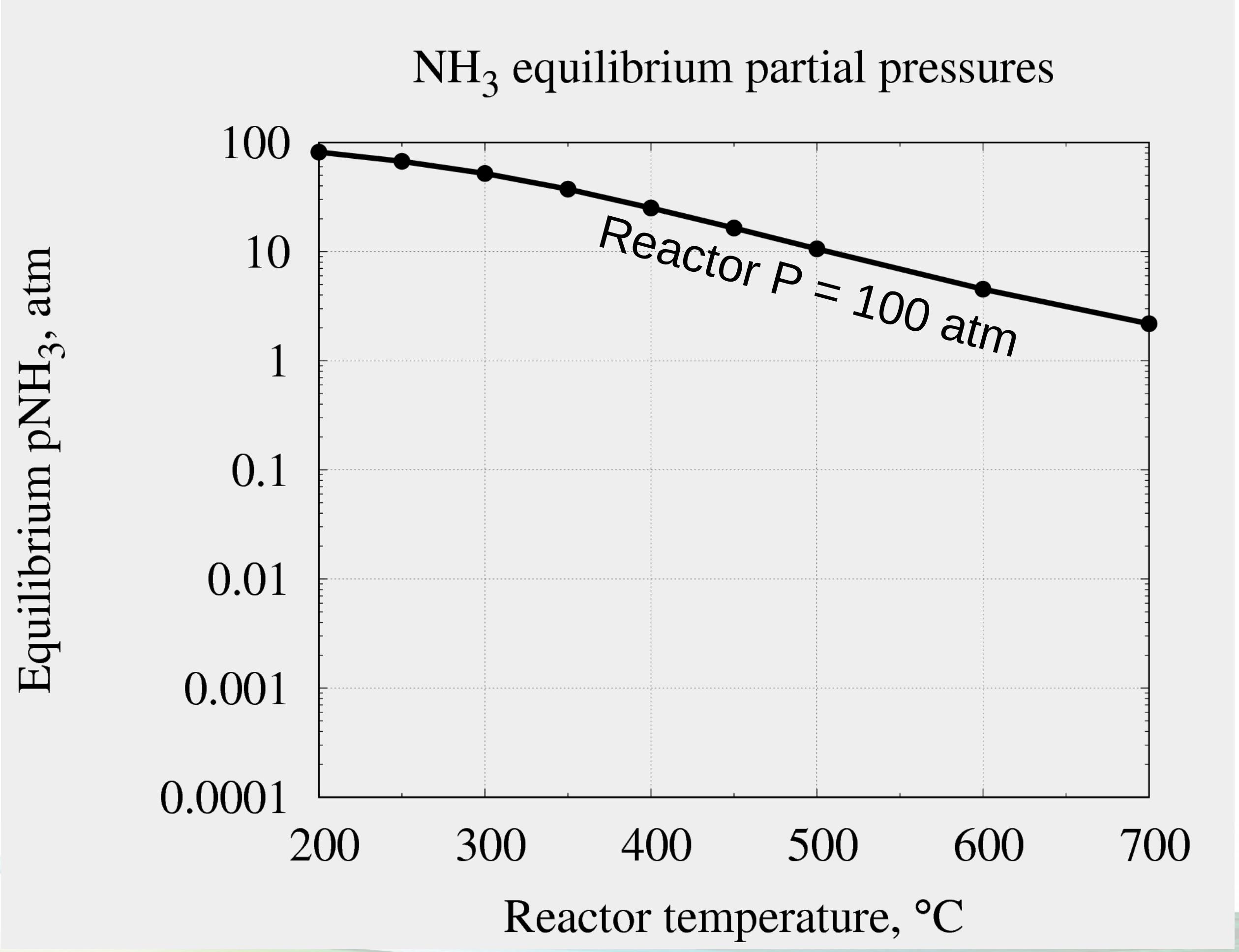
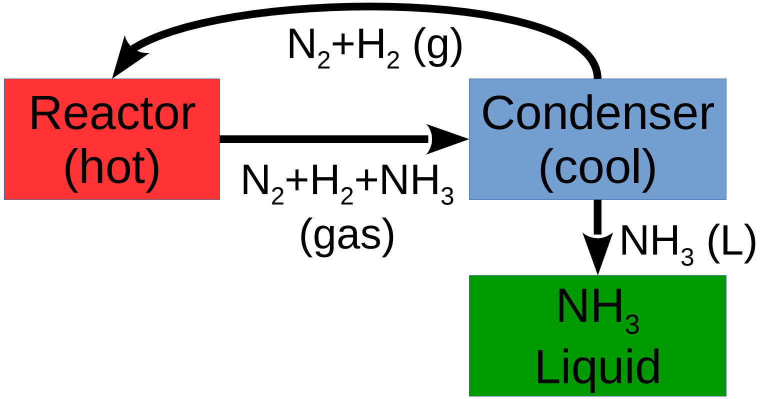


NH_3 liquefaction constrains operation





- NH_3 condenses from vapor to liquid just like water does

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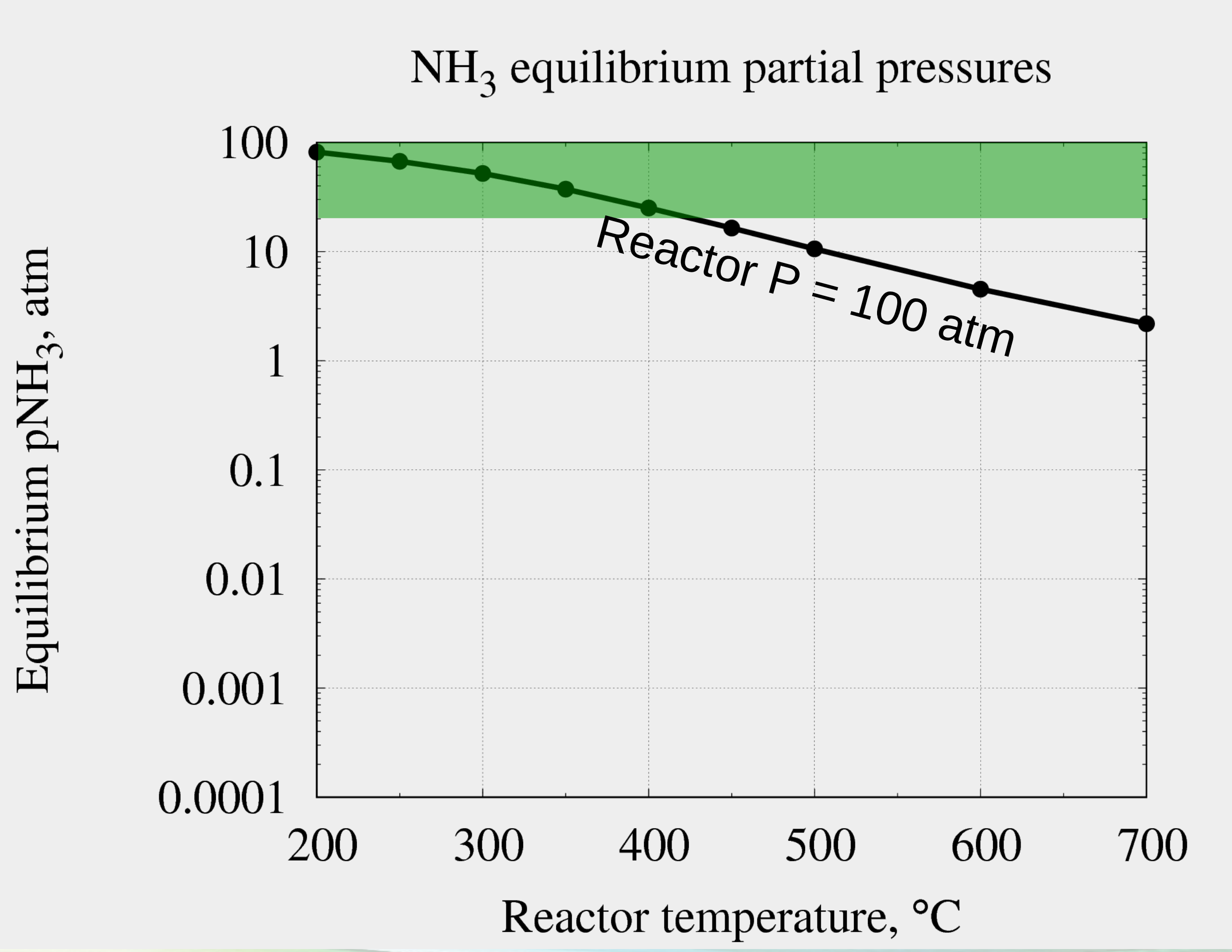

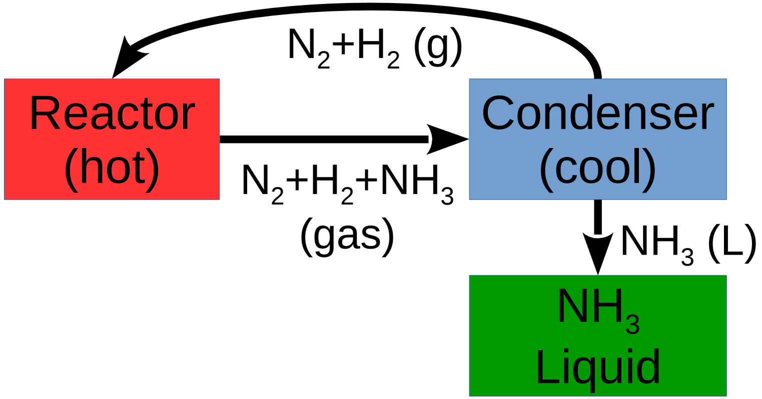

- NH_3 condenses from vapor to liquid just like water does
- Need 21 atm pNH_3 for condensation at 50 ºC

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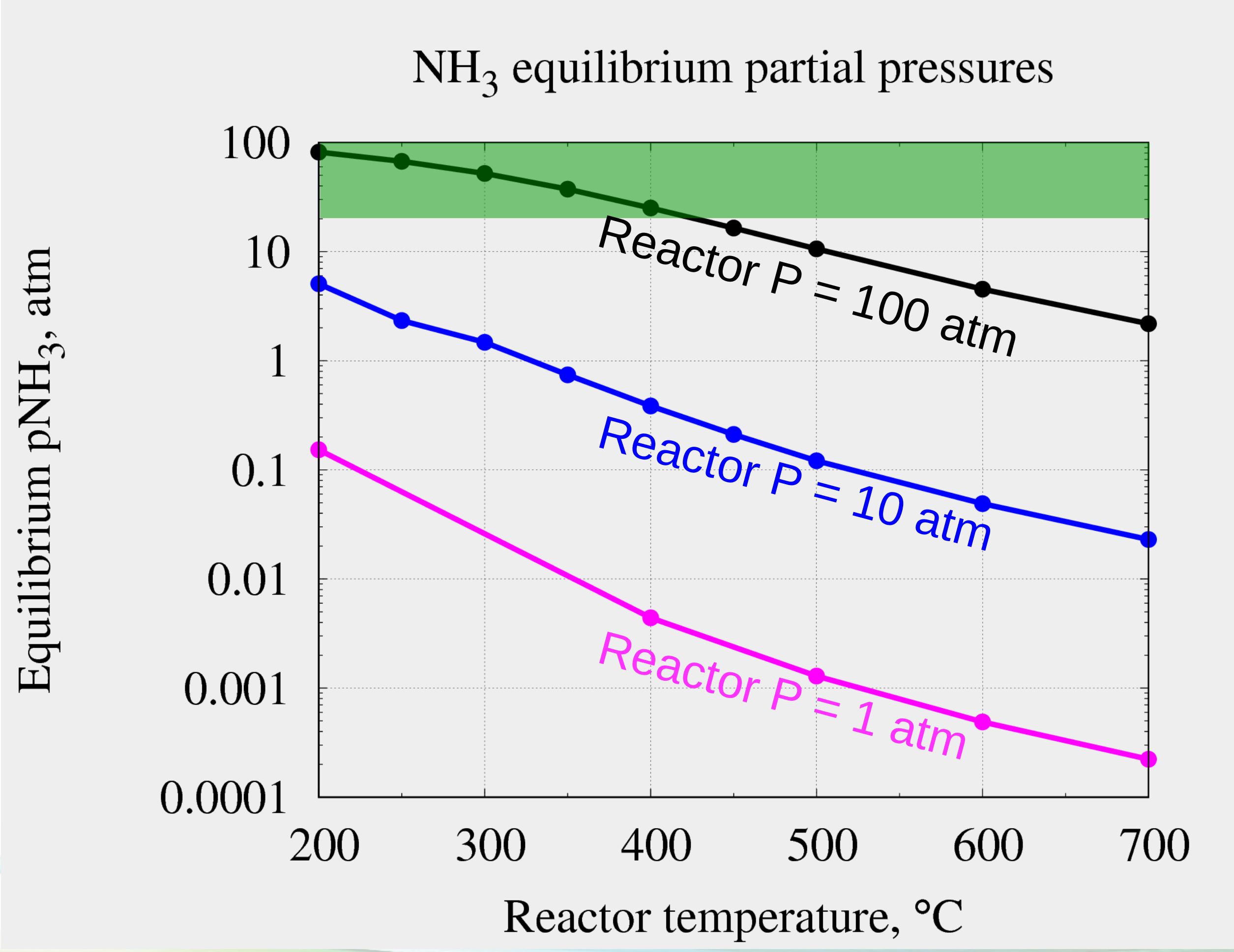

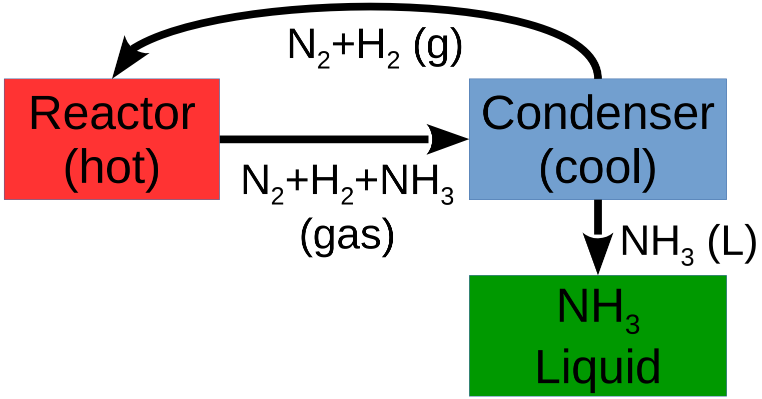

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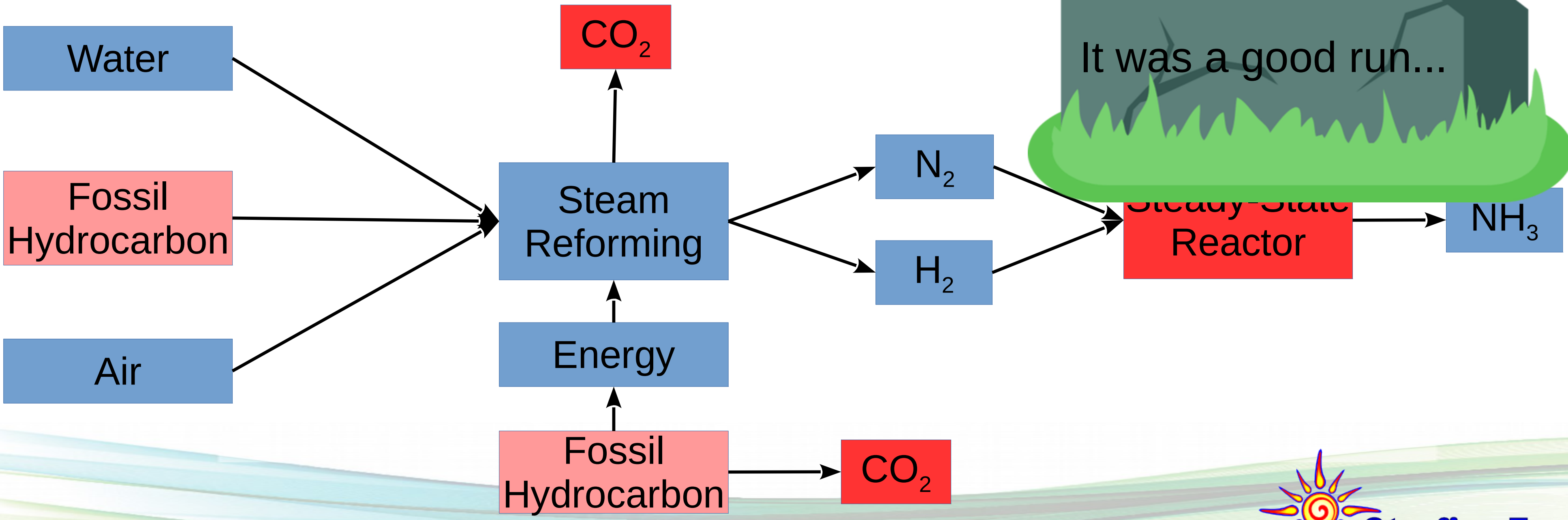

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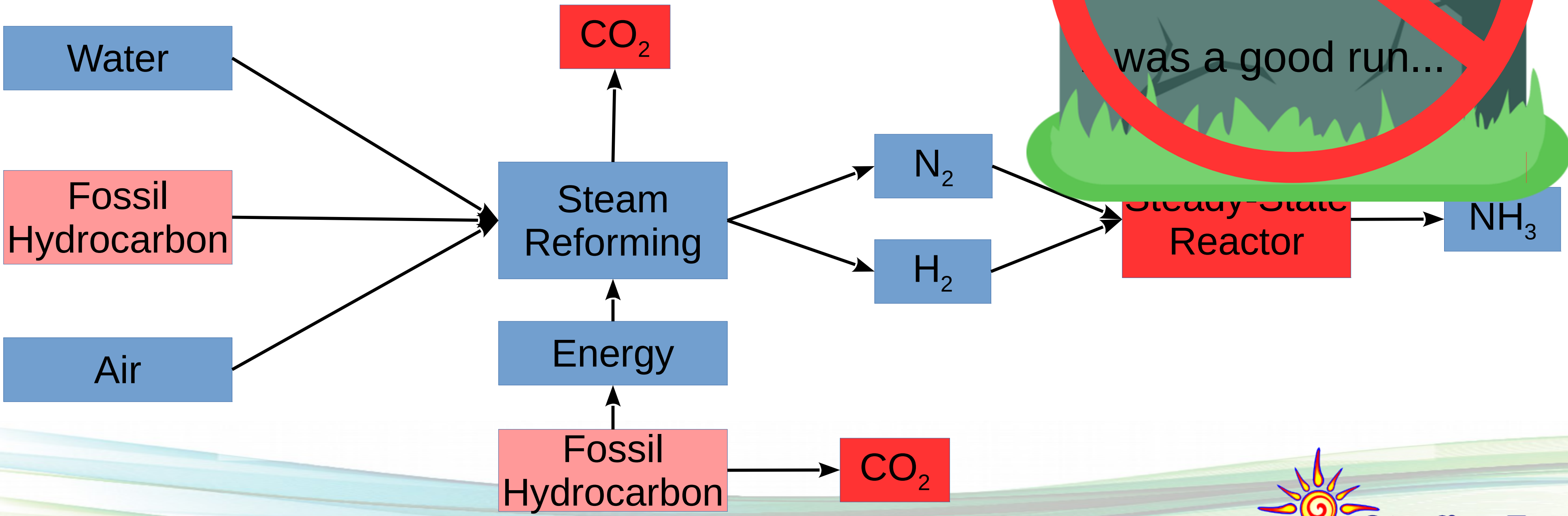
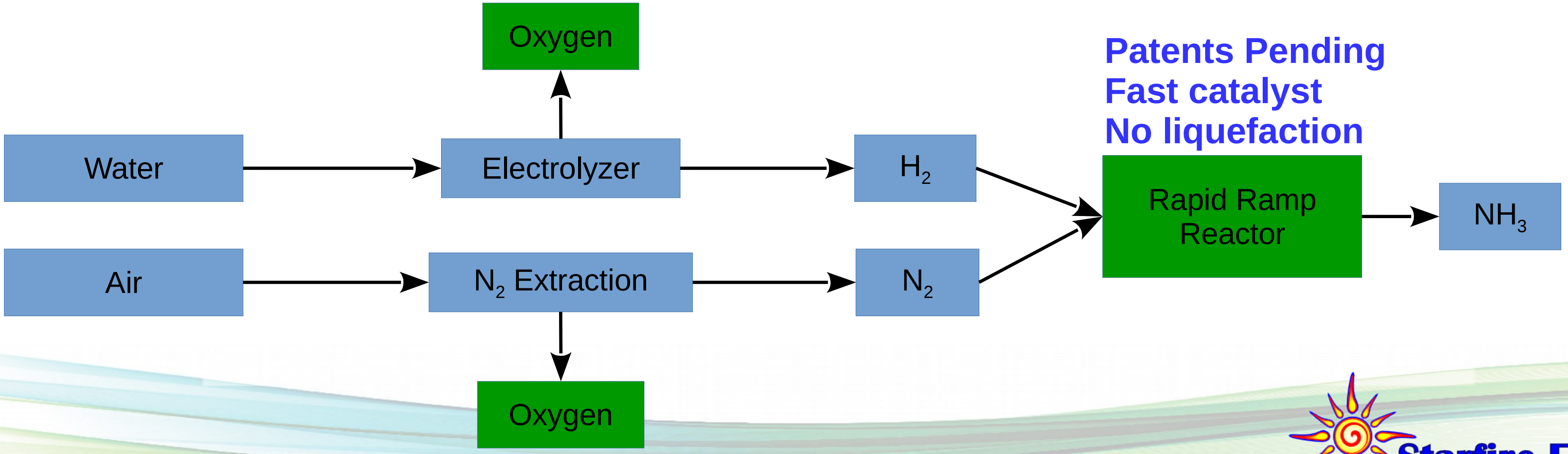


Rapid Ramp NH_3 solves the problems

- N_2 from air (air is 79% N_2)
- H_2 from water (water is H_2O)
- Fast ramping reactor follows wind & solar variation
- No fossil fuels, no CO_2



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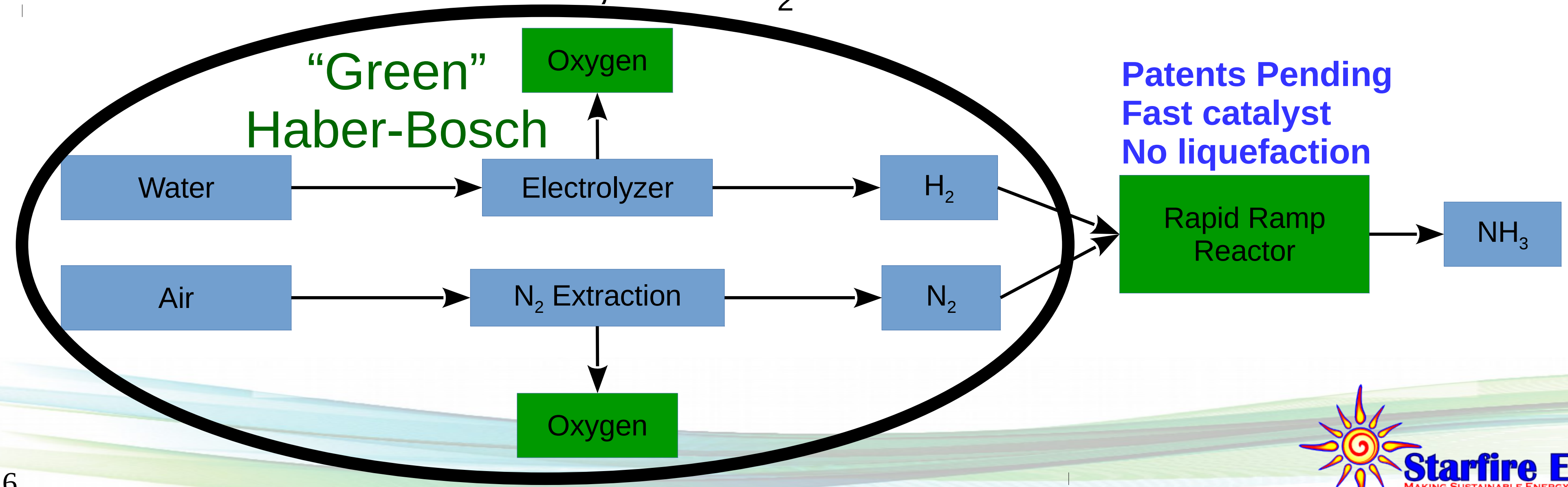

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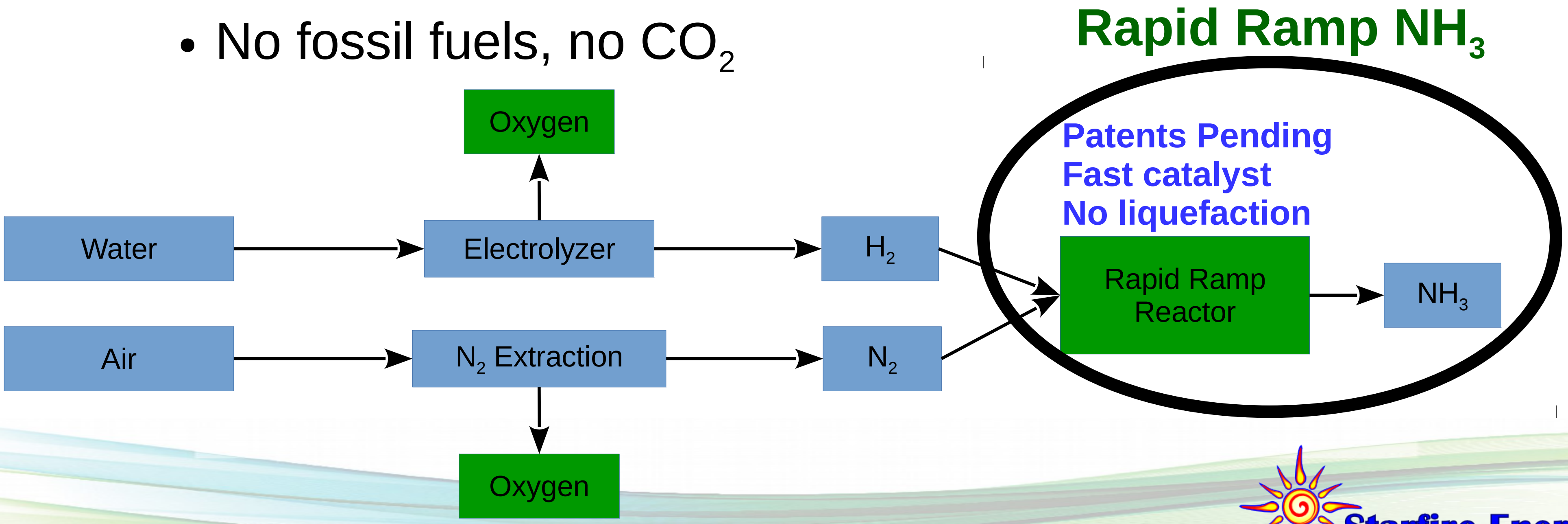
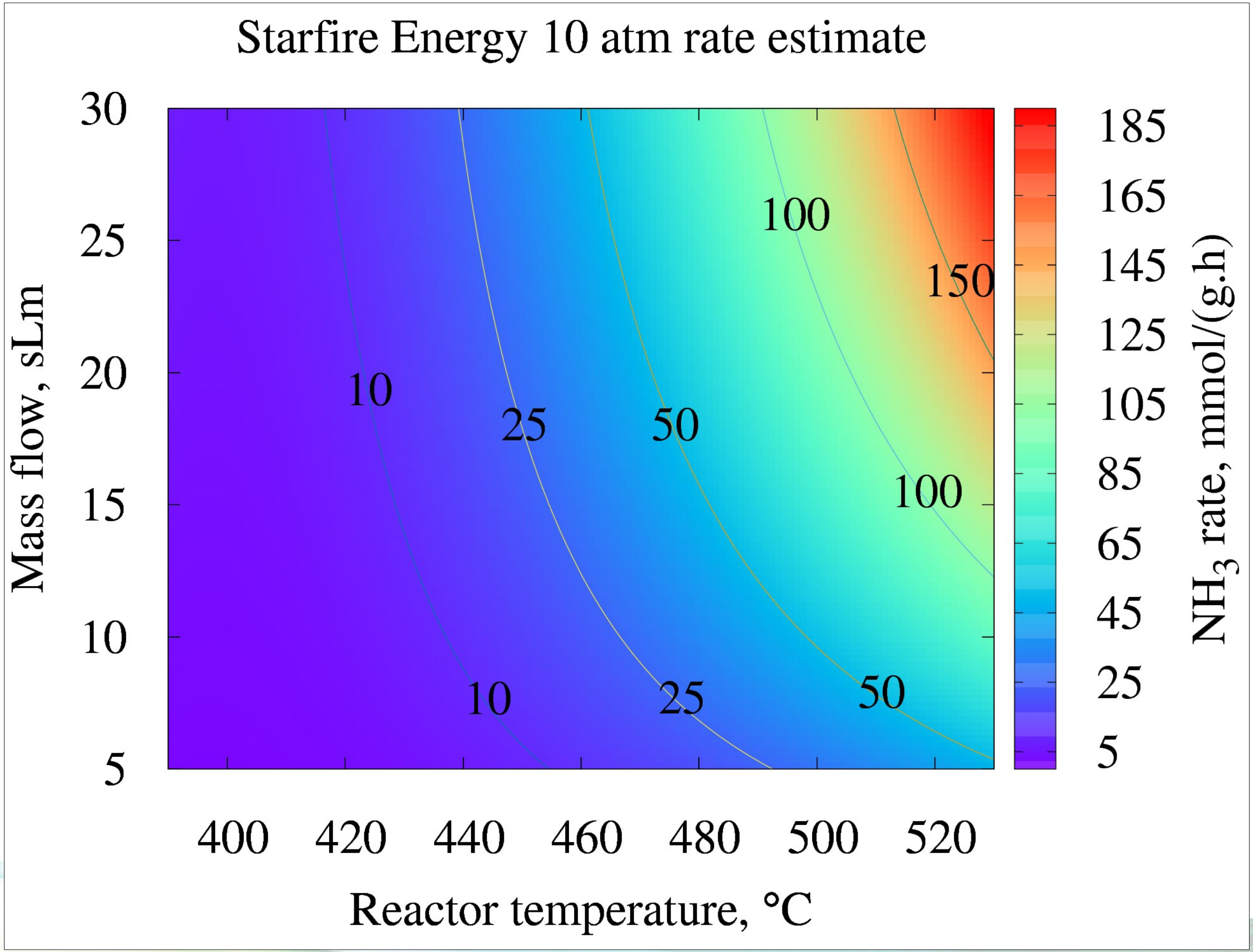


Fast NH_3 catalyst



- 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

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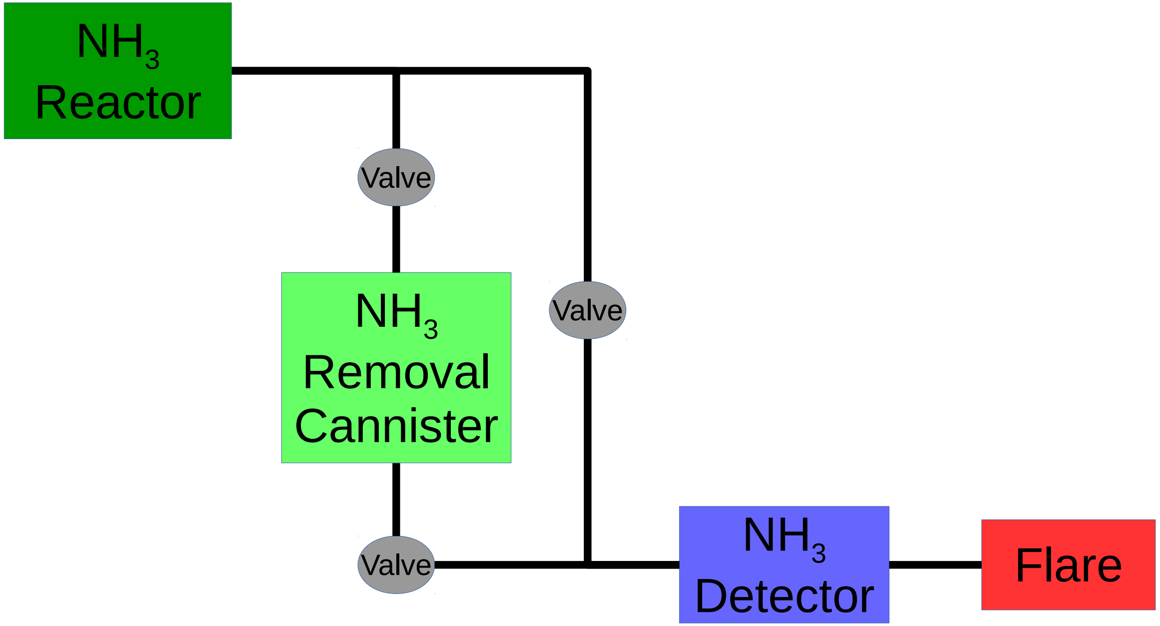
NH_3 removal by adsorption

- Non-dispersive infrared NH_3 detector gives “real time” data
- NH_3 and unused reactants flared for disposal



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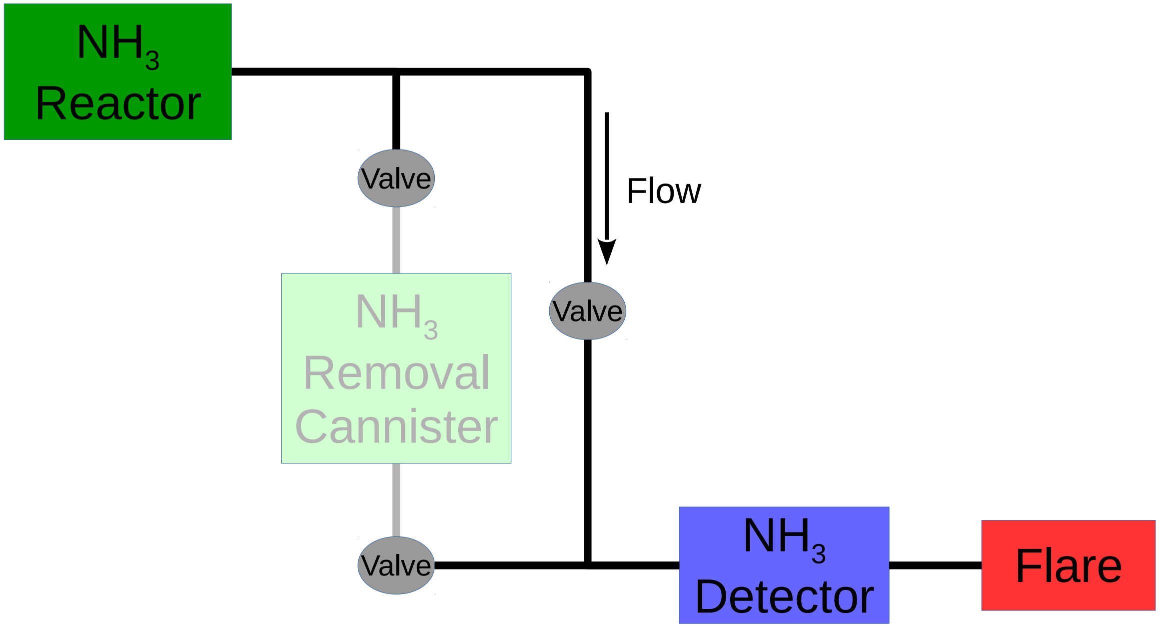
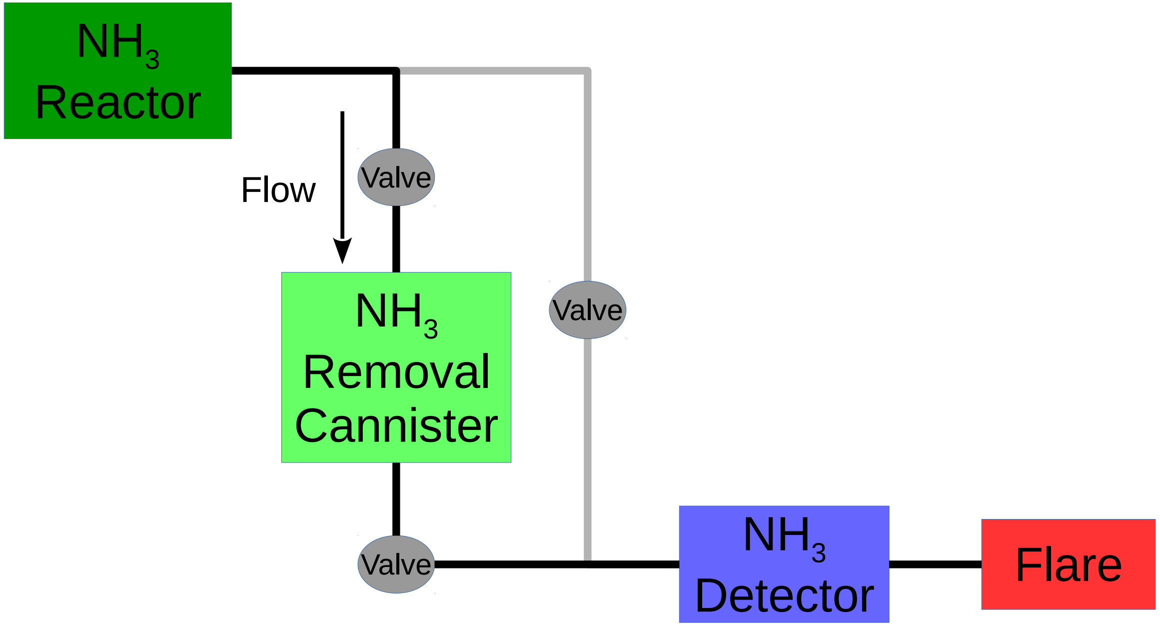


NH_3 removal by adsorption

- Non-dispersive infrared NH_3 detector gives “real time” data
- NH_3 and unused reactants flared for disposal
- NH_3 removal cannister bypassed to measure reactor output
- Reactor output directed through removal cannister to test capability



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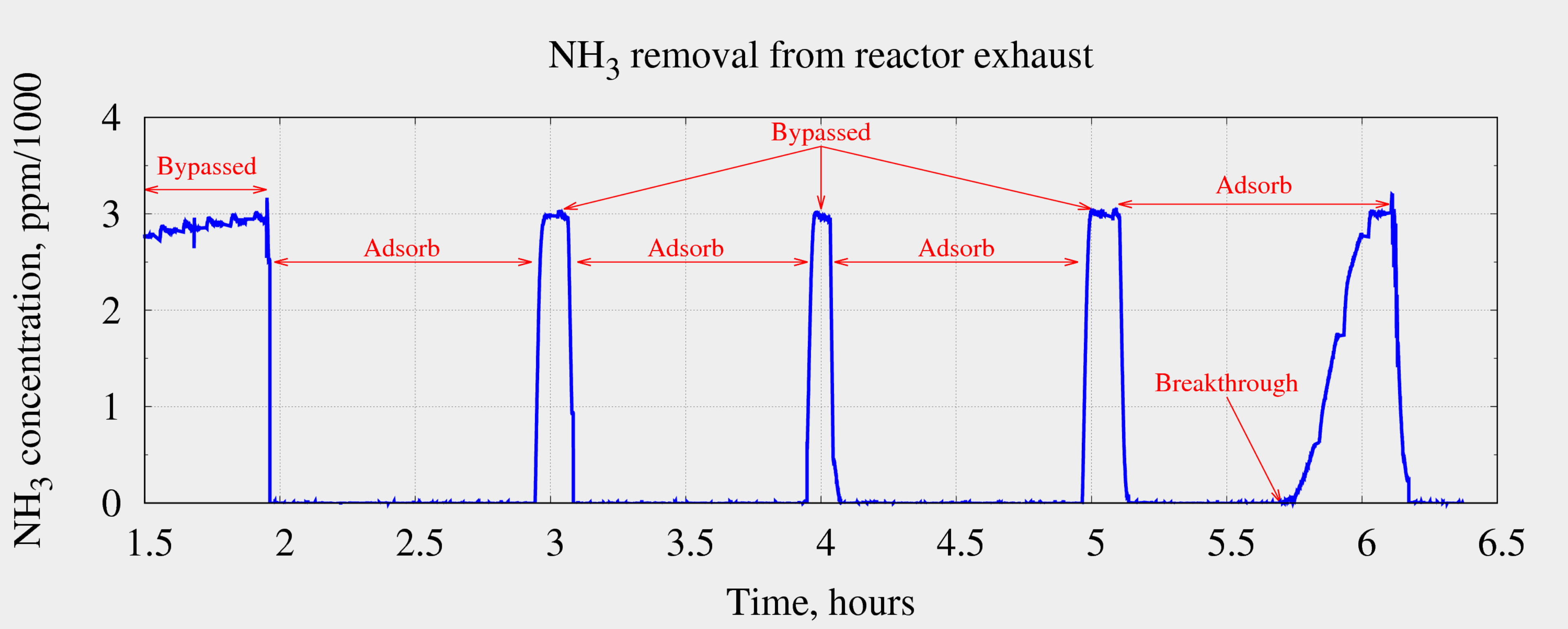

- Complete NH_3 removal at 140 mmol/(g·h) synthesis rate
- 9 wt% NH_3 capacity

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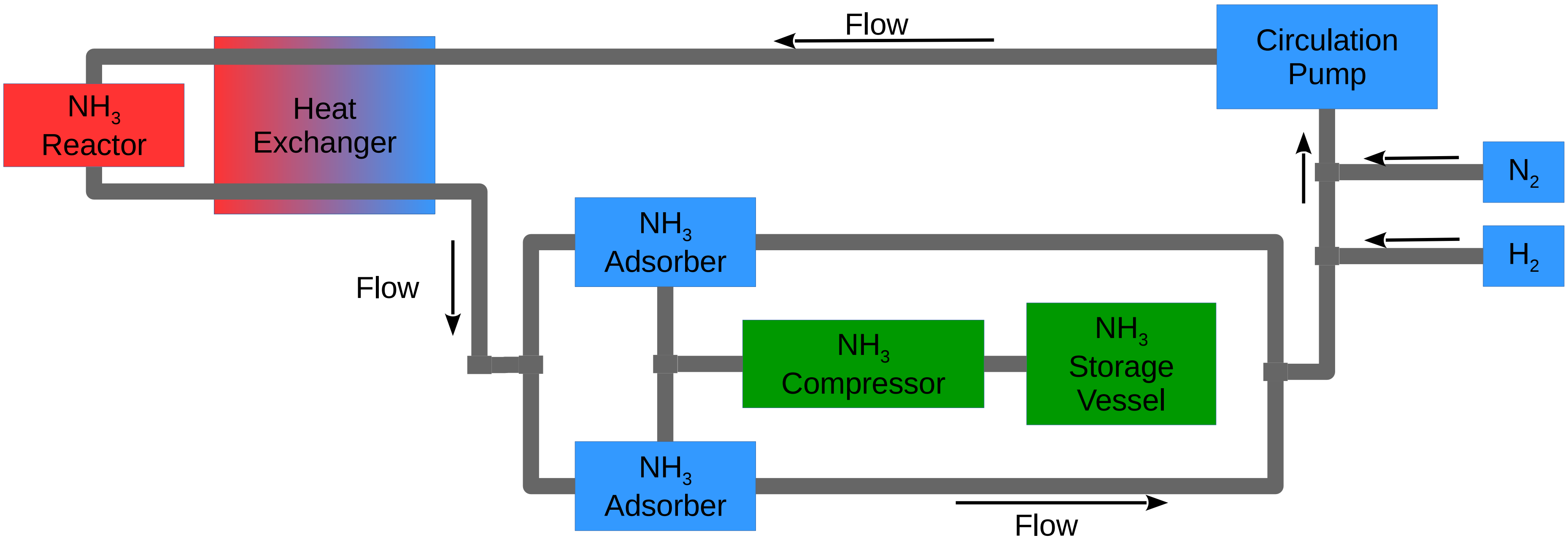
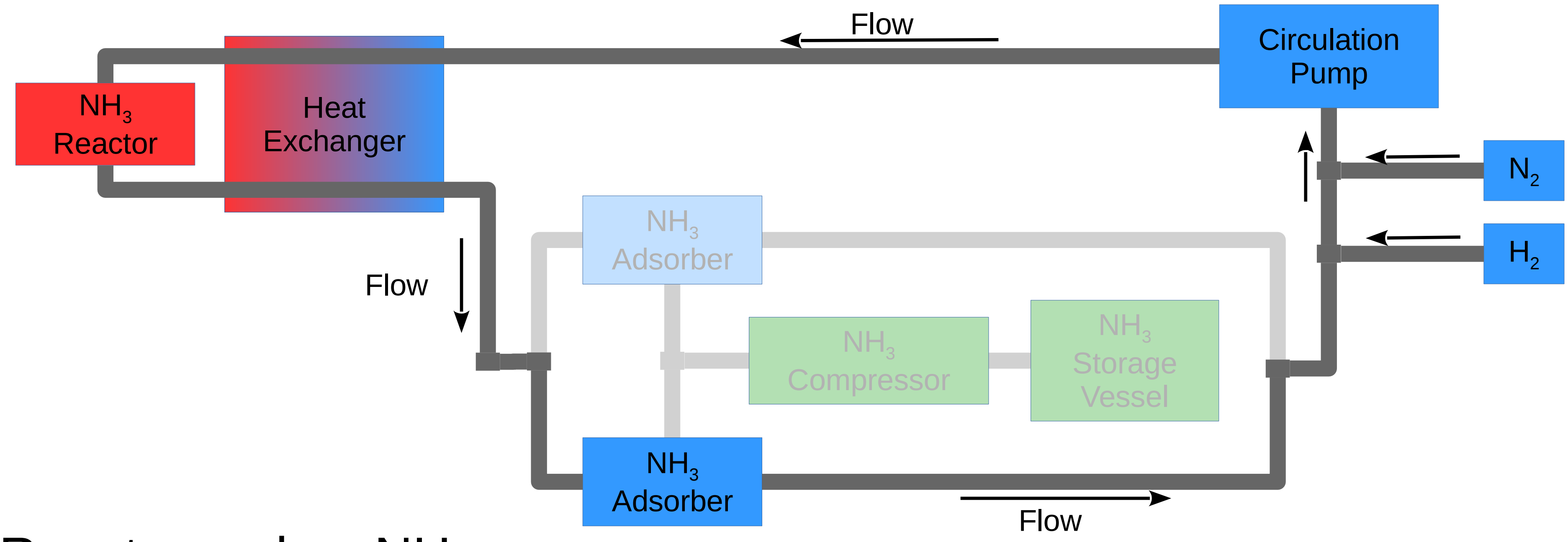
Prototype reactor



- Reactor makes NH_3
- NH_3 removed by one of adsorption cannisters
- Unused reactants recirculated
- Adsorber regeneration makes liquid NH_3

Prototype reactor



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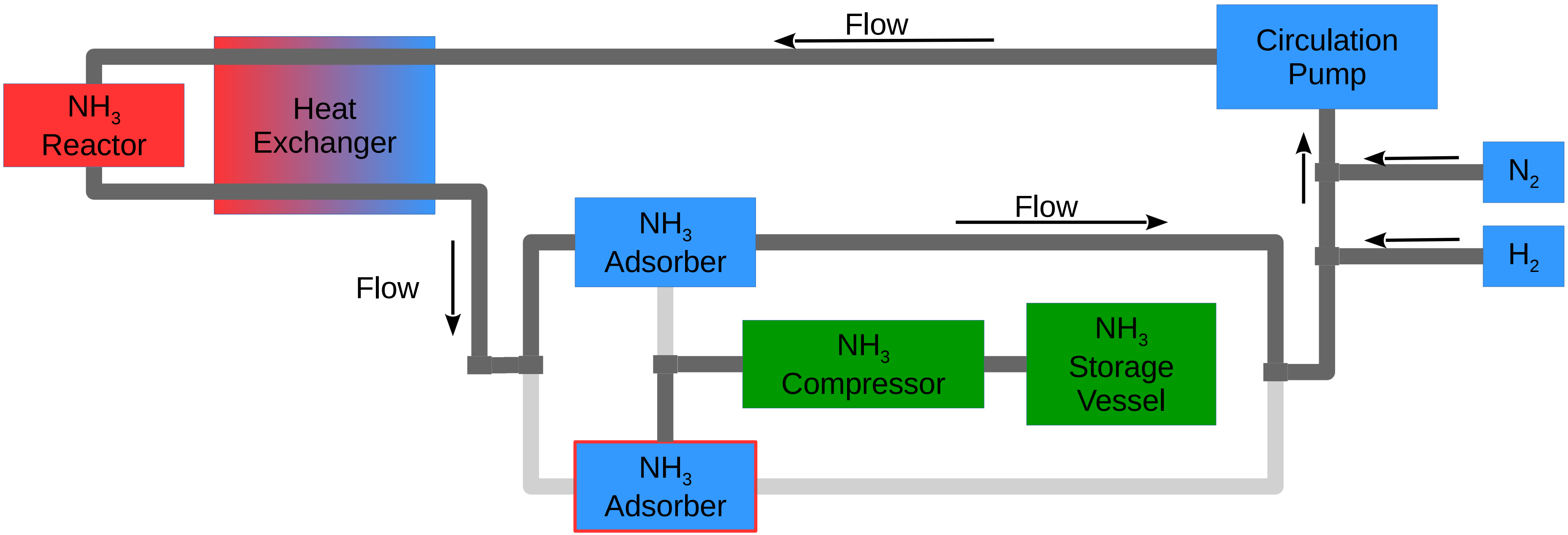

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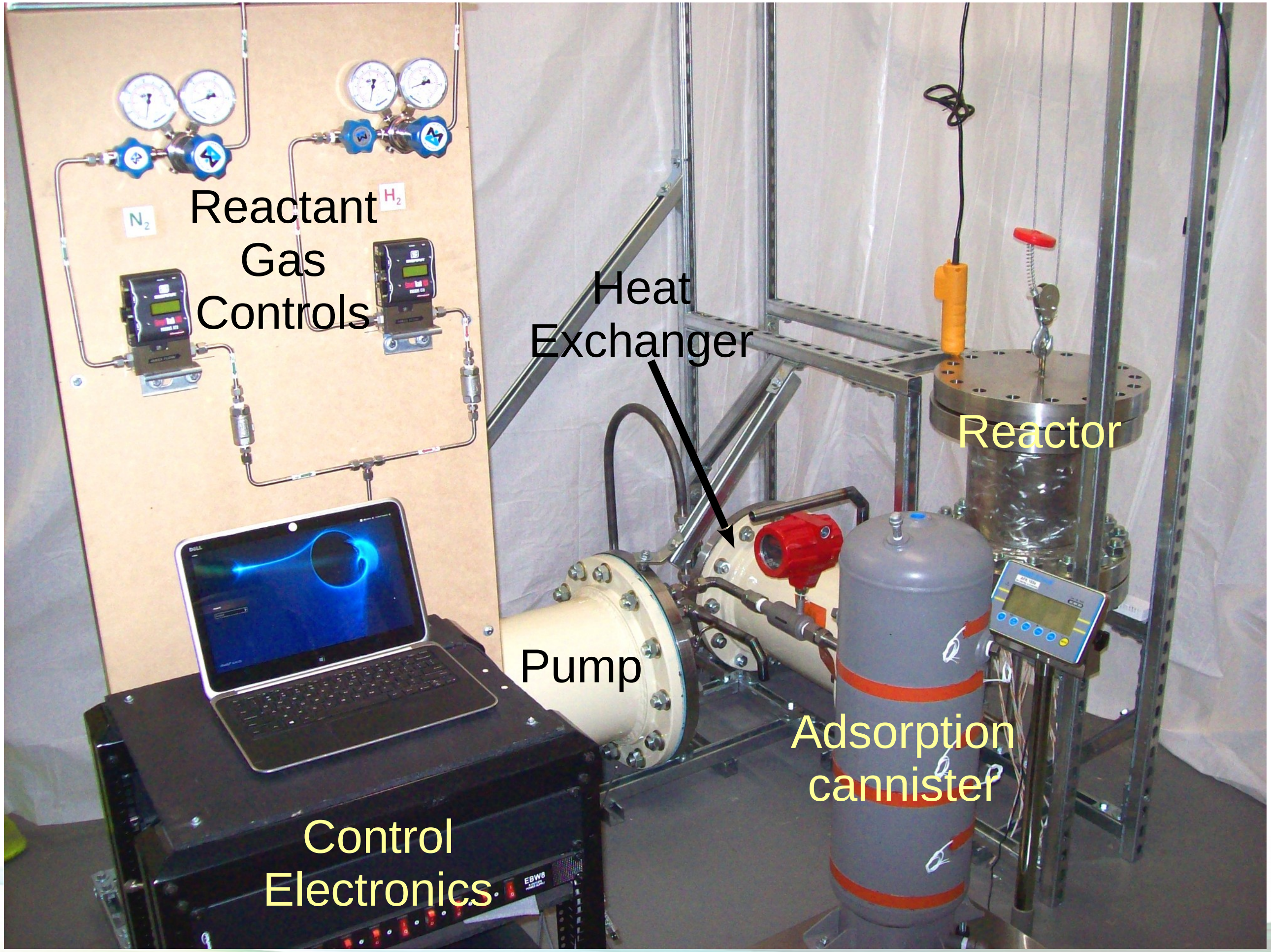
Prototype reactor fabrication



- Assembly complete in a few weeks
- Testing will include:
  - Synthesis rate
  - Rate ramp
  - Catalyst stability
  - NH_3 removal
  - Adsorbant stability

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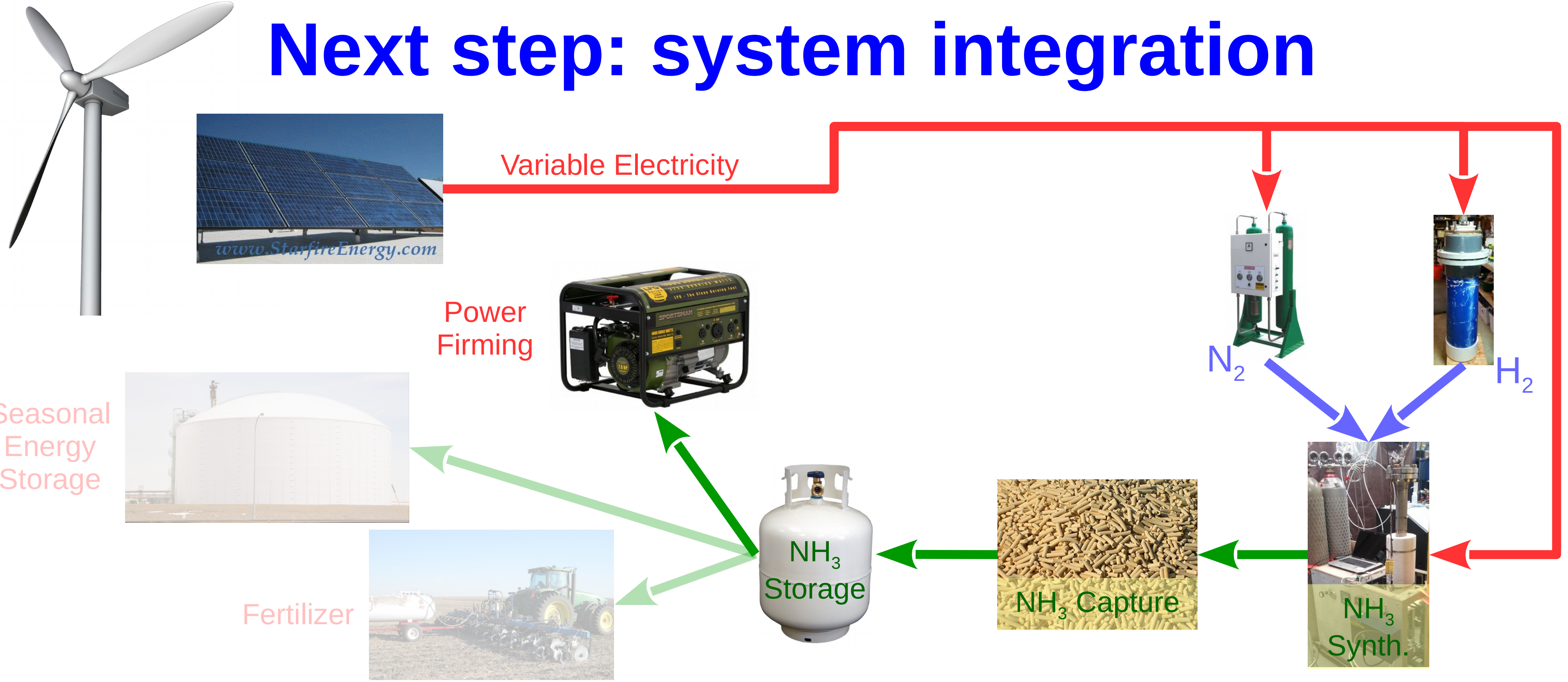
Risk reduced by staged development

Fast-ramping Reactor	Prototype System	Field System	Demonstration System	
ARPA-E	Series A	Series B	Series C	***Sales!***

2017 2018 2019 2020 2021 2022

	Project	Purpose	Finish
Now	Fast-ramping reactor	Compatible with wind & solar.	2018-Q1
Next	Prototype system	Very small scale (0.003 T/day). System integration, automation. Equipment conversion to NH_3.	2019-Q2
	Field System	Scale up (0.03 – 0.3 T/day). Remote automated operation. More accurate cost model. Partner engagement.	2020-Q4
	Demonstration System	Scale up (0.3-3 T/day). Tailor to likely first customers. Increase customer confidence. Cost model scale dependence.	2021-Q4

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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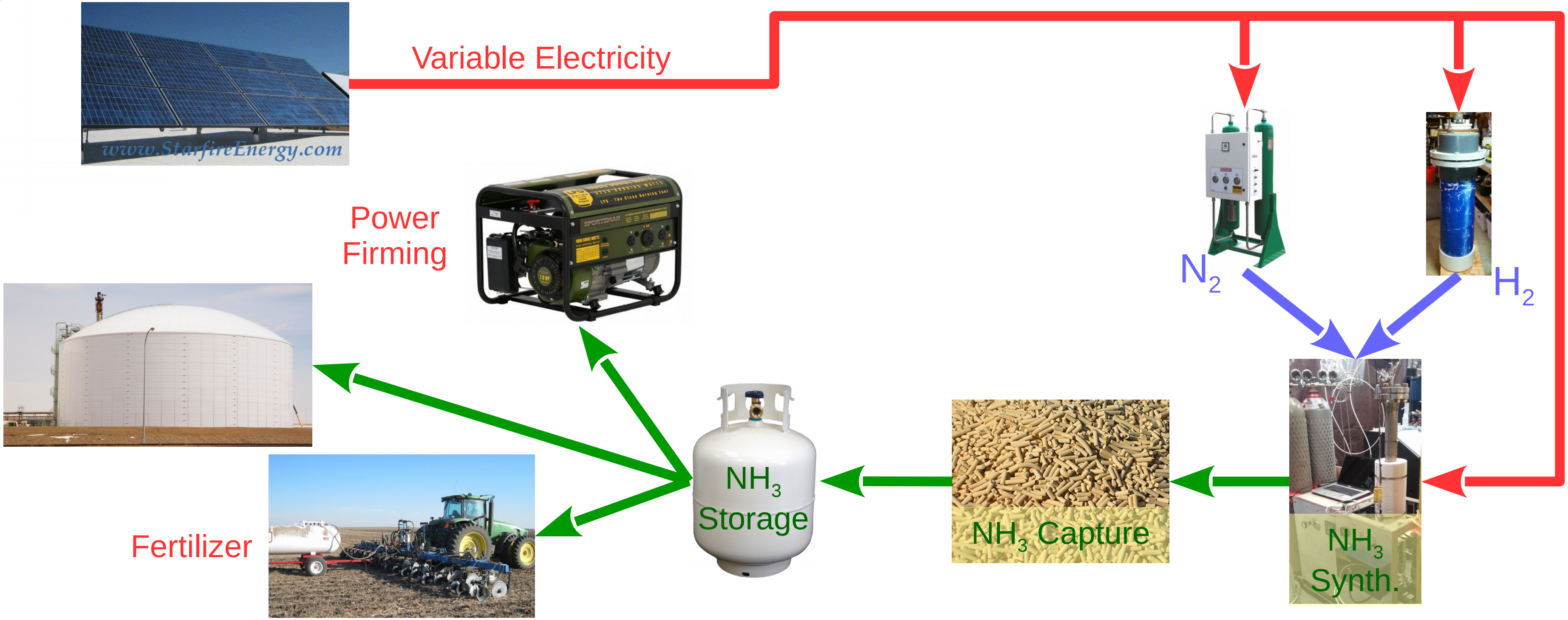

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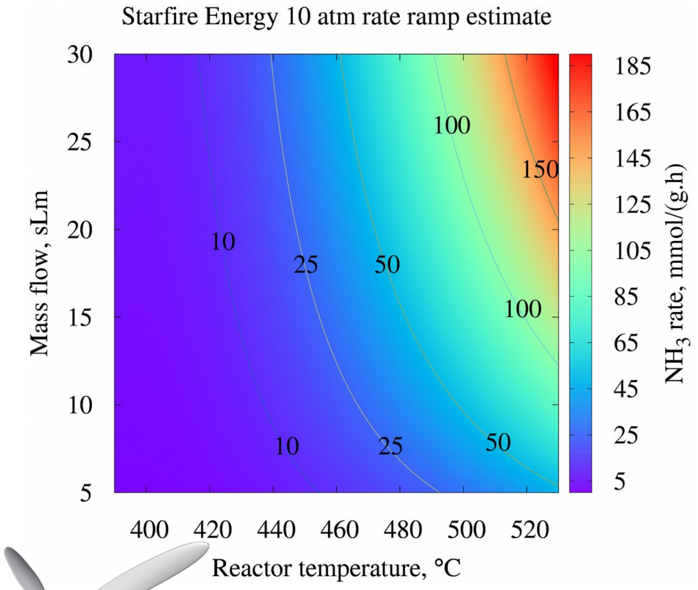
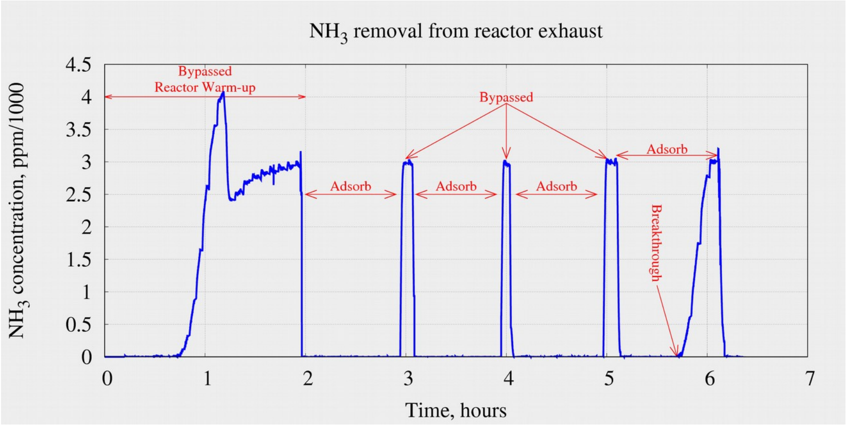
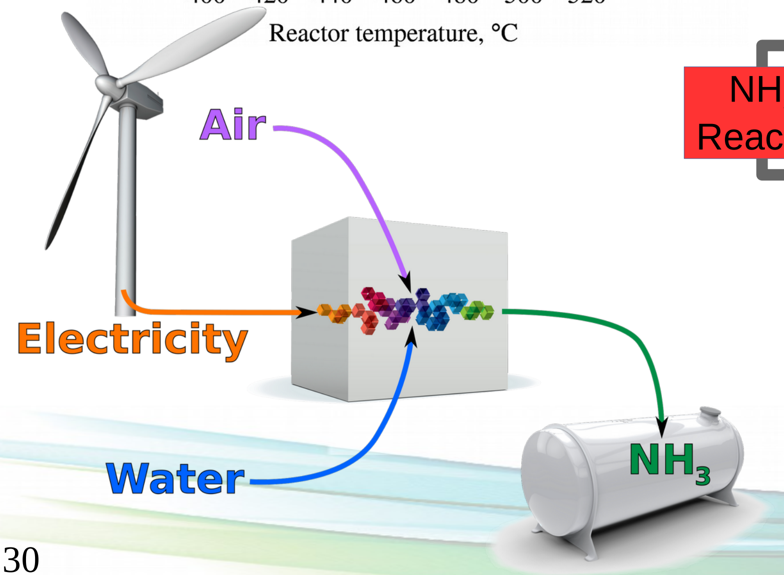
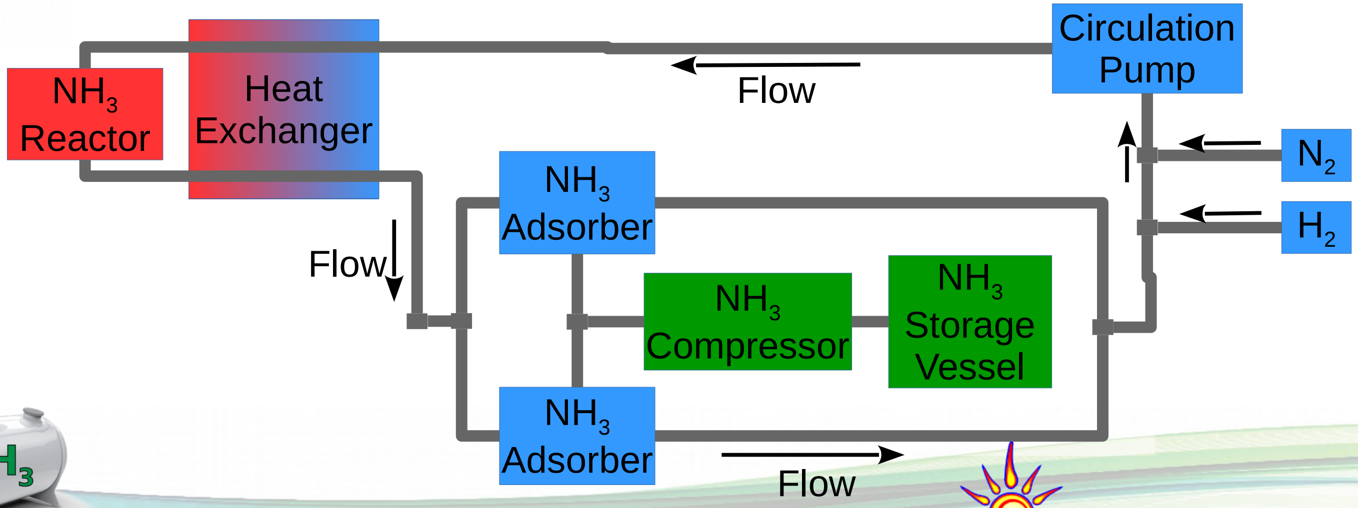
Questions?









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