Concept Model:

A Regenerative Ammonia Fuel Cell System

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Ammonia – Carbon-free Liquid Fuel
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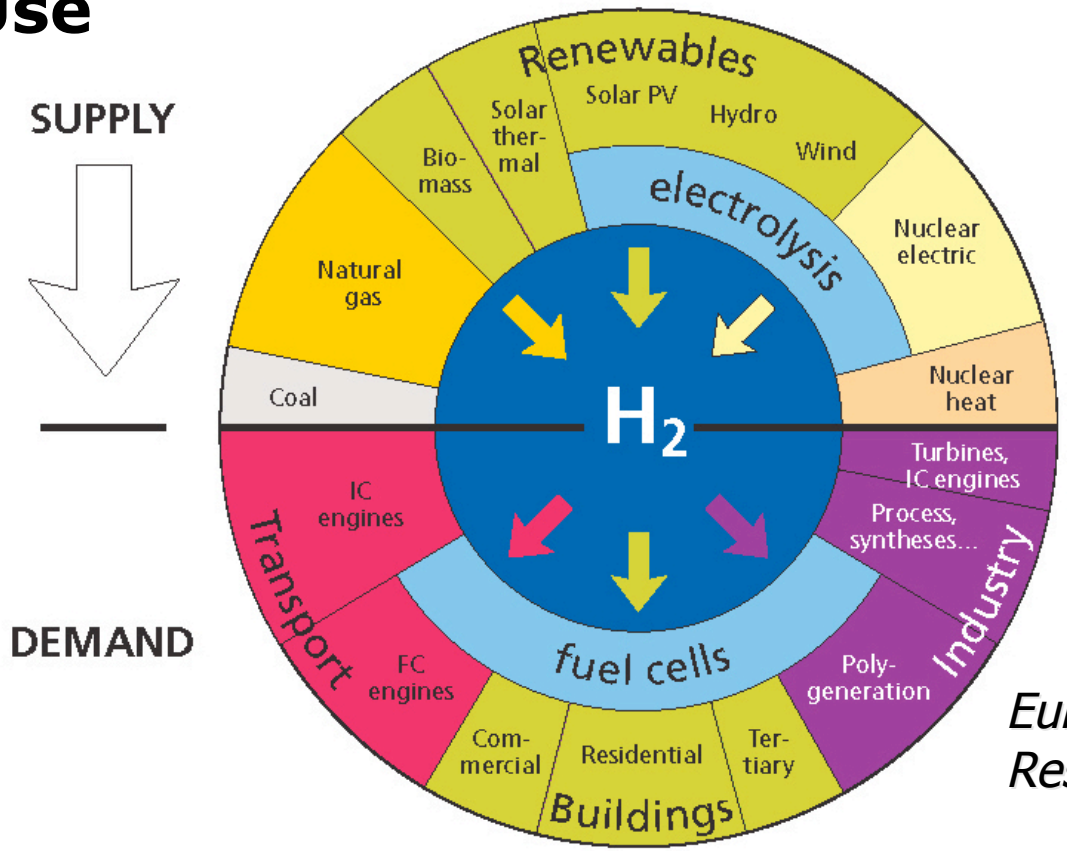
The "Hydrogen Economy"

The basis of any fuel-based energy economy:

1) Fuel Production

2) Fuel Storage/Transport

3) Fuel Use



European Union Research Directorate

And… the "Ammonia Economy?"

- **NH_3, as a replacement for H_2, changes the playing field slightly**
  - Production: Well-established; several options. Any method may be "green."
  - Storage and Transport: Easier and more efficient than that for hydrogen. Safer.
  - Use: Slightly more difficult in most applications – limited flammability, slower reaction kinetics
- **Long-term solutions for the hydrogen economy appeared to be:**
  - Production: Electrolysis from H_2O & renewable electricity.
  - Storage: H_2-resistant pipelines and ultra-high pressure tanks, perhaps chemical hydrides (a long shot).
  - Use: Hydrogen-fueled engines & turbines, fuel cells.

Fuel Production, Storage, Use

One device elegantly demonstrated all three.

A fuel cell – one that could also generate its own fuel: a regenerative fuel cell (RFC).

Regenerative Prime Movers

- **Mode 1: Power production**
  - Consumes an energetic chemical fuel
  - Produces chemical waste
  - Produces thermal waste
  - Produces useful power (mechanical or electrical)
- **Mode 2: Fuel production**
  - Produces an energetic chemical fuel
  - Consumes waste or environmentally-supplied chemicals
  - Requires a combination of thermal, mechanical, electrical power input

Constraints for an NH_3-specific system

- **Synthesis Issues**
  - Must occur at high temperature for reasonable rates
  - If Haber-Bosch, must have high pressure
  - Hydrogen source?

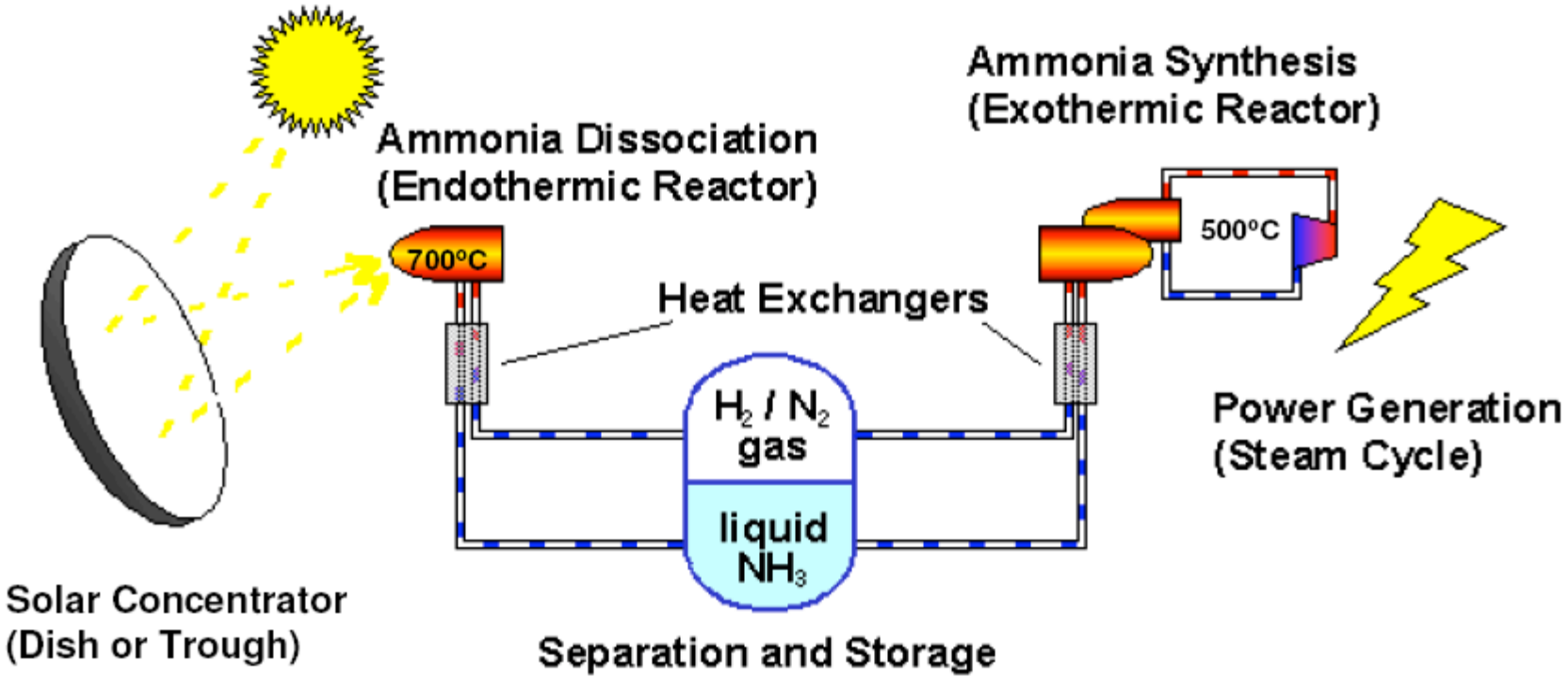
    H_2 is not a product of ammonia oxidation.
  - Nitrogen source?

    Must be free of oxygen.
- **Fuel Issues**
  - Combustion limitations
    - Oxygen enrichment?
    - Partial cracking?
  - Electrochemical oxidation (fuel cell) – usual concerns

All of this suggests that a completely closed system is necessary.

Regenerative Systems – Device Pairings

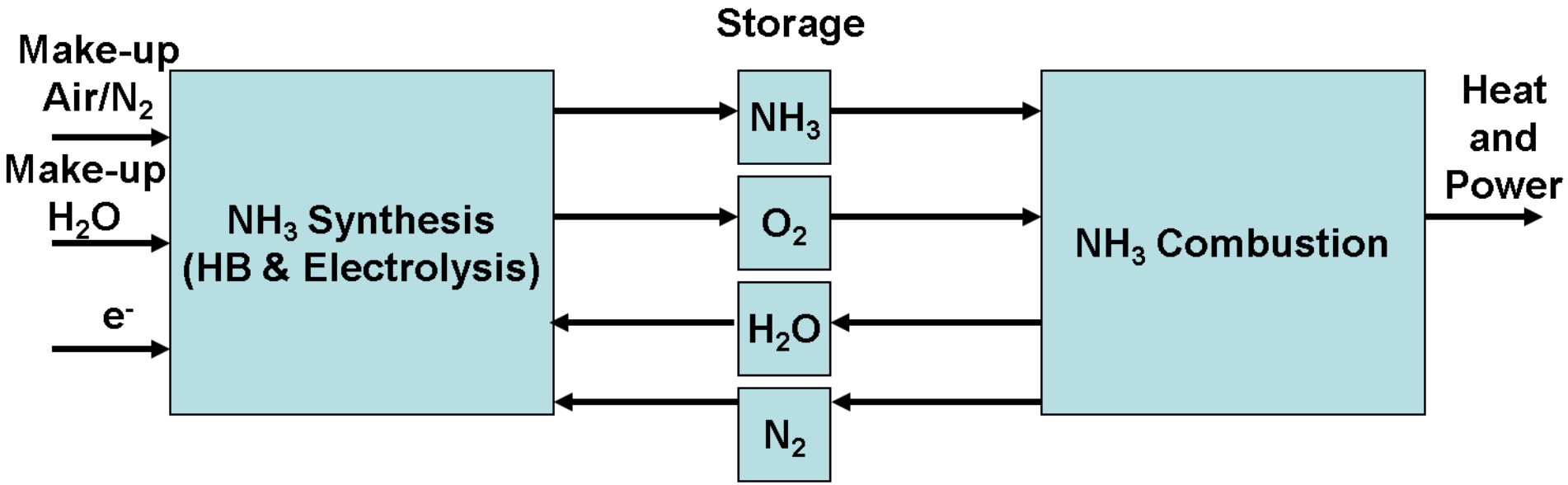
- **Heat engines – thermochemical fuel production**



Solar Thermal Group, Australian National University

Regenerative Systems – Device Pairings

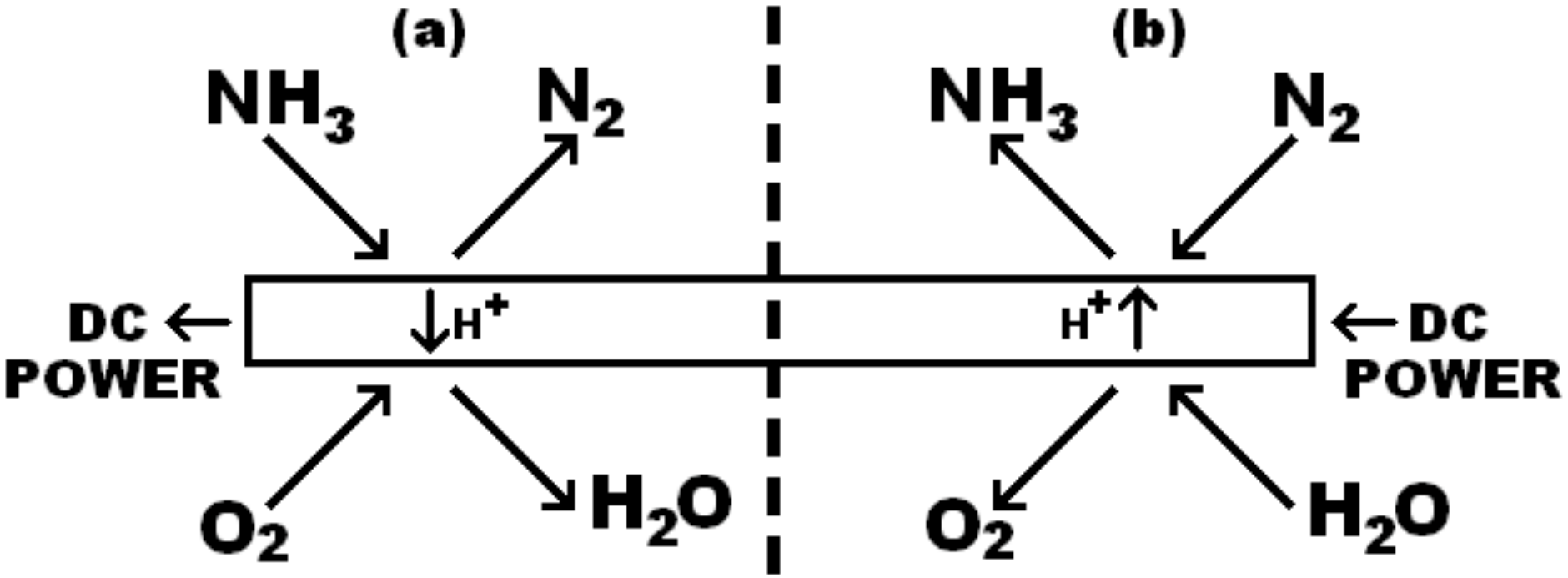
- **Direct fuel combustion – thermo-electrochemical fuel production**



Very difficult for a combustion engine to double as a compressor/ chemical reactor! Result: not a unified device.

Regenerative Systems – Device Pairings

- **Fuel cells – electrochemical fuel production**

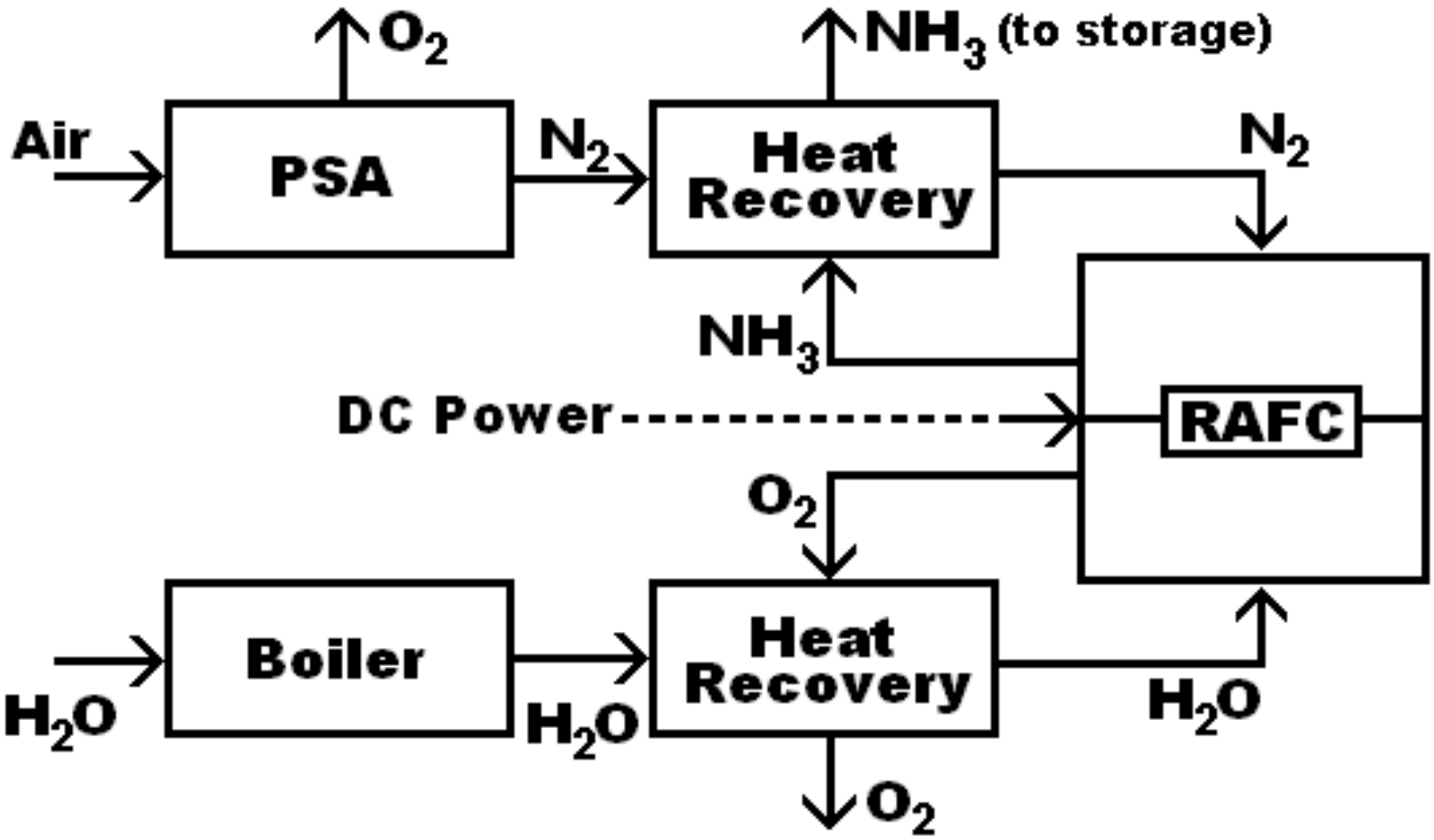


PCC membrane operating in (a) fuel cell and (b) fuel synthesis modes.

Features of the Electrochemical System

- **Four chemical Species are involved**
  - Steam and Ammonia - condensable
  - Nitrogen and Oxygen – non-condensable
  - Oxygen is only used during fuel cell mode – air feed
  - Nitrogen is used during fuel synthesis mode – trace oxygen will ruin system efficiency
- **Absence of Haber-Bosch process**
  - Hydrogen needs not be handled
  - Unified electrochemical process rather than a hybrid
    - High pressures require compressors
    - No separate electrolysis required to produce H_2

Process Layout Example



Operation in fuel synthesis mode.

Process Features

- **Auxiliary power-consuming units**
  - Boiler and nitrogen separation unit: used only for fuel synthesis mode
  - Nitrogen separation unit
    - -Cryogenic (large storage capacities required, infrequent changes in operation mode)
    - -PSA (moderate power requirements, some scalability issues)
    - -Membrane (cheap, best for small-scale, lots of power required)
- **Heat recovery units used regardless of mode of operation**

Conclusions

- **An ammonia-based regenerative fuel cell system may serve several purposes**
  - Intermittent power sources (wind, sun) may be firmed by generated and stored ammonia fuel
  - A single unit may be used with several types of electrical sources or loads
  - Units may scale to particular sources or loads by tandem operation
  - Co-located units may be selectively mode-switched to match source or load availability
- **High efficiency electrochemical processes**
  - Typical steam electrolysis: ~80% with heat recovery
  - Typical 400+°C fuel cell: ~80% with heat recovery

Questions?