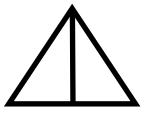

The Dual-Fuel Strategy

An Energy Transition Plan

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Ammonia hazard assessment

"[Ammonia's] toxicity and high production volume prompted EPA to list ammonia as an extremely hazardous substance...[and]…require that facility employees who could potentially be exposed to ammonia in any form be trained in the safe use and potential hazards posed by this chemical. *EPA stresses that although mishandling of ammonia can cause harm, there is no cause for undue alarm about its presence in the community. Ammonia is typically handled safely and without incident.*" [italics added]

U.S. EPA, *Chemical Emergency Preparedness and Prevention Advisory—Ammonia* (June 1990).

Personal Protective Equipment (PPE) Requirements For Ammonia

REQUIRED

RUBBER GLOVES

RECOMMENDED

FACE SHIELD
(not a substitute for goggles)

REQUIRED

EYE PROTECTION

RECOMMENDED

LONG SLEEVE SHIRT

SAFE Safe Ammonia Facilities Education

Ammonia-methanol dual-fuel pair

- Ammonia is **carbon-free**…

  …but high relative toxicity

- Methanol is **low relative toxicity**…

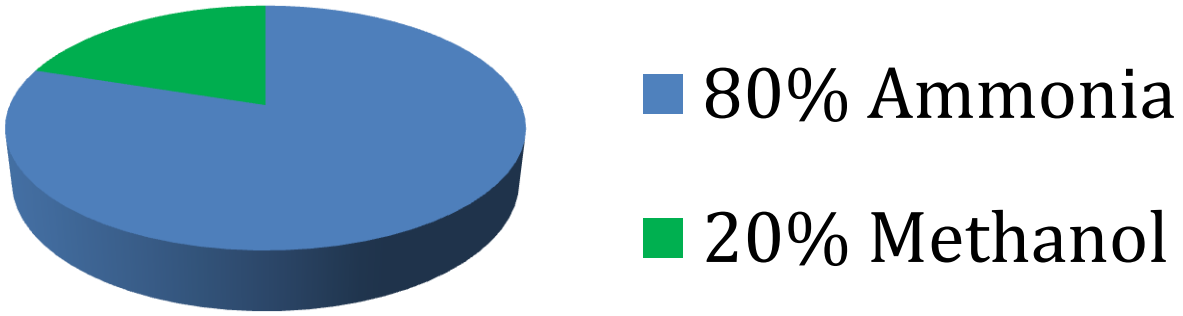
  …but contains carbon

- They are complementary:

  Each has strength to compensate the other's weakness.

Ammonia most, methanol the rest

- Ammonia: professional fuel-handlers with equipment and training
- Methanol: when non-professional persons must handle fuel



Better alternatives?

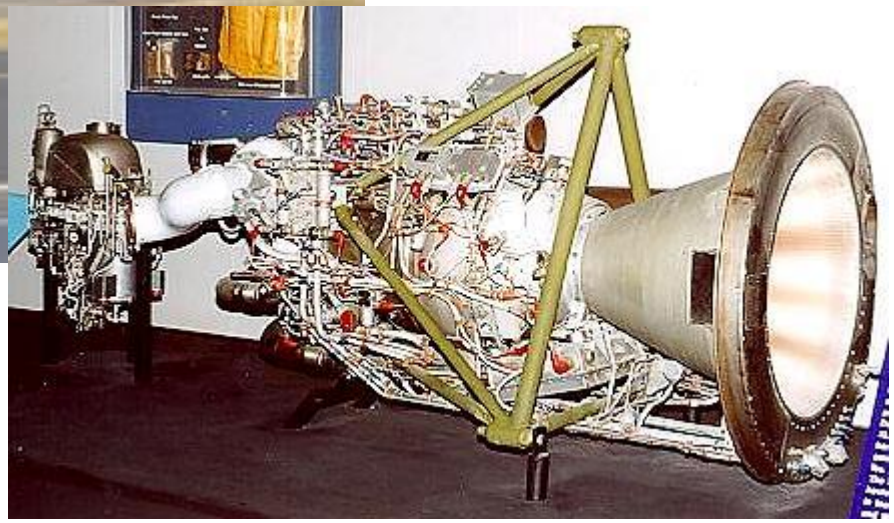
- *Nitrofuel* is nitrogen-based renewable fuel
  - NH_3 is the simplest example
  - Mixtures (e.g. Divers' solution) may be better
  - Key feature: *zero (or low) carbon*
- *Carbofuel* is carbon-based renewable fuel
  - CH_3OH is the simplest example
  - Others (e.g. EtOH, DME, CNHCs) may be better
  - Key feature: *low relative toxicity*

Methanol/C-fuel

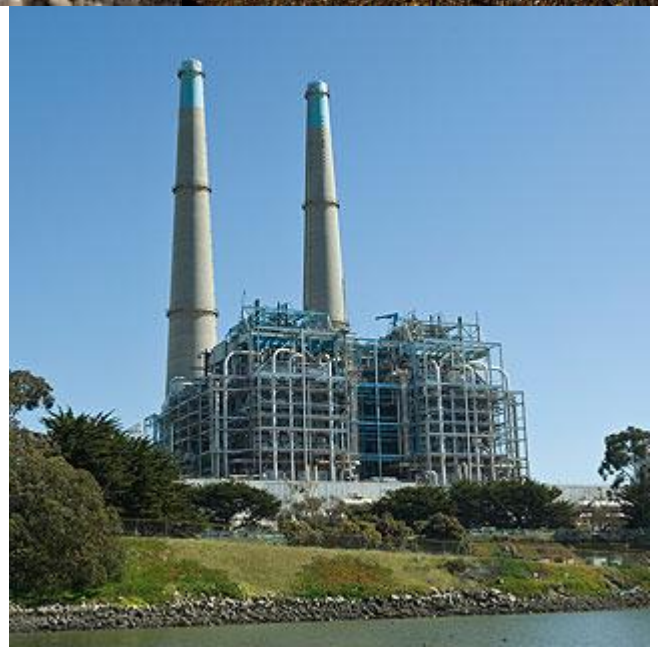
Methanol/C-fuel

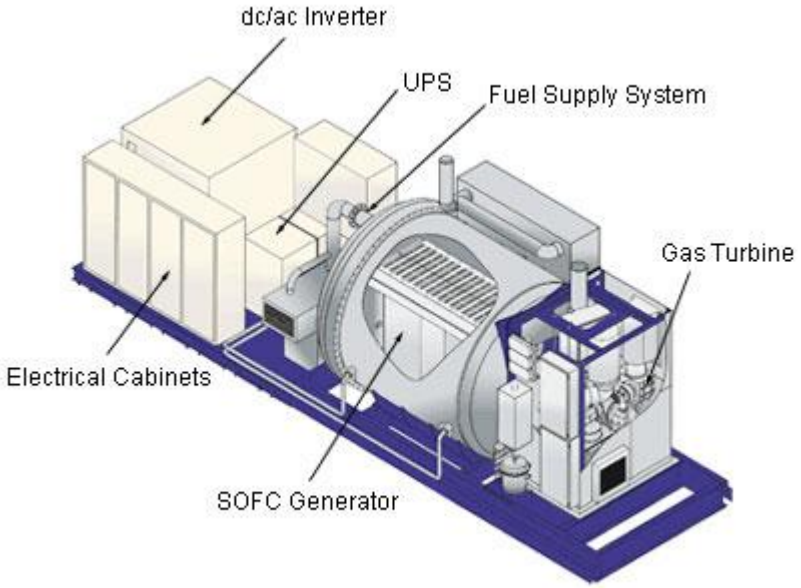
Ammonia/N-fuel

Energy density?



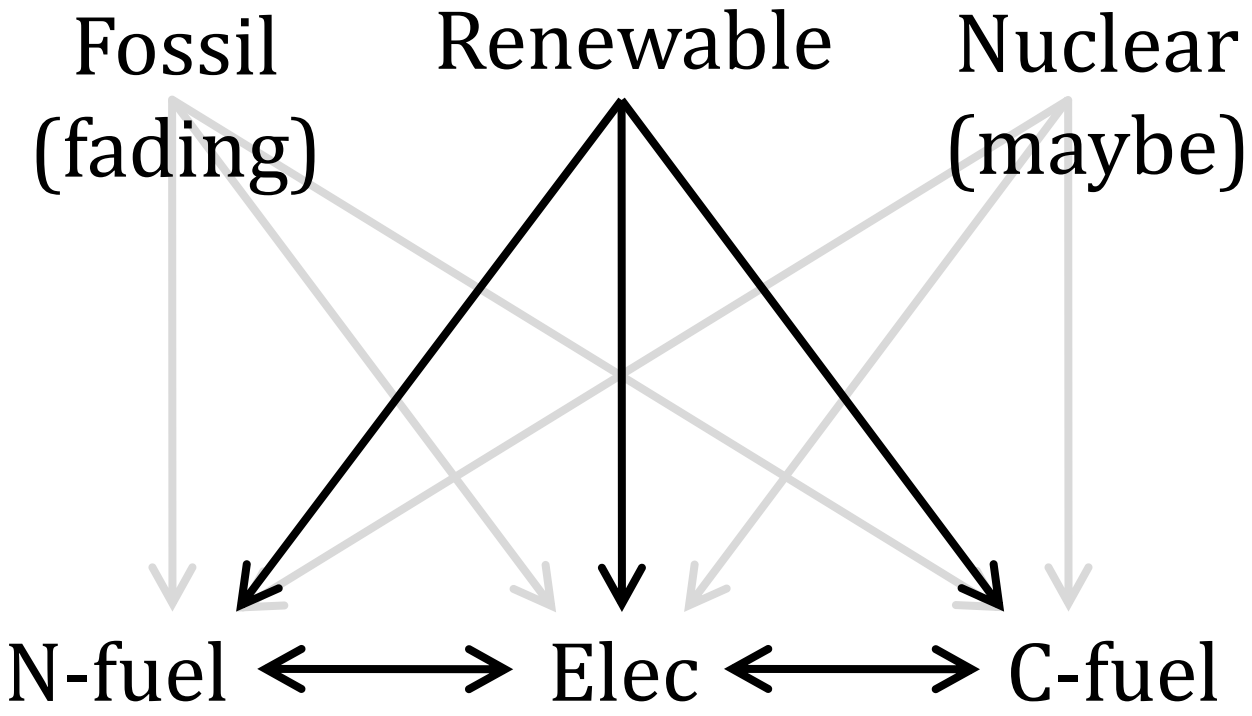
Ammonia/N-fuel





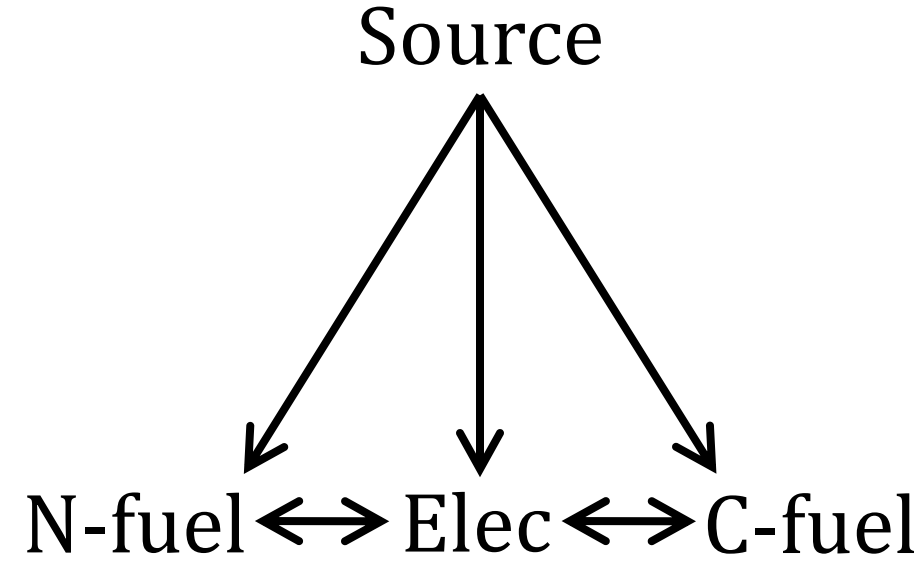
Ammonia/N-fuel

Sustainable global energy system



Highly inter-connected source-vector network makes for stable supply at low cost.

Dual-fuel energy triangle

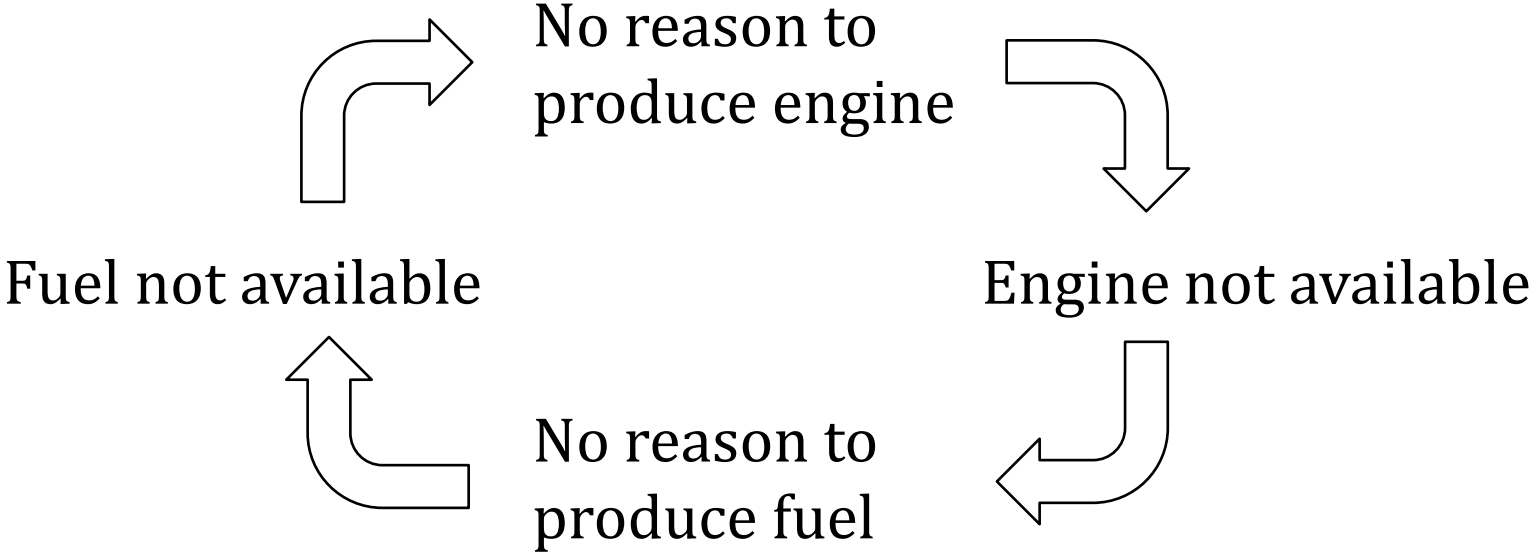


All energy trade is carried by two (or few) renewable fuels plus electric power, inter-convertible with each other.

Fossil fuels are hard to displace

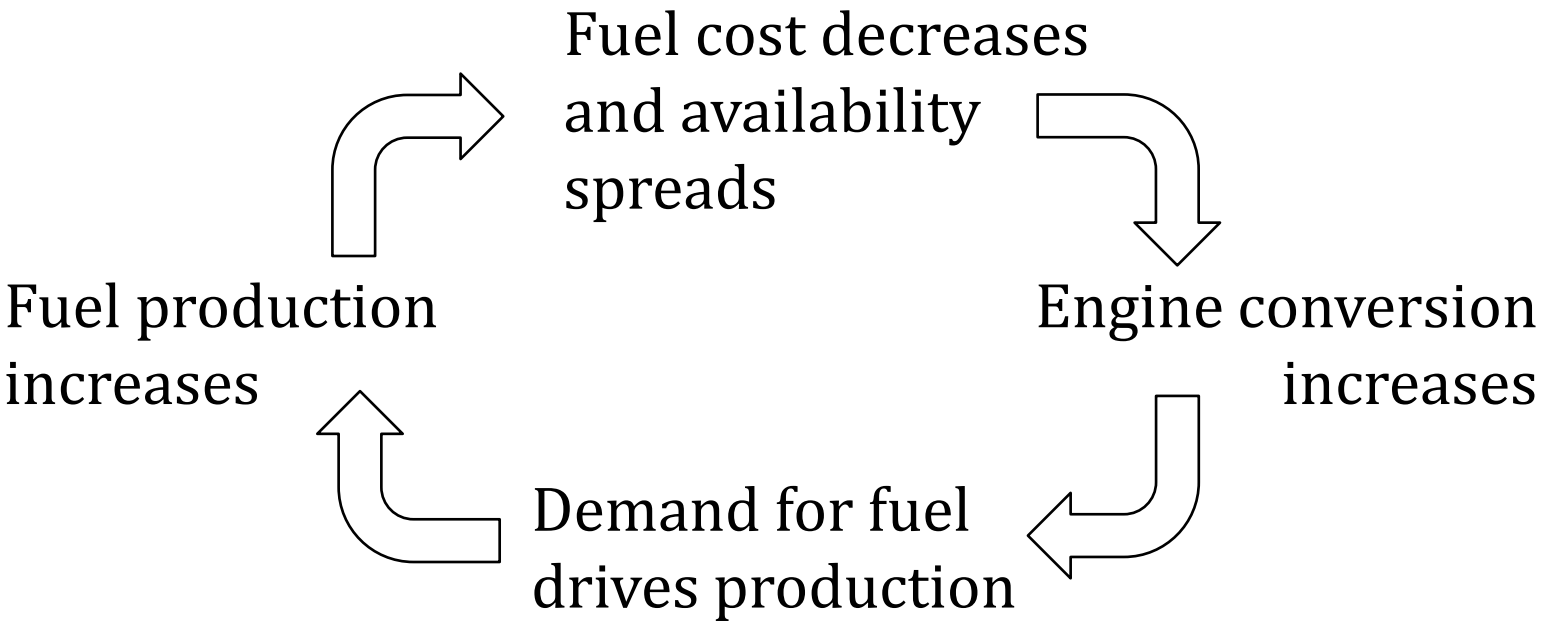
1. EROI
2. Economic inertia

Feedback prevents change



Status quo is stabilized in a <u>vicious</u> cycle: economic inertia.

Feedback will enable change



Change is driven by a <u>virtuous</u> cycle after a threshold stimulus is applied.

Trigger

Liquid renewable fuels with

- stable supply
- *one-half* cost per energy unit

…compared to competing fuels.

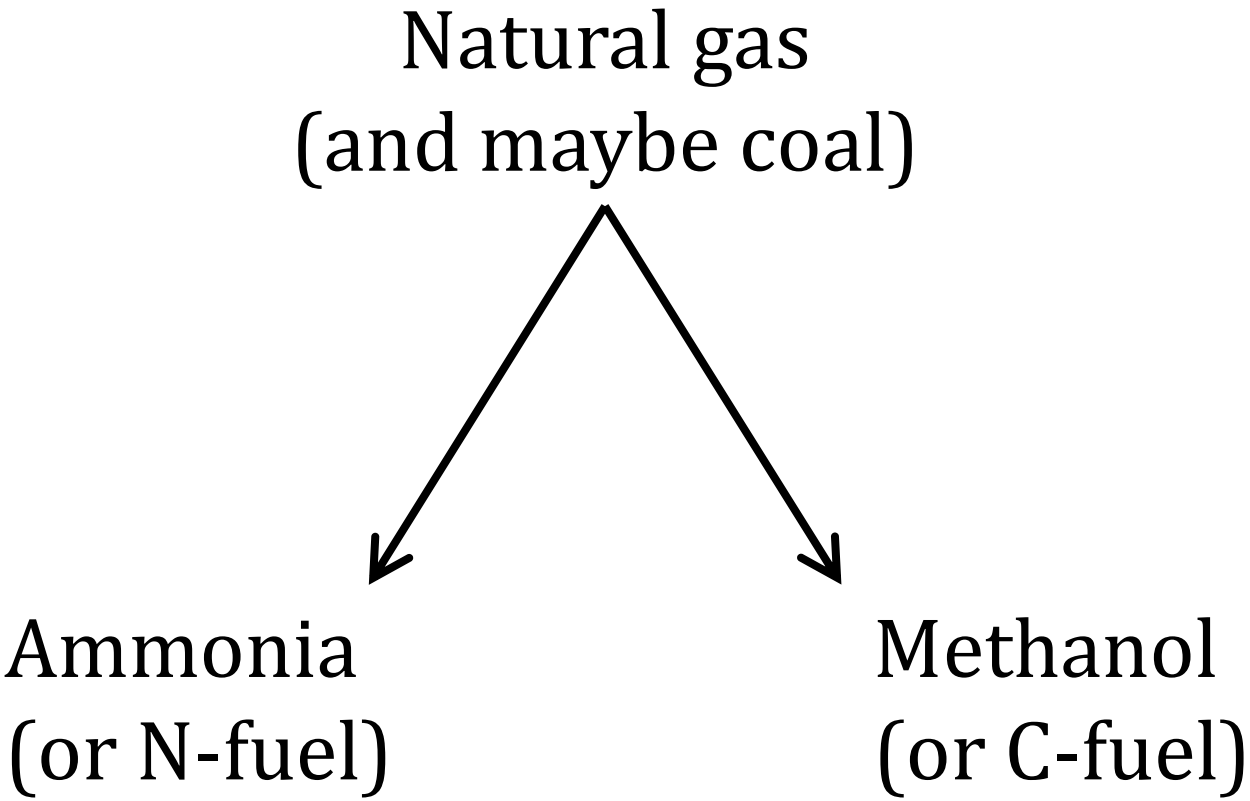
Dual-fuel strategy

- First establish market for renewable *fuel*
- Use natural gas as low-cost source to trigger the transition
- Gas-to-liquid provides competitive advantage
- Technology for production from renewable *sources* will follow

Fuel production

- Petrochemical (chemical-to-chemical)
- Thermochemical (heat-to-chemical)
- Photochemical (light-to-chemical)
- Electrochemical (electric-to-chemical)

Petrochemical production



Renewable fuels from fossil sources

- Standard practice today
- GTL/STL gives competitive advantage
- Trigger transition to DFX

It costs energy to convert NG to ammonia/methanol.
Why do it?

- Liquids are easy to transport and store
- Safety advantage—low explosion hazard
- Carbon advantage—no CO_2 emissions from ammonia at the point-of-use

⇒ *Lower cost delivered to consumer*

Are we there yet?

2009 cost estimates

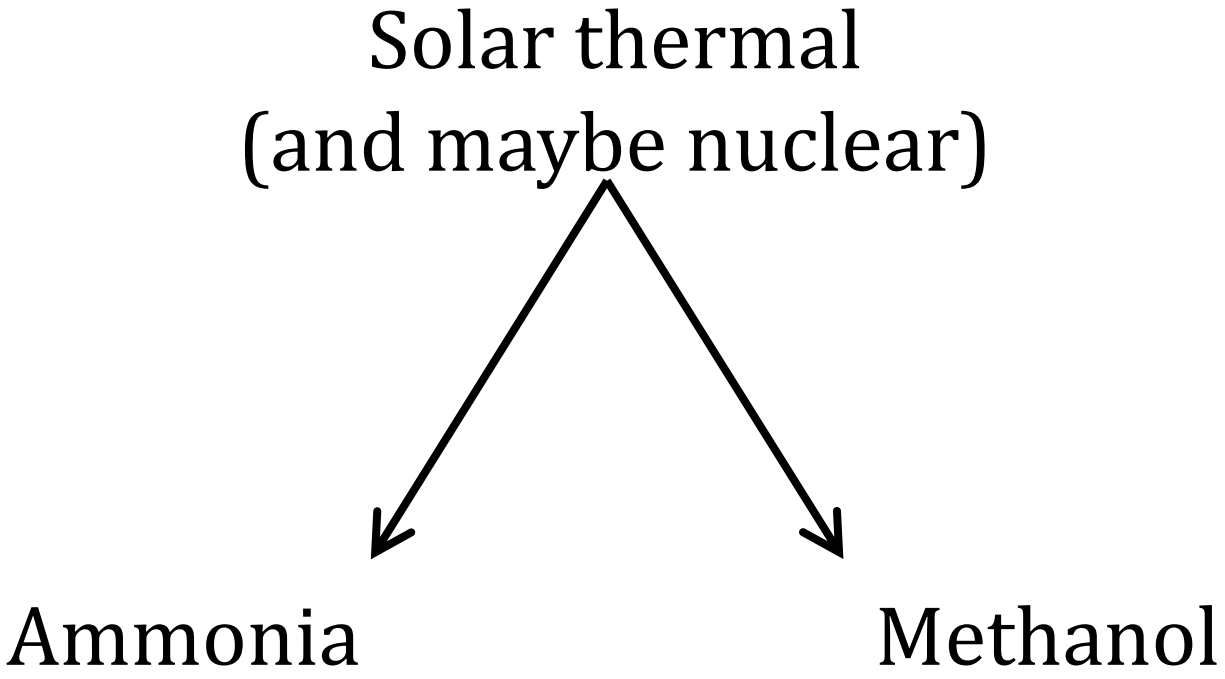
Fuel	P (bar)	Density ($kg \cdot L^{-1}$)	HHV ($MJ \cdot kg^{-1}$)	Energy density ($MJ \cdot L^{-1}$)	Cost per volume ($CN\$ \cdot L^{-1}$)	Cost per energy ($CN\$ \cdot GJ^{-1}$)
Ammonia	10	0.603	22.5	13.6	0.18	**13.3**
CNG	250	0.188	42.5	10.4	0.23	28.2
LPG	14	0.388	48.9	19.0	0.55	28.5
Methanol	1	0.786	22.7	17.8	0.42	**23.5**
Gasoline	1	0.736	46.7	34.4	1.00	29.1
Hydrogen	14	0.025	142	3.6	0.10	28.2

1 gal
= 3.8 L

C. Zamfirescu and I. Dincer, "Ammonia as a green fuel and hydrogen source for vehicular applications." *Fuel Processing Technology* 90: 729–737 (2009). Hydrogen storage as metal hydride is assumed. Methanol specific energy restored from reformer-adjusted to true value.

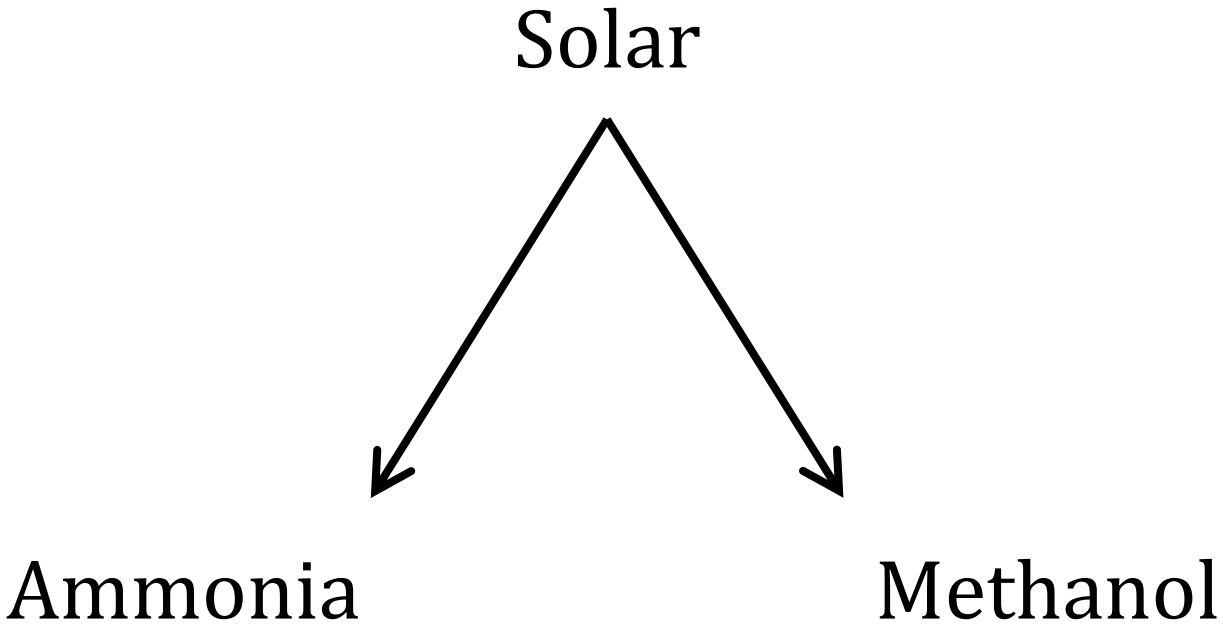
Thermochemical

Direct path from solar thermal and nuclear to renewable fuels.

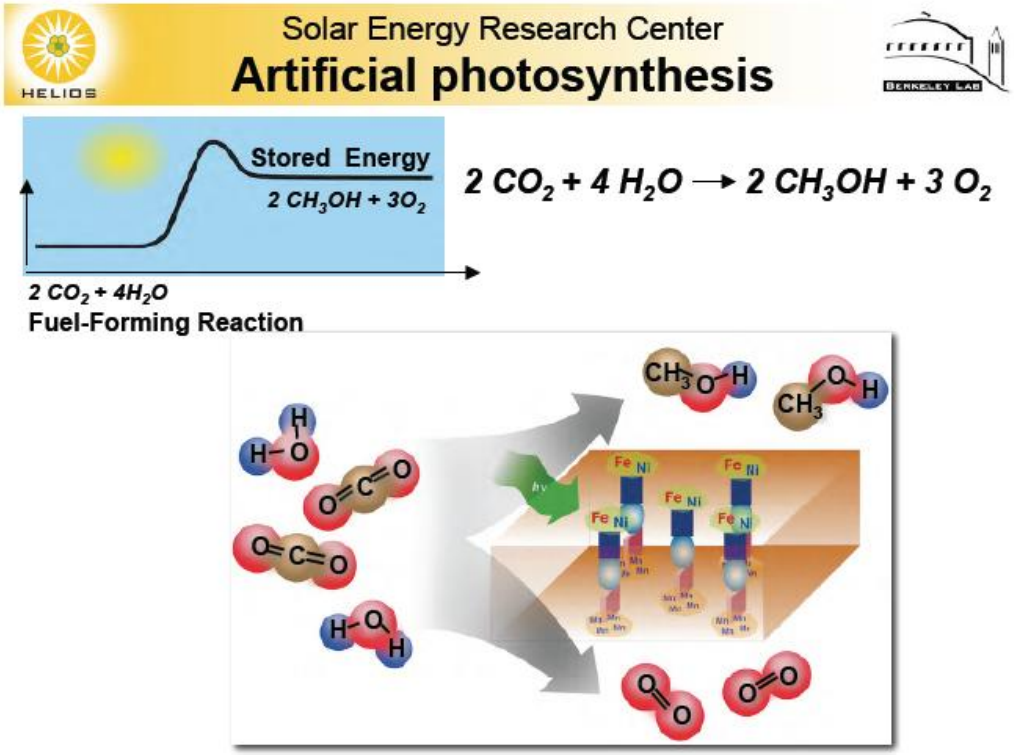


Photochemical

Direct path from solar to renewable fuels.



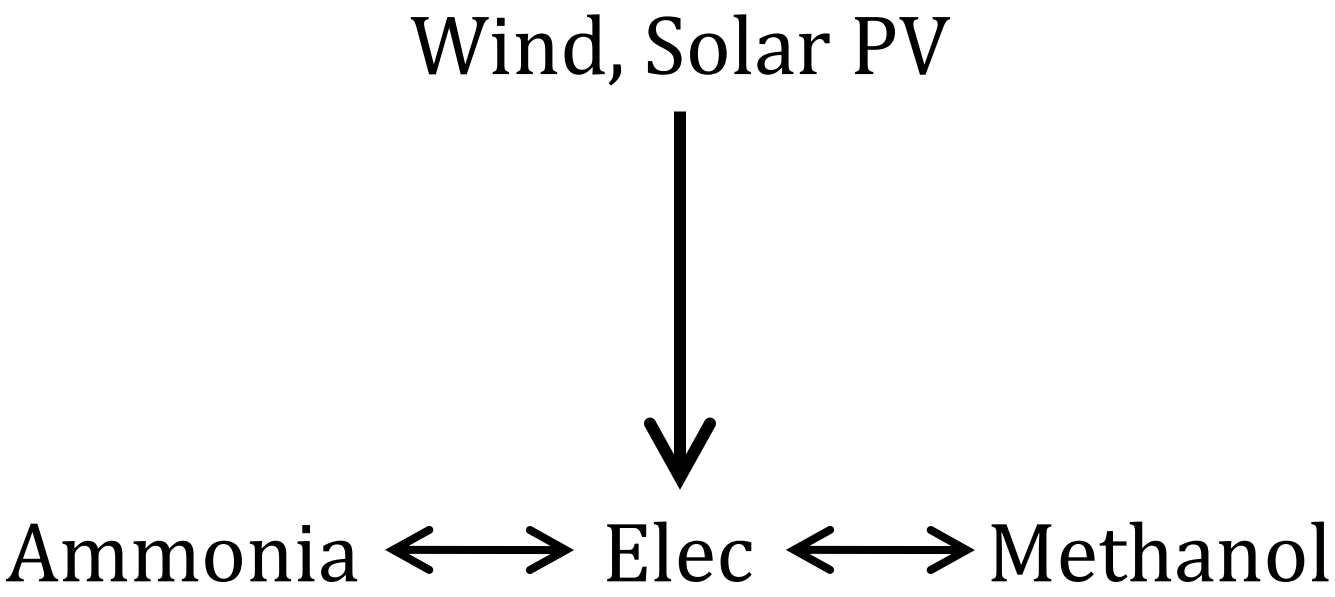
Example from LBNL



Applause!

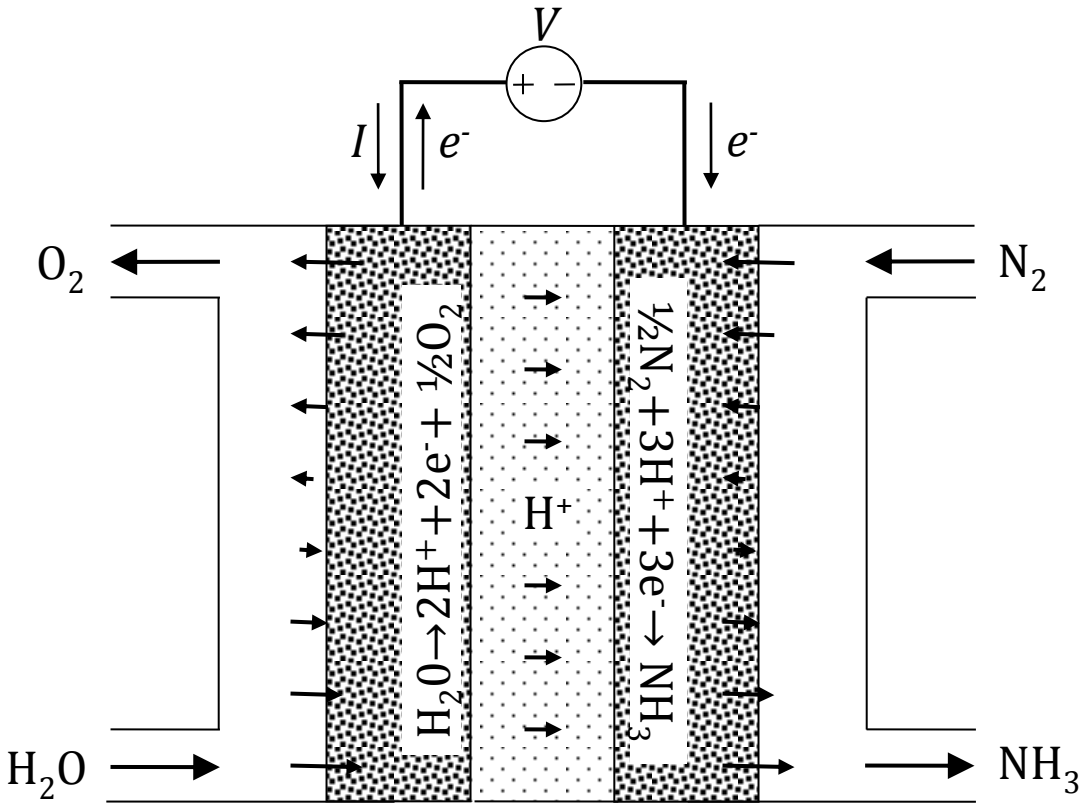
Electrochemical

An indirect path through electric power.



Example: HTEC

High-temperature electrochemical conversion using proton-conducting solid electrolytes



Conclusion

- Hydrogen as renewable fuel has a fatal flaw: it is a high vapor-pressure *gas*
- Ammonia and methanol have long been known as *liquid* renewable fuels
- Alone, each has it's own flaw that has historically discouraged development
- Together, they are a superior alternative to hydrogen